Impact of ethanol on gasoline prices in the U.S.: New evidence

David Zilberman
Department of Agricultural and Resource Economics, University of California, Berkeley, CA
zilber11@berkeley.edu

Karel Janda
Faculty of Finance and Accounting, Prague University of Economics and Business, Prague, Czech Republic
Institute of Economic Studies, Faculty of Social Sciences, Charles University, Prague, Czech Republic
karel-janda@seznam.cz

Jan Jezek
Institute of Economic Studies, Faculty of Social Sciences, Charles University, Prague, Czech Republic
39197000@fsv.cuni.cz

Vendula Letovska
Institute of Economic Studies, Faculty of Social Sciences, Charles University, Prague, Czech Republic
63605275@fsv.cuni.cz

Eva Michalikova
Faculty of Business and Management, Brno University of Technology, Brno, Czech Republic
michalikova@vutbr.cz

Paulo Rotella Junior
Department of Production Engineering - Federal University of Paraíba, João Pessoa, Brazil
Faculty of Finance and Accounting - Prague University of Economics and Business, Prague, Czech Republic
Institute of Economic Studies, Faculty of Social Sciences, Charles University, Prague, Czech Republic
paulo.rotella.junior@fsv.cuni.cz

Barbora Schererova
Faculty of Finance and Accounting, Prague University of Economics and Business, Prague, Czech Republic
schb02@vse.cz

Jan Sila
Institute of Economic Studies, Faculty of Social Sciences, Charles University, Prague, Czech Republic
Institute of Information Theory and Automation, Czech Academy of Sciences, Prague, Czech Republic
jan.sila@fsv.cuni.cz

1. Executive summary

This research report examines the impact of the U.S. policy of blending ethanol into gasoline and its subsequent effect on gasoline prices at the pump. Since the beginning of the

Renewable Fuel Standard program (RFS) in 2005, the U.S. ethanol industry has substantially increased its size and now has a direct effect, not only on the U.S. market alone but also on global crude oil prices. The size of the U.S. ethanol market has risen due to increased ethanol fuel production from 92,961 thousand barrels (Mbbl) in 2005 to 357,517 Mbbl in 2021. Several strands of research are interested in the consequences of blending mandates and policy supports, and they examine mainly the benefits for climate change mitigation, effects on the food market and food security, energy security for the U.S., and consumer benefits in transportation. This report focuses on the effect of the usage of ethanol on the retail price of gasoline. Firstly, it provides a comprehensive review of the results that may be found in the literature and analyzes available estimates. Secondly, it brings new results in quantifying the cost benefits for U.S. retail customers and understanding the dynamics through which ethanol interacts within the economy.

This report quantifies the consequences of the RFS with respect to retail prices of gasoline. The RFS program started in 2005 and, due to its volume, can and does influence global crude prices, along with U.S. gasoline prices. The accessibility of renewable fuels limits the bargaining power of the largest oil producers and brings about a higher degree of fuel security to the U.S. We estimate that blending roughly 330 million barrels of ethanol into U.S. gasoline lowers global crude oil prices as well as retail gasoline prices.

The main conclusion is that the RFS program has lowered the prices of gasoline at the pump at a statistically significant level. The estimates naturally vary in time across regions and also are dependent on the model used. Various factors play an essential role in the overall effect. Primarily, fuel demand and supply functions are very inelastic. Even more in periods where there is a relative scarcity of fuel, and thus, the price impact of ethanol policies is high. However, in periods when the market is saturated, demand and supply elasticities are higher, and consequently, the price impact of the RFS program is lower. Shortages in the fuel market are then associated with very low elasticities. Our models are based mainly on the period from 2010 to 2022, when the price of the WTI crude oil fluctuated between \$20 and \$120. This price volatility then translates naturally to our estimates.

Our main result is that adding ethanol to gasoline decreases the price paid by U.S. drivers at the pump. We estimate the average discount per gallon to be \$0.77 between 2019 to 2022 and averaged across our models. Considering an average yearly U.S. consumption of 2,940,000 Mbbl of gasoline, or 123,480 million gallons of gasoline, this would add up to total savings of \$95.1 billion per year for U.S. consumers. Compared to the 2021 GDP of \$22,996 billion, the savings represent around 0.41% of the U.S. nominal GDP.

Our average result summarizes the central tendency of the range of our estimated results coming from different models and scenarios ranging from the lowest savings of \$0.32 to the highest savings of \$1.74 per gallon. We provide a comprehensive discussion of the result in Section 4.4. Moreover, we provide additional evidence from qualitative models in Section 5, which lay out more context to the point estimates.

Contents

2. Introduction

Agriculture is linked to everyday life globally in the context of providing food and fuel. For several years, the biofuel industry has been growing substantially around the world, particularly due to biofuel programs established in the United States, the European Union, and Brazil, which aim to tackle the availability of transportation fuel, the balance of trade and climate change (Zilberman et al. 2013). Naturally, the increase in biofuel production sparked a keen interest in research in various aspects, whether they contribute to energy or environmental goals. Biofuels in the U.S. have developed into a very important topic relevant to energy and food security, environmental change, rural economic development, and transportation, to name a few.

Notably, the discussion over the benefits of ethanol changed during the food crisis in 2008 when it inclined more toward the negative sentiment. The affordability of food due to higher demand for corn has been discussed intensively in numerous articles during the food crises between 2008 and 2010 (Tokgoz et al. 2007, Abbott et al. 2008, Rosegrant 2008, Collins 2008, Trostle 2010, Hochman and Zilberman 2018), or in a comprehensive review of the then available literature by Janda et al. (2012). Later, Hochman et al. (2014) show that for most crops, biofuels were not the most significant factor responsible for the price spike in food commodity prices. They note that price spikes can be mitigated by appropriate inventory-management policies or mechanisms that would allow poor countries to purchase food at predetermined prices.

More recently, Hochman and Zilberman (2018) provide a meta-analysis of the estimates of corn ethanol on food and fuel prices a decade after the 2008 food crisis and review the biofuel impacts with additional data. While this is not the only quantitative meta-analysis concerned with ethanol, it is the most comprehensive one since it covers different features of the biofuel economy. This study links the concerns about food security to the overall merit of ethanol for fuel prices, greenhouse gases (GHG), and indirect land use change (ILUC). The main result is that assumptions in assessing the biofuels effect play an important role; models which allow for feedback mechanisms usually report a lower impact of biofuels on food and petroleum prices. Also, emission effects are smaller in models considering connectedness among markets and regions. Besides, Hochman and Zilberman (2018) find that studies that assume more inelastic supply and demand curves report greater price effects of biofuels.

Generally, biofuels are a controversial topic that is rich in research avenues. One large strand of literature focuses on the ecological impact of biofuels, particularly the life-cycle analysis (Oehlschlaeger et al. 2013, Rajagopal and Plevin 2013, Hill et al. 2006, Demirbas 2008). Along this direction Farrell et al. (2006) estimate that ethanol can contribute to ecological and environmental goals by significantly reducing greenhouse gas emissions, petroleum inputs, and soil erosion. The other large body of literature concerns the price impacts of biofuels on oil or gasoline. The price effect of ethanol on fuel prices is still an open question to which we contribute in this report.

The literature included in Hochman and Zilberman (2018) estimates an average of $0.12 per gallon of fuel savings in 2005 U.S. dollars. However, the meta-analysis finds a large measure of heterogeneity among the included studies. In a similar fashion to Hochman and Zilberman (2018), Khanna et al. (2021) compares the most recent results, but their study focuses on the effects of biofuels on food commodity prices, GHG emissions, and ILUC-related issues rather than the economic benefits of biofuels for transportation. Nevertheless, they conclude that the ecological effects of ethanol are smaller than generally believed. Du and Hayes (2009) estimate the impact of ethanol on regional wholesale gasoline prices between 1995 and 2008. By modeling the crack ratio and the crack spread, they find that the impact varies considerably across regions with savings of $0.07 per gallon in the Rocky Mountains, $0.28 per gallon in the Midwest, and $0.14 per gallon on average. An updated study (Du and Hayes 2012) concludes that the average ethanol cost cut across all regions increases to $1.09/gallon and regionally ranges between $0.73/gallon in the Gulf Coast to $1.69/gallon in the Midwest. The work of Du and Hayes (2009) and Du and Hayes (2012) is replicated and thoroughly questioned by Knittel and Smith (2015).

This report contributes to the discussion by estimating the economic benefits of ethanol blending in the U.S. for retail customers. In order to achieve robust results, we use several different methodologies to obtain answers to our research question about the possible discount retail consumers obtain at the pump due to gasoline blending. The main result of the positive net effect (lower prices) at the pump is confirmed. We construct both structural models as well as time series econometrics-based models. We obtain a comparable set of estimates from all methodologies, and our new estimation results are well related to the existing results documented in our systematic literature review.

This report proceeds as follows. Firstly, we offer a comprehensive systematic review of the current literature and extract numerical results based on a replicable and structured review procedure in Section 3. In this way, we obtain a unique up-to-date overview of the estimations of the effect of ethanol on U.S. gasoline retail prices provided by academic peer-reviewed literature. Secondly, we provide new estimates of the price effect using time-series regressions and a partial equilibrium model in Section 4. Thirdly, we discuss findings concerning the relationship of ethanol with other biofuels, commodities, and their dynamics in Section 5.

3. Systematic literature review

The biofuel policy debate is ongoing and evolving rapidly and substantially. We take the rich discussion presented above as evidence not only of the complexity of the biofuel topic but also of the evolution of results over time. In this study, we add to the discussion on price impacts; more specifically, we review the literature concerning the impact of blending ethanol into gasoline in the U.S. Our systematic literature review identifies the methods used in the research and their contribution to modeling ethanol's effect. The aim of this study is to provide a review of the state-of-the-art literature regarding the impact and contributions of corn ethanol on retail gasoline prices in the US. To assist in achieving this goal, we propose these research questions **(RQ)**:

RQ1: What are the main characteristics of the literature regarding the impact and contributions of ethanol on US retail gasoline prices?

RQ2: What was the numerical impact of the former Volumetric Ethanol Excise Tax Credit (VEETC), which expired in 2011, and the ongoing Renewable Fuel Standard (RFS) mandate on the price of gasoline and what are the main methodologies used for calculation in the literature?

RQ3: What are the main article clusters identified in the evaluated literature?

RQ4: What are the main trends and possibly new research directions for this literature?

In the main part of this report, we focus on the first two RQs, which are the most relevant. Additional material answering RQ3 and RQ4 can be found in the Appendix.

3.1. Materials and methods

Systematic literature review (SLR) can be defined as a structured review process that allows other researchers to replicate and validate the research conducted and exactly follow the path chosen for the research (Tranfield et al. 2003). In this way, SLR differs from a traditional exploratory review, reducing the researcher's subjectivity, and resulting in a scientific, transparent, and replicable process (Pires et al. 2021). In the SLR proposed in this study, we conduct a systematic process composed of three phases: Input (i), Processing (ii), and Output (iii) (Levy and J. Ellis 2006, de Oliveira Azevêdo et al. 2020). In the Input phase, we define the research problem and its objectives along with studies relevant to the literature. We identify the main keywords of the publications that would contribute to the discussion about the appropriate search strings for performing the SLR. It is important to note that the proposed research questions guide the research development and the presentation of results. Due to its sufficient acceptance and breadth, the Scopus database (from Elsevier) was selected.

After carrying out exploratory attempts, we adopt the search strings presented below, considering the Boolean logic "and" between levels (i), (ii) and (iii). The use of the symbol " " guarantees the exact sequence of words. Finally, some variations as plural and singular were considered.

i **Title** ("ethanol" or "biofuel" or "bioethanol" or "renewable fuel)
ii **Paper title, keywords or abstract** ("U.S" or "US" or "USA" or "U.S.A" or "United States" or "Midwest" or "corn")
iii **Paper title, keywords or abstract** ("gasoline price" or "fuel price" or "gas price" or "petrol price" or "petroleum price" or "retail price" or "gasoline market" or "fuel market" or "gas market" or "petrol market" or "petroleum market" or "petroleum product market" or "wholesale" or "price support")

It is pertinent to point out that we use the term "corn", since the research focuses on North American ethanol, along with the use of "Midwest". In this way, we use the term "corn" in the geographic section of the filter to capture studies that deal with corn ethanol and that, for some reason, do not use the U.S. (or similar) descriptor in the title, abstract, or keywords. We used the bibliometric analysis software VOSviewer and *Bibliometrix* R Package (Aria and Cuccurullo 2017) for some of the analysis.

In the Processing phase, we proceeded to define the eligibility criteria while ensuring that the sample responds adequately to the formulated RQs. The inclusion and exclusion filtering procedure was conducted by all co-authors of this study in sequence, thus ensuring the quality of the final sample. In a search carried out in September 2022, the search strings resulted in 202 publications in the Scopus database. After reading the title, abstract, keywords, and search results, we reduced the list to 130 articles since part of the initial sample was outside the scope of the research. After an initial read of the results and conclusions, we applied the second filter and obtained a sample of 112 articles. Finally, the articles were subjected to a complete reading, and we narrowed down the sample to 109 articles.

We list the most important exclusion criteria here:

(a) Studies from foreign countries (such as Brazil, Argentina, Mexico, EU, Thailand, etc.) whose ethanol comes primarily from sugar-related feedstocks
(b) Evaluation of different biofuel feedstock (cellulosic, lignocellulosic, agricultural biomass, oilseeds, etc.)
(c) Studies focused on other issues (food price impact, greenhouse gas impact, ethanol blending, government impact and opinions about subsidies, etc.)
(d) Studies of other fields (chemistry, the technology of production, etc.)

3.2. Results and discussion

3.2.1. Sample characterization To answer RQ1 (what are the main characteristics of the literature regarding the impact and contributions of ethanol on US retail gasoline prices), we start with the temporal distribution of the articles. Figure 1 presents the annual distribution of articles in the sample. This figure also displays the percentage of the sample in the general literature on the topic, that is, when the search string (ii) is removed, without any restriction by country or area (obtaining the ratio of the publications related to the U.S. to the World). It is important to highlight the interest in the subject in the U.S. compared to the general literature. Even though we observe a greater interest in the topic between 2009 and 2012, our report shows that this topic is still very relevant and important to researchers.

The journals with the highest number of publications are Energy Policy, Energy Economics, and the American Journal of Agricultural Economics. Figure 26 in the Appendix

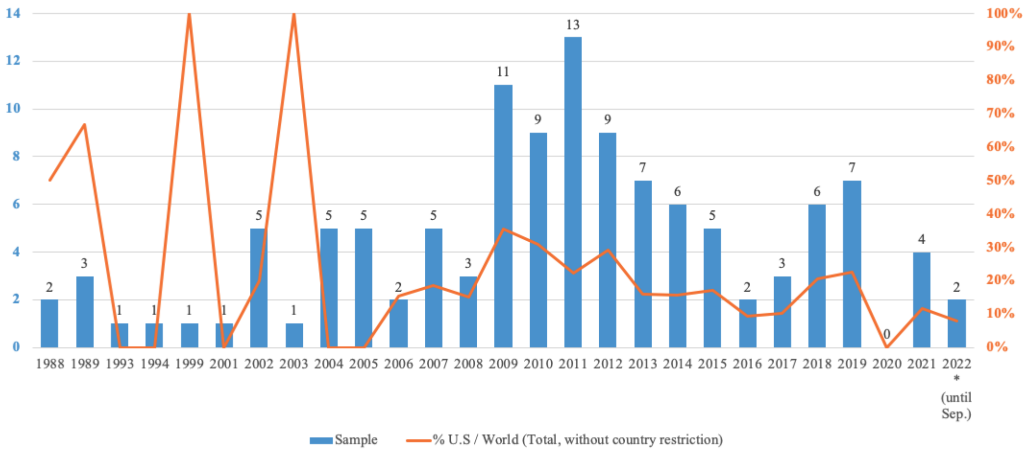


Figure 1 Annual distribution of publications from 1988 to September 2022

presents the prominent scientific journals with at least three articles in our sample. Most publications are found in journals with expertise in energy, agriculture, and others more specific to ethanol and biofuels. Interestingly, the shortlists also include the Journal of Environmental Economics and Management, which has a broader scope and is not exclusively focused on the above-mentioned areas. Figure 27, also in the Appendix, presents the authors or co-authors (individually) most representative in the sample with the largest number of publications. Thompson and Zilberman stand out, with eight and six articles each, respectively. Followed by Meyer, Whistance, and Yacobucci, who each contributed to the list of publications with five manuscripts.

With respect to citations, authors Hill (Hill et al. 2006) and Demirbas (Demirbas 2008) dominate with more than 2000 and 800 citations, respectively. Studies by Zilberman (Zilberman et al. 2013) and de Gorter and Just (de Gorter and Just 2009a) are also very relevant, with over 140 citations each. The most cited publications include different scopes, such as existing relationships and the impact of biofuels on commodity food prices (Zilberman et al. 2013, Serra et al. 2011, Zhang et al. 2009, Martin 2010), the environmental impacts of biofuels (Hill et al. 2006, Sahin 2011, Thompson et al. 2011), policy issues and their implications (de Gorter and Just 2009b, Condon et al. 2015). Here we present a summary of the article's contents.

- **Hill et al. (2006)** · The study carries out an environmental and economic assessment of energy costs and the benefits of biodiesel and ethanol biofuels. Through life cycle assessment, the study evaluates corn ethanol and soybean biodiesel. The main finding is, that compared to fossil fuels, biofuels have a lower environmental impact. However, no biofuel had the ability to replace oil without affecting food supplies and subsidies are needed to make biofuels profitable.
- **Demirbas (2008)** · The manuscript presents definitions, details, compositions, production information, use, and future perspectives that address biofuel sources, biofuel policy, biofuel economy and global biofuel projections. The study considers scenarios of the impacts of biomass on the world economy.
- **Rajagopal et al. (2007)** · The authors argue using the conceptual model with back-of-the-envelope estimates that ethanol subsidies in the short run actually pay for itself and that impact of the production of biofuels from food feedstock will be bigger on food prices rather than energy prices.
- **Zilberman et al. (2013)**· The study uses time series econometrics to assess the impact of biofuels on commodity food prices. The main finding is that the price of ethanol increases as the prices of corn and gasoline increase. The study also finds that ethanol prices are positively related to sugar and oil prices in equilibrium.
- **de Gorter and Just (2009a)** · The study presents a conceptual framework that allows analyzing the economics of a mandate for biofuels and evaluates the economic implications of the combination with a tax credit. Results indicate that tax credits result in lower fuel prices than under a mandate for the same level of biofuel production. If tax credits are implemented along with mandates, tax credits would subsidize fuel consumption instead of biofuels, thus creating a contrary effect to the energy policy objectives.
- **Serra et al. (2011)** · The study evaluates price relationships and transmission patterns in the US ethanol industry between 1990 and 2008. The research describes the relationships between corn, ethanol, gasoline, and oil prices. Overall, the results indicate a strong relationship between food prices and energy.

- **Mueller et al. (2011)**· In an extensive literature review, the article assesses the impact of biofuel production and other supply and demand factors on rising food prices. The results indicate that the production of biofuels had a smaller contribution to the increase in the prices of food commodities until 2008.
- **Sahin (2011)** · The study assesses the environmental impacts of biofuels. The results indicate that ethanol produced from biomass offers environmental and economic benefits and is considered a cleaner and safer alternative than fossil fuels.
- **Zhang et al. (2009)**· The study proposes a multivariate modeling framework to assess short and long-term relationships between corn, soybean, ethanol, gasoline, and oil prices. The paper evaluates if these relationships change over time. The results indicate that in recent years there are no long-term relationships between agricultural commodity prices and fuel prices.
- **de Gorter and Just (2009b)**· This study proposes a framework to assess the effects of a tax exemption on the biofuel consumer and the interaction effects with a price-contingent agricultural subsidy. It finds that the tax credit reduces the costs of the loan fee program, but this increased the costs of the tax credit.
- **Gardner (2007)** · This study analyzes whether farmers prefer a direct subsidy on corn production or rather a subsidy on ethanol produced from corn. The study uses a vertical model of ethanol, byproducts, and corn and it finds that farmers are better off with direct corn subsidies.
- **Thompson et al. (2011)** · The authors propose the use of economic models applied especially in the US to assess the effects of biofuel policies on petroleum product markets and their consequences for greenhouse gas emissions.
- **Condon et al. (2015)** · The study proposes a literature review and a meta-analysis model to assess the impacts of ethanol policy on corn prices between 2007 and 2014. The results indicate that an expansion of the corn ethanol mandate can lead to an increase of 3 to 4 percent in next year's corn prices.
- **Martin (2010)** · The study, through a literature review, evaluated the corn ethanol industry, its impacts on food prices, and the role of biotechnology in the U.S. Among their findings, the authors identified that biotechnology had little impact on the biofuels sector.

Figure 2 shows the Tree-Field plot, establishing relationships between the most frequent journals in the sample, the main authors, and the author's keywords. Thompson, one of the most relevant authors in the sample, has had his studies published in journals such as Energy Policy, Eurochoices, and The Economics of Alternative Energy Sources and Globalization. This author has used terms such as “ethanol”, “greenhouse gas emissions”, “renewable fuel standard”, “biofuel mandates” and “gasoline” as keywords in his studies. In the same perspective, Zilberman, another relevant author on the topic, has published in journals such as Agricultural Economics, American Journal of Agricultural Economics and Agbioforum. The main keywords included in his works are “biofuels”, “greenhouse gas emissions”, “energy prices”, “energy policy”, “climate change” and “corn ethanol”.

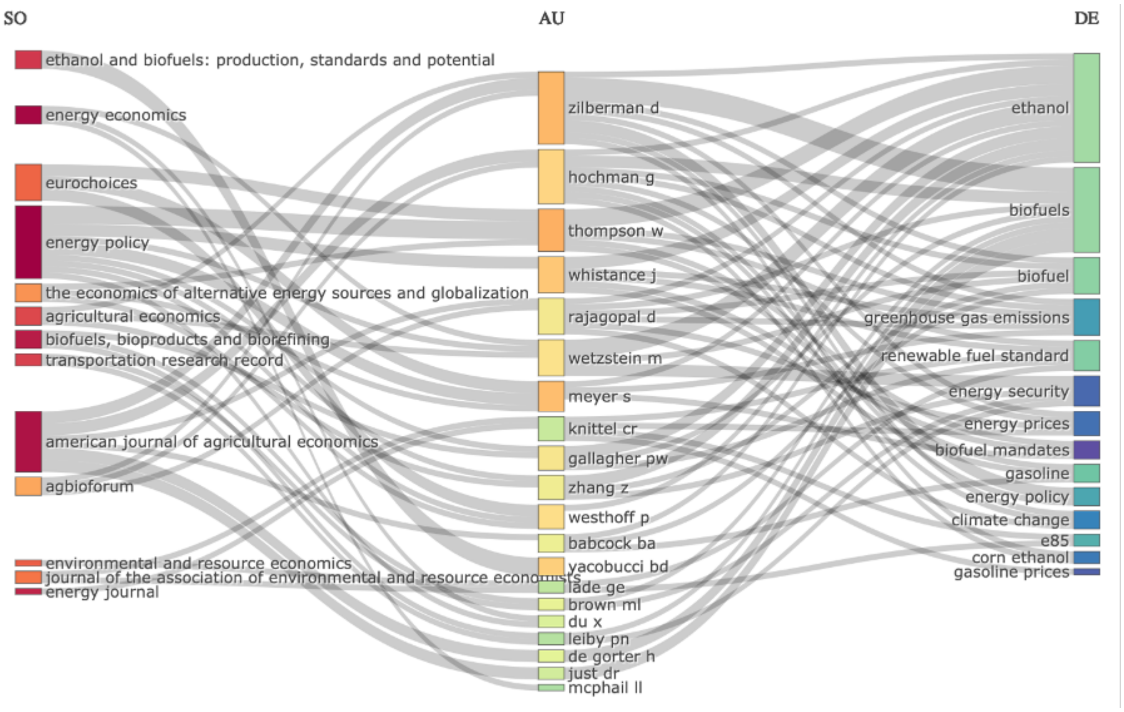


Figure 2 Tree-Field plot (Authors x sources x keywords)

In sequence, we created Figure 22 using the VOSviewer software and it is based on the co-occurrence information of the authors' keywords (van Eck and Waltman 2010).

In this figure, the node sizes represent the number of times the articles in the sample used these keywords; the connecting lines indicate that these keywords were used in the same publication, while the colors are related to the year of publication. The relevance of the topics “Renewable Fuel Standard” and “policy” protrude, even though they were not included in the search strings. This network also allows the identification of trending topics for the area, as they represent interests in recent research, such as “retail fuel spreads”, “pass-through”, “fuel markets”, “E85”, or even “energy prices” and “meta-analysis”.

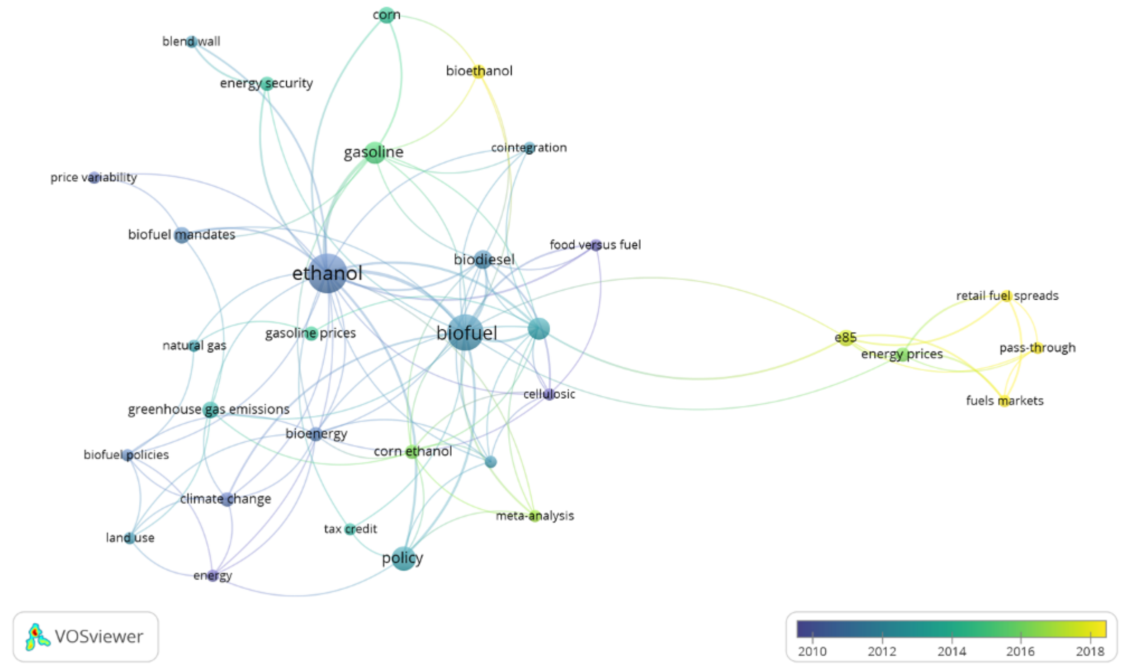


Figure 3 **Keyword co-occurrence map**

3.2.2. Numerical estimates We now turn to our sample to analyze numerical estimates of changes in gasoline prices caused by changes, or rather a lack of changes, to ethanol mandates. We extracted 20 articles that provide numerical results that relate to our research question. After the initial inspection, we notice that many of the articles included in our sample also make part of the meta-analysis article by Hochman and Zilberman (2018). Consequently, we have decided to include 4 missing articles that were not a part of our sample but were included in Hochman and Zilberman (2018) to further our understanding of the numerical interpretation of the results. It is important to highlight that these four studies are relevant and recognized for the field of research, but they were not identified in the search due to the fact that they were not present in the Scopus database.

First, we briefly discuss the approach, methodologies, and models used in the aforementioned articles. Figure 4 shows the most frequent models used. The most popular are General and Partial equilibrium models, Biofuel and Environmental Policy Analysis Models (BEPAM), and Supply-Demand models.

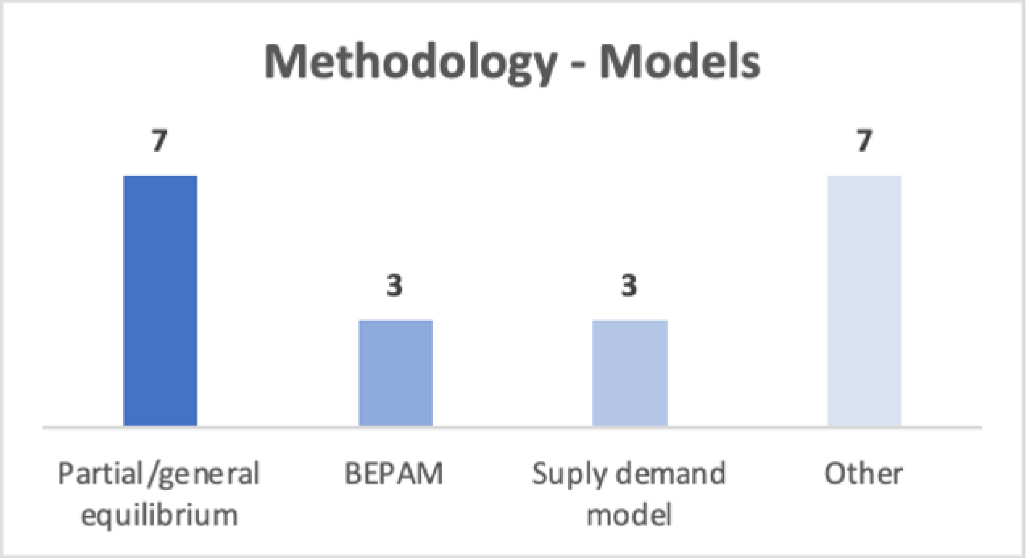


Figure 4 **Count of models used in the literature**

When it comes to the policies that affect the price of gasoline, the articles mostly use the Volumetric Ethanol Excise Tax Credit (VEETC) created by the American Jobs Creation Act of 2004 and the Renewable Fuel Standard for corn ethanol established in 2005 and expanded in 2007 as the drivers of the change of the price of gasoline. Some articles, such as Bento et al. (2015), inspect many possible outcomes based on different scenarios where there are no mandates in place for the baseline price and where VEETC or RFS or their combination are introduced, changing the outcome by 1-2 percentage points. Some other articles, such as Chen et al. (2011), take into account only the RFS ethanol mandate and its impact on gasoline prices.

Overall, we identify 13 papers that provide us with exact numerical results for the answer to our research question **RQ2**: (What was the numerical impact of the VEETC/RFS mandate on the price of gasoline, and what are the main methodologies used for calculation in the literature). Detailed information about the papers in our sample coming from the SCOPUS database is summarized in Table 1 while Table 2 presents the four papers not included in the SCOPUS database.

The prevailing result is that adding ethanol cuts down the price of gasoline at the pump. However, no direct consensus exists on the discount provided, not even in proportional expression. The estimates vary from no effect up to almost 10% discount in the gasoline price, as shown in Figure 5. Our models instead try to come up with original numerical estimates. We introduce them in the following section.

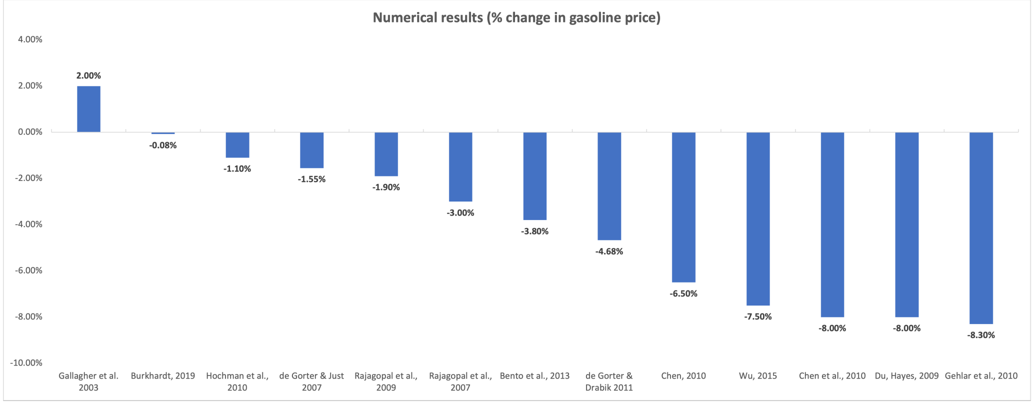


Figure 5 Ethanol relative effects reported in the literature

Table 1 This table summarizes publications providing numerical estimates of the impact of ethanol on fuel price. The first column references the publication and the second column the inspected time period. The third column reports on the model used, while the Relation column suggests whether ethanol and gasoline are considered to be substitutes (Sub), complements(Comp) or perfect substitutes (pSub)

Publication	Period	Model	Relation	Result
McPhail and Babcock (2012)	2006 2010	Stochastic partial equilibrium	Sub	Gasoline CV → from 0.21 to 0.26 CV
Pouliot and Babcock (2016)	2015	Open economy partial equilibrium	n/a	Increase in biofuel mandate up to 16.6% results in 1.46% decrease in gasoline price
Koto (2015)	10/2006 12/2013	TAR, M-TAR, M-TVECM	Compl	Retail prices of gasoline and ethanol are cointegrated. There exists a bi-directional Granger causality between them. Shocks to ethanol prices have lasting effects on gasoline prices rather than vice versa.
Burkhardt (2019)	2012 2014	Primary fixed effects model	n/a	1 cent per gallon increase in the RIN tax obligation resulted in a 0.971 cent/gallon increase in gasoline prices and a 0.781 cent/gallon increase in USD prices respectively. (approx. 0.08%)
Du and Hayes (2009)	1995 2008	The crack ratio (pCR)	Sub	Ethanol production lowers gasoline prices by \$0.14/gallon (average of 8%)
McPhail (2011)	1994 2010	Joint structural VAR	n/a	Ethanol demand expansion indicates stronger support for biofuels and more competition for crude oil demand, which leads to a decrease in oil prices.
Bento et al. (2015)	2009 2015	General equilibrium model	pSub	Policies cause gasoline price to decrease from 2.8% to 4.8% (averages)
Drabik and de Gorter (2011)	2007 2022	BEPAM	n/a	Tax credit leads to 3.8% decrease of world gasoline price; RFS mandates lead to a decrease from 5.2% - 5.9% in world gasoline price; RFS and tax credit lead to a 4.9% - 5.2% decrease in world gasoline price
Gehlhar et al. (2010)	2005 2022	General equilibrium model	Sub	RFS2 in 2022 causes gasoline price to decrease by 9.8% if the petroleum import supply elasticity is 2 and by 6.8% if the elasticity is 5.5
Hochman et al. (2010)	2007	Cartel-of-Nations model (CON)	Sub	Ethanol causes oil prices in importing countries to decline by 1.07-1.10%
Rajagopal et al. (2007)	2006	Conceptual model of supply and demand	n/a	Ethanol causes decrease in fuel price by 3%
Rajagopal et al. (2009)	2007	Partial-equilibrium multimarket framework	n/a	Without ethanol supplies, gasoline prices would be between 2.4% and 1.4% higher
Wu and Langpap (2015)	1976 2005	General equilibrium model	pSub	RFS Ethanol mandates and subsidies lowered the price of gasoline by 5 – 10%

Publication	Period	Model	Relation	Result
Chakravorty et al. (2019)	2005 2011	Simple partial equilibrium dynamic model	Perfect substitutes	RFS ethanol mandate leads to a reduction in poverty in rural areas by approximately 4.8 ppt, and an increase in poverty in urban areas by approximately 1.04 ppt.
Chen et al. (2011)	2007 2022	BEPAM	Imperfect substitutes	RFS ethanol mandate reduces the price of gasoline by 8% in 2022
Chen (2010)	2007 2022	BEPAM	Imperfect substitutes	Ethanol mandate reduces gasoline consumption by 5-8%.
de Gorter and Just (2008)	2006 2015	Stylized supply-demand model	Substitutes	RFS mandate decreases gasoline price by 1.4% in 2006, RFS mandate decreased gasoline price by 1.7% in 2015

Table 2 This table summarizes publications in the analysis of Zilberman et al. (2013) concerned with the impact of ethanol on fuel price or welfare. The first column references the publication and the second column the inspected time period. The third column reports on the model used, while the Relation column suggests whether ethanol and gasoline are considered to be perfect or imperfect substitutes.

4. Novel core quantitative findings

4.1. Full sample regression

The most straightforward approach to determining the impact of growth in ethanol production on U.S. retail gasoline prices is to run a full sample regression to explain gasoline prices with ethanol supply. The linear model, which is fitted on weekly data from June 2010 to June 2022, suggests that the gasoline prices relate to ethanol supply according to the following regression equation:

$$gasoline_t = 4.15 - 0.0008221 \cdot ethanol\ supply_t + \epsilon_t$$

This simple model suggests that for each additional unit (thousands of barrels of ethanol per day), the gasoline retail price decreases by \$0.0008. We report the complete regression output in Figure 28 in the Appendix. The current share of ethanol in gasoline is roughly 10.3% of the resulting fuel volume. Assuming that this relationship is stable over time, and the share of ethanol increases to the currently desired 15% of volume, it would take an increase in the supply of 45.6% (4.7 ppts from 10.3% to 15%). Given that the 2022 average daily supply was about 1,005 thousand of barrels, this increase would require an additional 1005*0.456 = 458 thousand barrels, which would decrease the retail gasoline prices by 458*0.0008221=\$0.377, which is approximately 38 cents.

Clearly, the market has changed substantially, and so has the role of ethanol's impact on the global crude oil market. Such a naive approach does not capture time-varying characteristics of the market and does not model ethanol's effect on gasoline prices well. This example merely motivates the following research and suggests that the investigation of ethanol's role is economically meaningful.

4.2. Model of elasticities

In order to properly investigate the effect of ethanol blending into petroleum gasoline on fuel price, we use an adjusted version of the core model introduced by Drabik et al. (2016). The model by Drabik et al. (2016) is based on interconnections between the fuel, food and corn markets. Biofuel production is generally significantly dependent on policies in force. In 2010, the dominant policies affecting the amount of ethanol produced were the blend mandate and a binding blender's tax credit. Our source model by Drabik et al. (2016) therefore offers three versions. Firstly, there is a benchmark scenario with no applicable laws. The authors here determine a system of equations for the total U.S. corn supply, total demand for food, price transmission elasticities, ethanol supply, and equilibrium in the fuel market. Secondly, Drabik et al. (2016) introduce a binding blend mandate and, finally, a binding blender's tax credit scenarios into the system of equations with definitions of fuel price, ethanol supply, equilibrium of ethanol market price, and price transmission elasticities. The original source model with the introduced scenarios is calibrated to 2010 with the conversion of all fuel prices and quantities into gasoline energy equivalents, which are further used for the simulation of the no biofuels benchmark and policy scenarios. For the determination of the price transmission effect, additional exogenous shocks in corn supply, corn export, and corn feed demands are introduced, and price transmission elasticities are estimated with Monte Carlo simulation. The simulation of 2009 data then indicates that the response of corn and food prices to shocks in the corn or food markets is lower in the presence of biofuels.

Even though the detailed price transmission in corn and food markets, resulting from implemented ethanol policies, is not the main aim of this project, the structure of the original model by Drabik et al. (2016) provides an important second output in the form of a simulation of fuel price dependent on the effective policies. Therefore, the original model is thoroughly examined through tracking of all essential equations with its raw input data and, as previously mentioned, we extract a narrower specification to model fuel price.

Modest adjustment to the original model is made to update it for effective policies. Contrary to the situation in 2010, only the blend mandate policy has been relevant in the past years; hence the two other scenarios from Drabik et al. (2016) are not taken into account. The blend mandate scenario provides a rich structure that allows for a thorough examination of the effect of ethanol blending. As the model and its system of equations work with fuel prices dependent on the level of blended ethanol in petroleum gasoline, extraction of the model might be used to analyze the effect of different blend mandates on fuel prices.

Finally, we build an updated model for Fuel price (PF). It is dependent on the Foreign gasoline consumption (DF), U.S. gasoline supply (SH), Foreign gasoline supply (SF), an auxiliary calibrated parameter for the U.S. fuel consumption (A), the level of blend mandate (αE) and U.S. fuel demand elasticity (ηDH)

$$PF = \frac{SH + SF - DF}{((1 - \alpha E)A)^{\frac{1}{\eta^{DH}}}} \tag{1}$$

In this case, the inputs of Foreign gasoline consumption (DF), U.S. gasoline supply (SH), and Foreign gasoline supply (SF) are simulated variables that are based on raw data for Gasoline price (PG), Foreign fuel demand elasticity (ηDF), U.S. gasoline supply elasticity (ηSH) and Foreign gasoline supply elasticity (ηSF), as well as auxiliary calibrated parameters B, C and D:

$$DF = B(PG + tROW[1])^{\eta^{DF}} \tag{2}$$

$$SH = C \cdot PG^{\eta^{SH}} \tag{3}$$

$$SF = D \cdot PG^{\eta^{SF}} \tag{4}$$

The auxiliary calibrated parameters B, C, and D, which are used for scaling the simulated variables, are computed through raw data for both the U.S. and foreign gasoline supply and prices.

The initial calibrated parameter for U.S. fuel consumption (A) is equal to the ratio of U.S. fuel consumption (DH) and Price of fuel (PF), adjusted by the U.S. fuel demand elasticity (ηDH)

$$A = \frac{DH}{PF^{\eta^{DH}}} \tag{5}$$

The U.S. fuel consumption (DH) is merely the sum of the ethanol production (E) and the U.S. gasoline consumption (GUS) (both expressed in energy terms)

$$DH = E + GUS \tag{6}$$

The energetic equivalent of ethanol production is equal to the ethanol consumption and is derived from raw data variables for U.S. production of yellow corn (SC), U.S. domestic corn demand as food/feed ($DNY\ US$), U.S. corn exports (X), Miles per gallon of ethanol relative to gasoline (λ) and Ethanol yield per bushel of corn (β).

$$E = (SC - DNY\ US - X) \cdot \lambda \cdot \beta \tag{7}$$

Variable GUS determines the level of U.S. gasoline consumption by subtracting the amount of U.S. ethanol supply (e) from the total amount of U.S. motor fuel consumption ($DF\ US$).

$$GUS = DF\ US - e \tag{8}$$

The U.S. ethanol supply (e) is the ratio of ethanol production (E) and the energetic equivalent of ethanol relative to gasoline (λ).

$$e = \frac{E}{\lambda} \tag{9}$$

The second significant part of the calibrated parameter (A) is the Price of fuel (PF), which corresponds to the weighted average of the ethanol and gasoline prices, adjusted for the fuel tax (tUS), and the ethanol tax credit (tc)

$$PF = \alpha(PE + \frac{tUS}{\lambda} - \frac{tc}{\lambda} + (1-\alpha) \cdot (PG + tUS) \tag{10}$$

Here, similarly to the U.S. ethanol supply (e), PE is computed as the ratio of the ethanol market price (Pe) and the energetic equivalent of ethanol relative to gasoline (λ)

$$PE = \frac{Pe}{\lambda} \tag{11}$$

After the complete deduction of the extracted part of the model into all necessary core equations, we identify 17 base variables of raw data for prices, quantities, elasticities, taxes, and technical parameters during the process. The summary of all base variables, along with their sources and other details, can be found in Table 8. Building upon the original model, the consistency with original sources of the data is maintained in order to replicate the model most precisely.

The main data sources used were the U.S. Energy Information Administration (EIA) and the Economic Research Service of the U.S. Department of Agriculture (USDA). For the last couple of decades, EIA has been, among other activities, gathering and assessing energy data, hence providing an extensive database and information on energy production, stocks, demand, imports, exports, and prices. The Economic Research Service (ERS) of USDA aims to research and analyze the U.S. food supply system in order to forecast tendencies and issues mainly related to the agricultural environment and rural America, as well as provide independent and quality information for the general public. Reuters Datastream served as a source for the ethanol market price series. All values for elasticities were taken from Drabik et al. (2016) as these are long-run data, similar to the technical parameters for ethanol equivalency relative to gasoline and ethanol yield per bushel of corn. The overview of variables and their sources is in Table 8 in the Appendix. Eventually, the corn ethanol blender's tax credit was set to zero as the policy expired on January 1, 2012.

The original 2009 raw data from Drabik et al. (2016) are put into the new model with the resulting price of \$2.56 per GEEG of fuel which is exactly in line with the paper. The replication of the original data and model is a necessary confirmation of the accuracy of our model for further replication of the data from recent years and an indication of a correct approach. Continuing with the analysis, we simulate data for the years 2018 – 2021 and compare the resulting fuel prices from our new model with the actual fuel prices from the respective years. As the simulated prices fit the reality (with only slight deviations in some years, maximal deviation of 6.8%), we are able to calibrate the model to 2022.

We input all the raw data of 2022 into the model with the resulting simulated fuel price of \$4.77 per gasoline energy-equivalent gallon (GEEG). Compared to the actual average fuel price of 2022 at \$4.78 per GEEG, the simulated price deviates negligibly from the real price by circa 1 cent. Such negligible deviation confirms the consistency and accuracy of the model's calibration to reality. Note that the \$4.78 per GEEG is the price of blended fuel, including an adjustment of the ethanol price for its energy content as shown in Equation 11 and Equation 10, so it is higher than the actual price of finished gasoline at the pump.

The simulated fuel prices, based on the actual ethanol blend rates for the consecutive years as taken from the EIA, are presented in the eight row in the middle of Table 3. The table then displays different scenarios for possible levels of blend mandate. For example, if there were no ethanol blended into the petroleum gasoline, such a scenario would result in an additional cost for the customer at the pump, as estimated to be ranging from \$1.08 in 2020 to predicted \$1.74 in 2022 per GEEG. On average, from 2018 to 2022, the costs are \$1.326. For 2022, consumers would have to pay \$0.86 per gallon more if the blend mandate were lowered to 5% and an even higher surcharge of \$1.56 per gallon in the case of a 1% ethanol blend mandate or the mentioned \$1.74, in case that ethanol is not mixed in at all. However, the real effects of the blend mandate set to 5% or less would need more inspection as the actual blending might be higher due to the need for ethanol as a gasoline octane source.

Having the partial equilibrium model, we can change the input value of the blend mandate and run the scenario. Increasing the blending ratio from the current 10.34% to 15% results in the final price of \$4.10 per GEEG, causing a saving of an extra \$0.67 per each gallon of fuel at the pump for the consumers, when compared to the estimated 2022 fuel price.

Besides the considered 15% level of ethanol mixed into the petroleum gasoline, other significant values of blend mandate can be included for us to compare the effect of different blend rates on the final fuel price. Table 3 introduces the accurate values for the level of ethanol blended into the gasoline in the years 2018-2022, as reported by the RFA (source of the data for the report is EIA). Additional scenarios that vary from 0% to 30% with a 5% difference are included.

For the 20% level, the resulting saving from the simulated fuel price is \$1.32 per gallon. A 25% level of blended ethanol would lead to almost \$2 per gallon saving, precisely \$1.90. Consumers would save on average \$2.40 per gallon of fuel thanks to the 30% blend mandate.

Figure 6 illustrates the trend of decreasing per-gallon fuel prices as blended ethanol increases. The range of the blend levels starts at 0% and increases all the way to 30%.

	2018	2019	2020	2021	2022*
No blended ethanol (0%)	4.69	4.50	4.02	5.25	6.51
Cost for 0% blend rate	1.26	1.22	1.08	1.33	1.74
E5 (5%)	4.03	3.87	3.46	4.58	5.62
Cost for 5% blend rate	0.60	0.59	0.53	0.66	0.86
E10 (10%)	3.44	3.31	2.96	3.96	4.82
Cost for 10% blend rate	0.01	0.02	0.02	0.04	0.05
Actual blend rate of ethanol	10.08%	10.2%	10.25%	10.34%	10.34%
Simulated Fuel price (PF)	3.43	3.29	2.94	3.92	4.77
E15 (15%)	2.90	2.80	2.51	3.40	4.10
Saving for 15% blend rate	0.53	0.49	0.43	0.52	0.67
E20 (20%)	2.43	2.35	2.11	2.89	3.45
Saving for 20% blend rate	0.99	0.94	0.83	1.03	1.32
E25 (25%)	2.01	1.95	1.75	2.43	2.87
Saving for 25% blend rate	1.42	1.34	1.18	1.49	1.90
E30 (30%)	1.65	1.60	1.44	2.02	2.37
Saving for 30% blend rate	1.78	1.69	1.50	1.90	2.40

Table 3 This table shows scenarios of fuel prices for different ethanol blend rates. The first row shows the effective blend mandates for the consecutive years, while the second row presents the simulated fuel prices obtained from our model, based on the blend rates, with the year 2022 predicting the yearly price. The table continues with possible scenarios for different levels of blended ethanol and resulting fuel prices, along with associated additional costs or savings for consumers, as compared to the Simulated Fuel price (PF) - for example, E15 stands for fuel with 15% of blended ethanol. All data for prices, costs, and savings are in dollars per gasoline energy-equivalent gallon ($/GEEG).

The 5 rainbow lines represent different years for comparison purposes, with the X marks indicating the simulated per-gallon fuel price for the implied blend rate of ethanol. The pink triangles then highlight the blend level mandates for consecutive years and the associated fuel prices.

Similarly to Figure 6, Figure 7 shows the per-gallon costs (negative values) or savings (positive values) related to the different blend rates. The graph is a more detailed representation of Table 3 where we compare the resulting fuel prices from possible scenarios with simulated fuel prices based on actual blend mandates (E10). As shown in the graph, the breaking point for positive values, i.e. savings, is for all five years around the 10% ethanol blend level, which was actually in place.

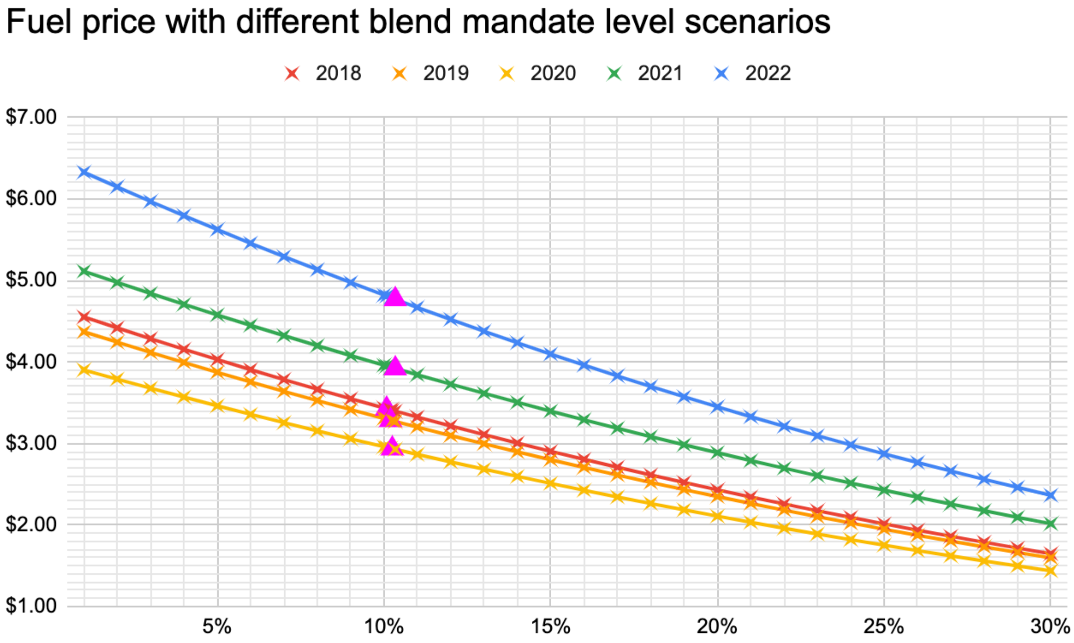


Figure 6 Predicted fuel prices

The model uses four types of elasticities as input variables: US fuel demand elasticity, Foreign fuel demand elasticity, US gasoline supply elasticity and Foreign gasoline supply elasticity. Values for the analysis were taken from Drabik et al. (2016) as these original data stand for long-run elasticities, hence should be a matter of only minor changes over the following years, if any. As Table 4 presents, changes of elasticity values in the scope of 20% interval - 10% higher or 10% lower elasticities - result in negligible changes of the simulated fuel prices obtained from the model. For the period 2018-2022, when considering a 10% increase in all implemented elasticity levels, the fuel price increases on average by 2.74¢. On the other hand, a 10% decrease in elasticities implies an average of 3.32¢ decrease of the fuel price.

The validity of applied elasticities is further confirmed by a meta-analysis of demand elasticity, conducted by Havranek et al. (2012). The paper summarises elasticity estimates of fuel demand from existing literature and corrects for publication selection bias. The method of mixed-effects multilevel meta-regression then results in average long-run elasticity of -0.31, which is close to values used in this paper: -0.37 for the US fuel demand elasticity and -0.40 for the Foreign fuel demand elasticity.

	2018	2019	2020	2021	2022
Simulated Fuel price PF [\$]	3.43	3.29	2.94	3.92	4.77
10% Higher elasticities [¢]	2.12	3.01	2.73	2.17	3.66
10% Lower elasticities [¢]	-2.57	-3.64	-3.30	-2.64	-4.43

Table 4 This table shows the changes in Simulated Fuel price (PF) in \$ when varying the original elasticites from (Drabik et al. 2016). Changing the elasticities either way by 10% produces negligible differences to the PF and thus the difference is reported in units of cents for clarity.

While our structural partial equilibrium model clearly shows that an increase in ethanol blending leads to a decrease in the price paid by U.S. gasoline consumers, we are going to check these qualitative and quantitative results using different methodologies in the following sections of this report.

4.3. Simulation evidence

In this part, we combine two intertwined models. First, we model the price dynamics of WTI crude oil prices, a benchmark for the U.S. crude, using data about OECD oil production and shocks to OECD inventories, which are prominent drivers of the price of crude (Ye et al. 2005, 2002) as well as biofuels (Hochman et al. 2011). Using the estimated parameters, we predict the future price of WTI crude from January 2019 to June 2022. Assuming that the RFS program finished in 2018, we can deduct the volume of blended ethanol and gauge the effects this would have had on the crude oil price. Consequently, the price of crude oil strongly determines the retail gasoline prices across the U.S. This motivates the second model, which then describes the connection of the retail gasoline prices with WTI crude oil prices and calculates the scenario without ethanol blending.

4.3.1. Modeling WTI price To understand the relationship between ethanol blending and gasoline prices, we follow the methodology described in Verleger (2014, 2019). The idea of Verleger's approach is that biofuels remove a significant part of the demand for crude oil from the global market. We assume that the markets operate within a "tight

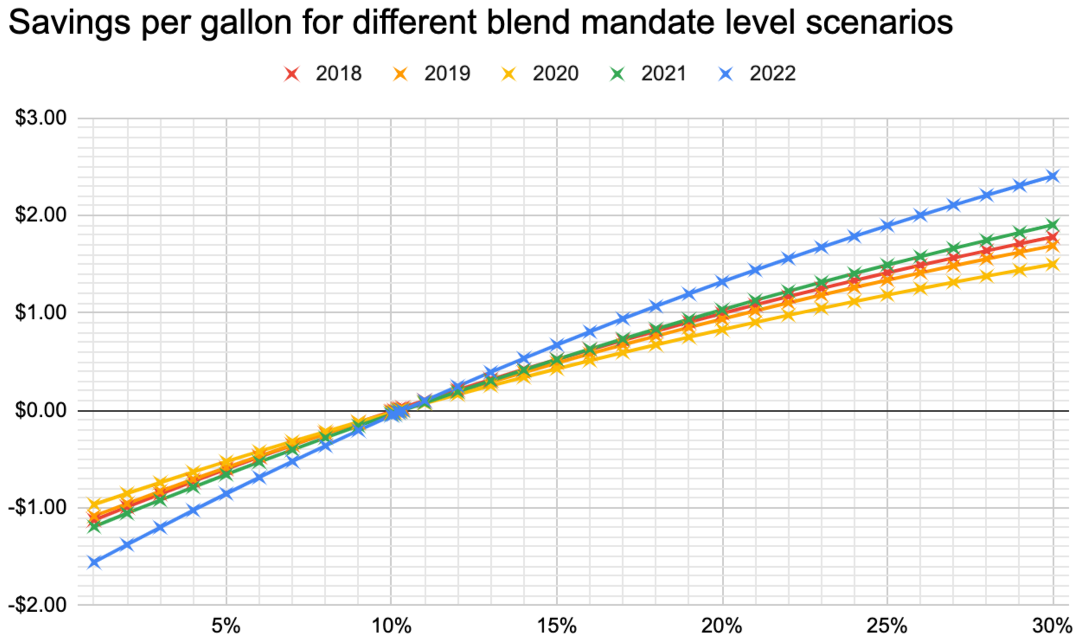


Figure 7 **Retail savings per gallon of gasoline depending on ethanol blend level for each year**

supply" environment, while the demand for crude oil is highly inelastic and the impact of U.S. blending is significant on a global scale (Ye et al. 2005). In the first step, we specify a model for WTI crude oil prices, and we show that the WTI prices predominantly drive the retail gasoline prices. Then, we use the learned parameters to estimate the effect of reducing the crude oil supply by subtracting the volume of used ethanol and predicting the future monthly prices. We use and model the data from January 2009 to June 2022.

To accurately understand the dynamics of the WTI crude prices, we refer to a specification in (Verleger 2019). The main idea behind the model follows the natural rate theory, where the level of OECD commercial inventories is decomposed into a normal level and short-term fluctuations, where the relative level of inventories (RLI), or rather a shock to inventories, is the difference between the real level and the normal level. Several other studies (Ye et al. 2002, 2003) document that relative inventory is a key determinant of short-term crude oil price fluctuations. On both the demand side as well as supply side, the respective price elasticities are rather small compared to inventory elasticity. On the demand side, people use fuels for transportation to drive to work or heat at home, regardless of price, just as it is difficult for refineries to adjust their production quickly. Hence, inventories also serve as the balancing mechanism between crude oil demand and supply (Ye et al. 2005).

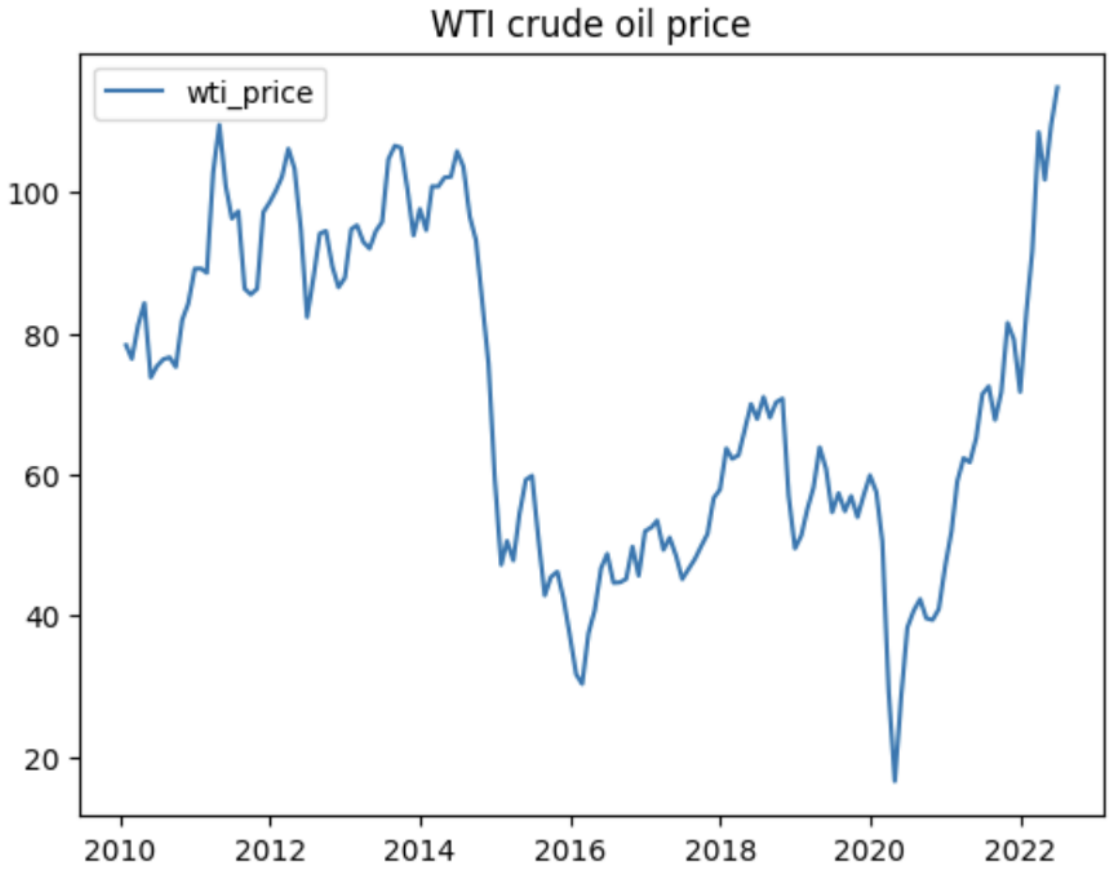


Figure 8 **Monthly WTI crude oil prices from 2009 to 2021. Source of data is EIA.**

For our purpose, similarly to Ye et al. (2005), we understand the RLI as

$$RLI_t = IN_t - IN_t^* \tag{12}$$

where IN_t is the actual OECD crude oil inventory level in a month t, and IN_t^* is the seasonal component. We construct a model explaining the ${IN_t}^*$ with a time trend and dummy variables for 11 months in a year, as follows:

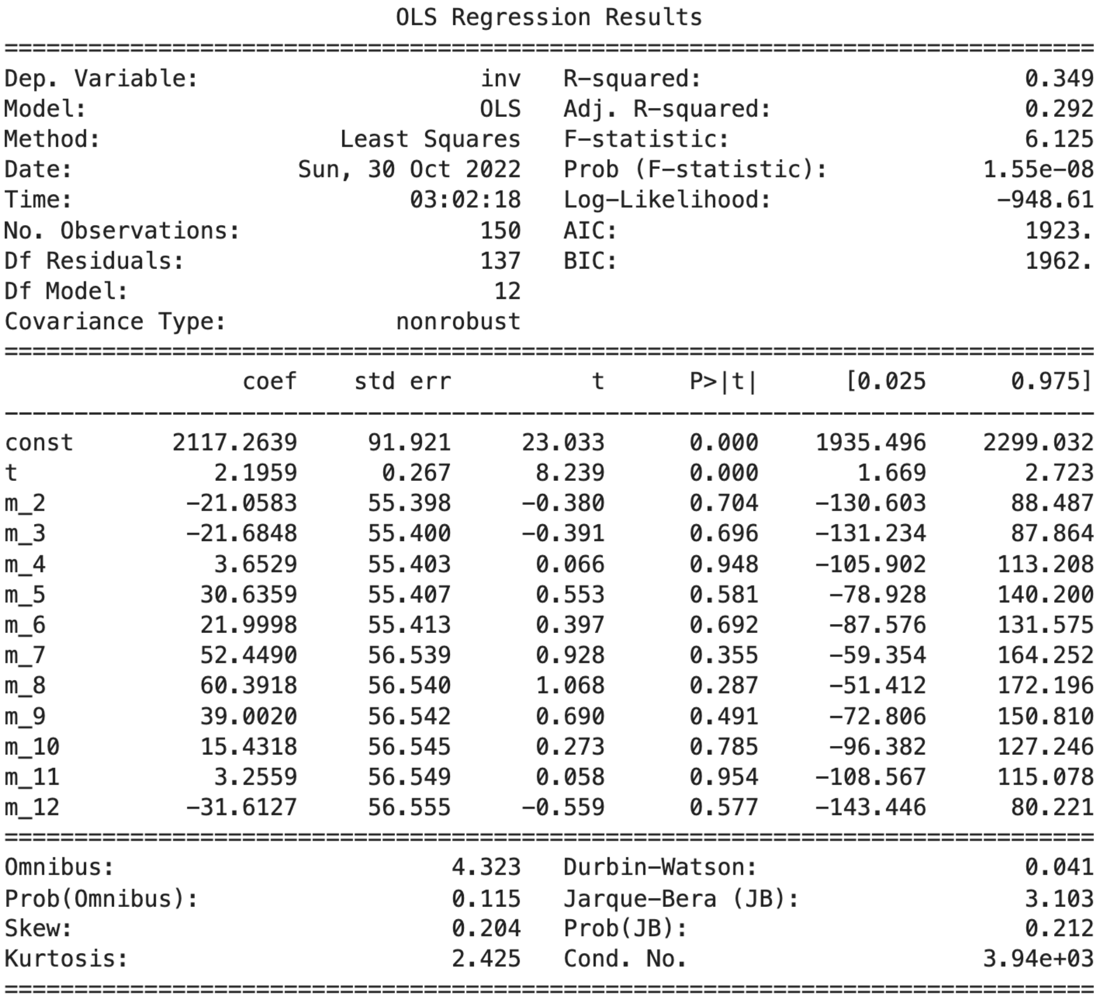
$$IN_t^* = \beta_0 + \beta_1 t + \sum_{k=2}^{12} \beta_k d_k + \epsilon_t \tag{13}$$

are then the coefficients estimates from de-seasoning and de-trending the OECD inventories. We download the data from the EIA website. The estimated values of the model of monthly OECD inventory levels across the full sample from January 2010 to June 2022 are shown in Figure 9.

Although the majority of the variables are not statistically significant, the model is well-specified and captures about 35% of the variation in inventories. Calculating the RLI from Equation 12 as the difference between the in-sample prediction and real values (the model's residuals, in fact), we also interpret RLI_t as shocks to inventories not explained by seasonal and trend components. Figure 10 shows the inverse relationship between RLI and the WTI price. The relationship not only follows the inverse trend well, but it also reacts in real time.

We aim to predict *WTI price* with the RLI_t variable. We add three variables that substantially improve the model introduced by Verleger (2019). We include OECD production, which provides information about the supply side. The following variable is VIX, which is the forward-looking fear index of the stock market. There is ample evidence of connectedness between oil and financial markets (Zhang 2017). Thus, incorporating a financial market-related variable is economically meaningful. Instead of deflating the WTI prices by the U.S. CPI, we find that the model has higher predictive power when using nominal prices and the CPI index separately, similarly to Bec and De Gaye (2016). We add the U.S. CPI in the form of first differences, thus, in fact, a month-on-month CPI. That way, the CPI variable is stationary, and the model avoids spurious correlation through time trend with the WTI price, which is a component of the CPI through high correlation with the gasoline price. We, therefore, define the model explaining the *WTI prices* in Equation 14.

$$WTI\ price_t = \beta_0 + \beta_1 RLI_t + \beta_2 OECD\ production_t + \beta_3 VIX_t + \beta_4 \Delta US\ CPI_t + \epsilon_t \tag{14}$$



```
                            OLS Regression Results
==============================================================================
Dep. Variable:                    inv   R-squared:                       0.349
Model:                            OLS   Adj. R-squared:                  0.292
Method:                 Least Squares   F-statistic:                     6.125
Date:                Sun, 30 Oct 2022   Prob (F-statistic):           1.55e-08
Time:                        03:02:18   Log-Likelihood:                -948.61
No. Observations:                 150   AIC:                             1923.
Df Residuals:                     137   BIC:                             1962.
Df Model:                          12
Covariance Type:            nonrobust
==============================================================================
                 coef    std err          t      P>|t|      [0.025      0.975]
------------------------------------------------------------------------------
const       2117.2639     91.921     23.033      0.000    1935.496    2299.032
t              2.1959      0.267      8.239      0.000       1.669       2.723
m_2          -21.0583     55.398     -0.380      0.704    -130.603      88.487
m_3          -21.6848     55.400     -0.391      0.696    -131.234      87.864
m_4            3.6529     55.403      0.066      0.948    -105.902     113.208
m_5           30.6359     55.407      0.553      0.581     -78.928     140.200
m_6           21.9998     55.413      0.397      0.692     -87.576     131.575
m_7           52.4490     56.539      0.928      0.355     -59.354     164.252
m_8           60.3918     56.540      1.068      0.287     -51.412     172.196
m_9           39.0020     56.542      0.690      0.491     -72.806     150.810
m_10          15.4318     56.545      0.273      0.785     -96.382     127.246
m_11           3.2559     56.549      0.058      0.954    -108.567     115.078
m_12         -31.6127     56.555     -0.559      0.577    -143.446      80.221
==============================================================================
Omnibus:                        4.323   Durbin-Watson:                   0.041
Prob(Omnibus):                  0.115   Jarque-Bera (JB):                3.103
Skew:                           0.204   Prob(JB):                        0.212
Kurtosis:                       2.425   Cond. No.                     3.94e+03
==============================================================================
```

Figure 9 **Regression output of modeling WTI prices with seasonal components for 2009 to 2022.**

Note that we directly model the nominal *WTI price*, instead of the more typical first differences in prices. Despite the unit root present in the *WTI price* series, modeling directly the price markedly improves the model's forecasting ability, which we introduce in the next part.

We estimate the model from January 2010 to December 2018 and predict the future monthly values from January 2019 to June 2022. Figure 11 shows that the model considering *RLI*, *OECD production*, *VIX index* and *U.S. CPI* is economically meaningful and

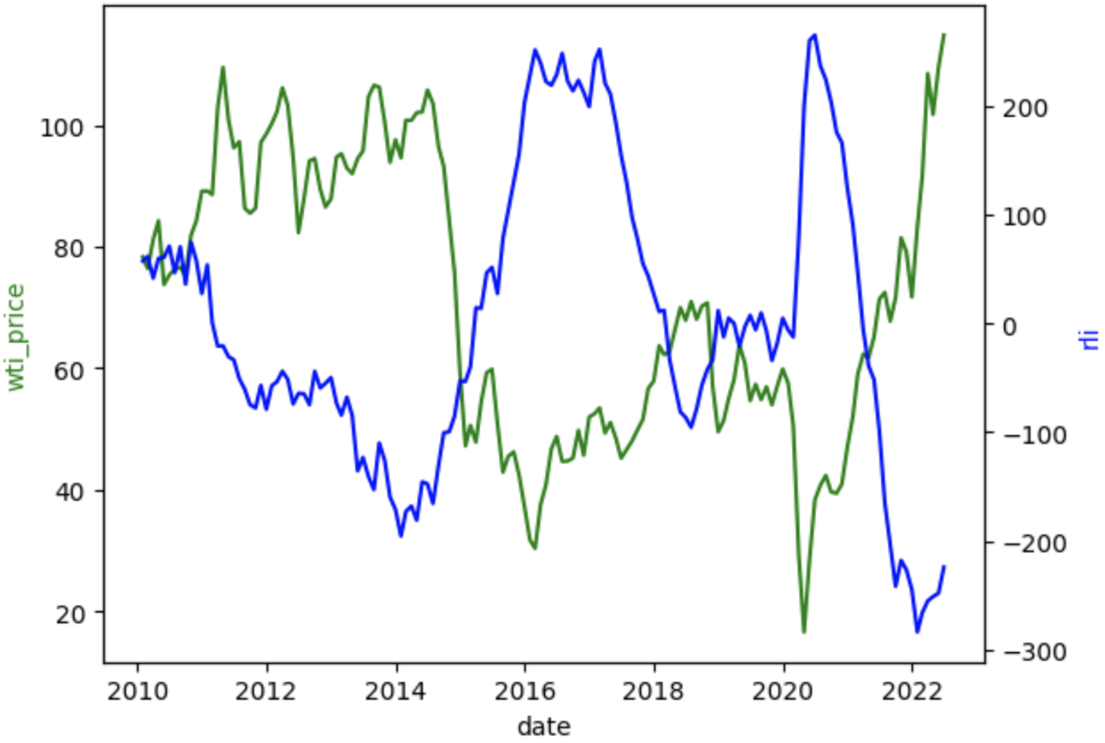
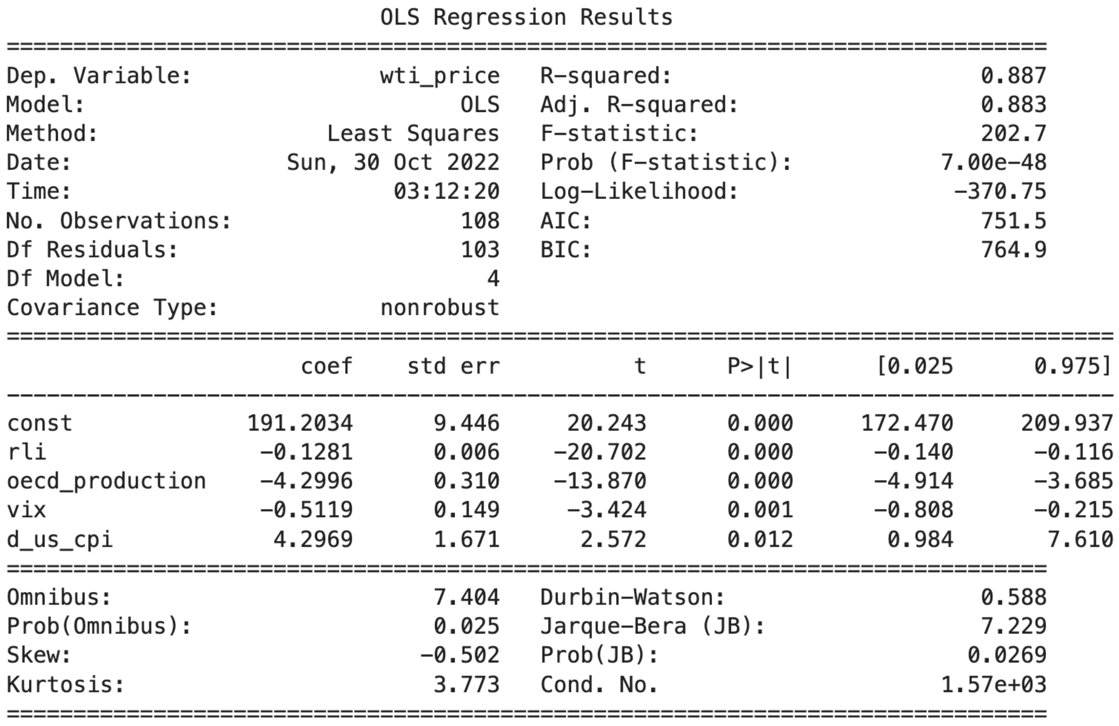


Figure 10 **Comparison of RLI and WTI price from 2009 to 2022**

explains the WTI crude oil prices well. The goodness of fit measure R^2 of 88% is rather high and suggests that our model captures the variation in WTI prices very well. Figure 11 reports full regression outputs.

The model suggests a statistically significant negative relationship exists between the relative level of inventories, the *OECD production* and VIX financial fear index. The CPI change (d_us_cpi) variable is positive, as an increase of the general level of prices intuitively increases the price of crude oil. According to our expectation, the OLS estimates all coefficients with negative values except the U.S. CPI with a positive one. This suggests a positive shock to inventories, higher production, and higher uncertainty in the financial markets drive the price of *WTI crude* down, while positive inflation shocks drive the price up.



```
                            OLS Regression Results
==============================================================================
Dep. Variable:             wti_price   R-squared:                       0.887
Model:                           OLS   Adj. R-squared:                  0.883
Method:                Least Squares   F-statistic:                     202.7
Date:               Sun, 30 Oct 2022   Prob (F-statistic):           7.00e-48
Time:                       03:12:20   Log-Likelihood:                -370.75
No. Observations:                108   AIC:                             751.5
Df Residuals:                    103   BIC:                             764.9
Df Model:                          4
Covariance Type:           nonrobust
===================================================================================
                      coef    std err          t      P>|t|      [0.025      0.975]
-----------------------------------------------------------------------------------
const             191.2034      9.446     20.243      0.000     172.470     209.937
rli                -0.1281      0.006    -20.702      0.000      -0.140      -0.116
oecd_production    -4.2996      0.310    -13.870      0.000      -4.914      -3.685
vix                -0.5119      0.149     -3.424      0.001      -0.808      -0.215
d_us_cpi            4.2969      1.671      2.572      0.012       0.984       7.610
==============================================================================
Omnibus:                       7.404   Durbin-Watson:                   0.588
Prob(Omnibus):                 0.025   Jarque-Bera (JB):                7.229
Skew:                         -0.502   Prob(JB):                       0.0269
Kurtosis:                      3.773   Cond. No.                     1.57e+03
==============================================================================
```

Figure 11 **Using the model from Equation 14, we estimate parameters on a sample from 2010 to 2018 and use those values to estimate the effect of the RFS policy on WTI prices from 2019 onwards.**

The main point is to investigate the predictive power. While using the estimated parameters, we consecutively predict the monthly WTI prices with no error correction using only exogenous variables. The predicted prices correlate strongly with the realized WTI prices with a correlation coefficient of 90% and mean error of the WTI price of the forecast of \$8.42 and a maximum error of \$11.65. Figure 12 shows the out-of-sample performance of the model.

The descriptive statistics suggest that the model predicts the overall dynamics quite well. However, our model is slightly more conservative and starts underestimating the price after a few months. It also lags behind during the swift price recovery after the Covid shock in 2021 and also the Russian invasion of Ukraine in 2022. Nevertheless, the model performs quite well in the overall trends over 42 future months for a set of parameters estimated on data prior to 2018 and never re-estimated.

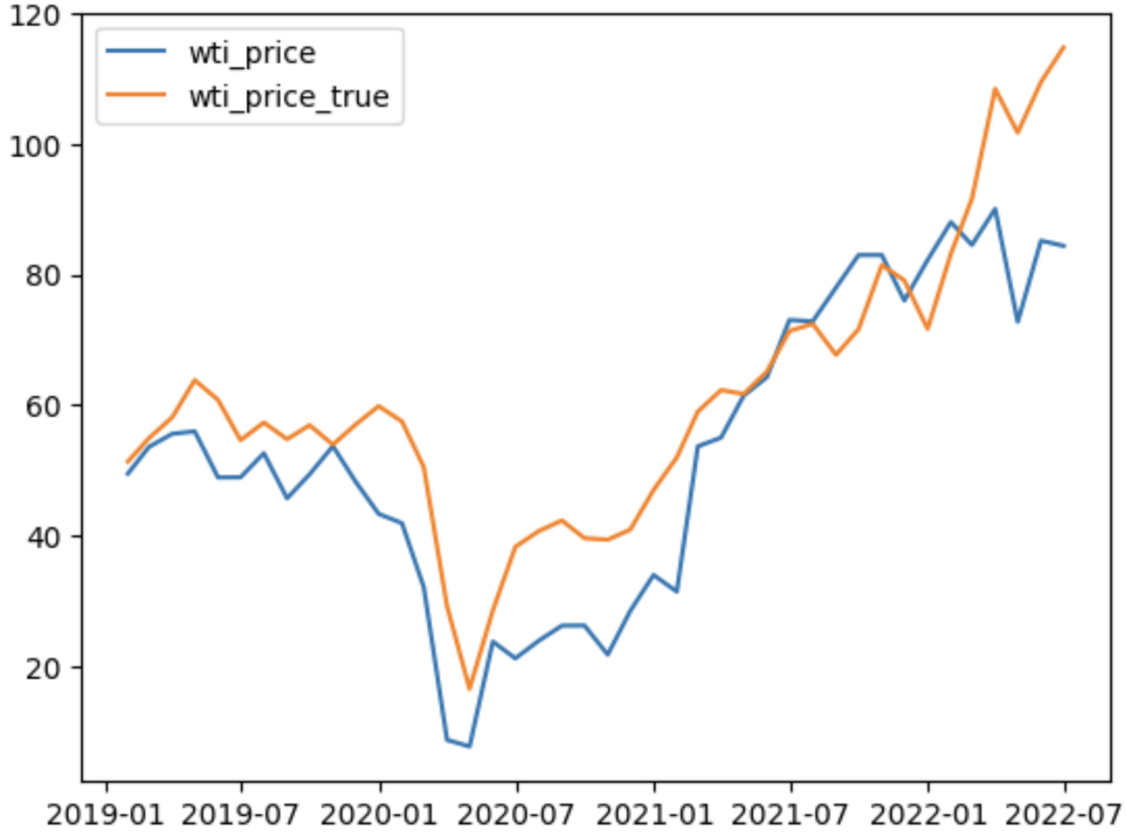


Figure 12 **Out of sample forecast of the WTI prices. The blue series wti_price is our prediction, while the orange line wti_price_true is the actual WTI price.**

Similarly to Verleger (2019), since our model depends on inventories and other exogenous variables, it can be used to assess specific impacts in the significant variables. Hence, we deduct the blending volume of ethanol from the *RLI*, because if the RFS program terminated at the end of 2018, it is the volume of fuel that would have been missing in the reservoirs driving the price up. We estimate that the effect of U.S. ethanol blending on global *WTI price* is roughly $3.45 per barrel over the years 2019 to June 2022. Reducing the volume of biofuels would have had a significant impact since global oil production was operating with no output constraints as per Verleger (2019). Figure 13 shows the estimated effect of a cut in ethanol blending on the WTI price.

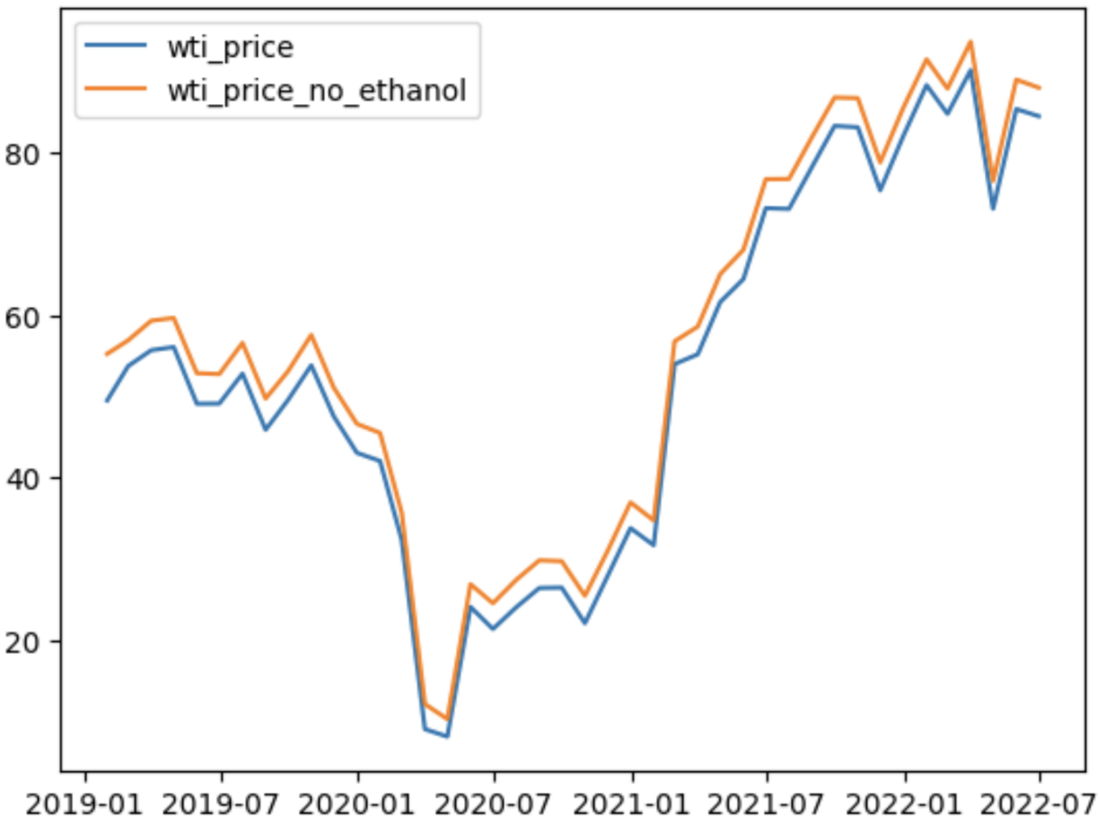
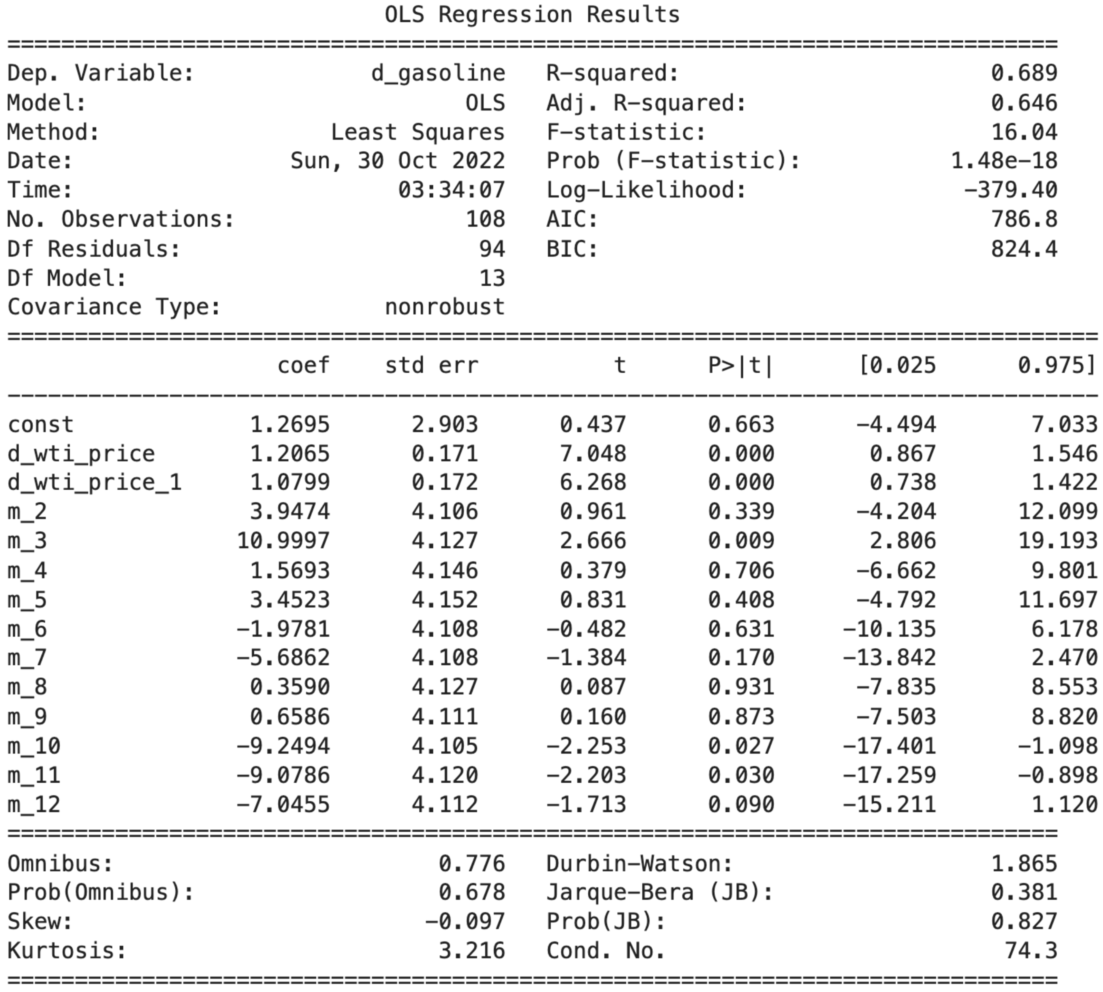


Figure 13 **Comparison of forecasted WTI prices in the scenario of no ethanol blending from January 2019 to June 2022. The wti_price series is the out-of-sample forecast of the model, and in orange wti_price_true is the realized true value of the WTI price.**

4.3.2. Impact of RFS on gasoline prices The model of crude oil prices is used to derive a model for retail gasoline prices. Firstly, we use a straightforward approach to model changes in gasoline prices with changes in WTI crude oil prices, to which we add seasonal variables. This significantly improves the model's explanatory power. The gasoline price is the U.S.-wide average taken from the EIA website. We denote this as Equation 15 and it reads as follows:

$$\Delta gas_t = \beta_0 + \beta_1 \Delta P_t + \beta_2 \Delta P_{t-1} + \sum_{k=2}^{12} \beta_{k+1} D_k + \epsilon_t \tag{15}$$

The OLS estimation method yields estimates of the parameter values shown in Figure 14.



```
                            OLS Regression Results
==============================================================================
Dep. Variable:             d_gasoline   R-squared:                       0.689
Model:                            OLS   Adj. R-squared:                  0.646
Method:                 Least Squares   F-statistic:                     16.04
Date:                Sun, 30 Oct 2022   Prob (F-statistic):           1.48e-18
Time:                        03:34:07   Log-Likelihood:                -379.40
No. Observations:                 108   AIC:                             786.8
Df Residuals:                      94   BIC:                             824.4
Df Model:                          13
Covariance Type:            nonrobust
=================================================================================
                    coef    std err          t      P>|t|      [0.025      0.975]
---------------------------------------------------------------------------------
const             1.2695      2.903      0.437      0.663      -4.494       7.033
d_wti_price       1.2065      0.171      7.048      0.000       0.867       1.546
d_wti_price_1     1.0799      0.172      6.268      0.000       0.738       1.422
m_2               3.9474      4.106      0.961      0.339      -4.204      12.099
m_3              10.9997      4.127      2.666      0.009       2.806      19.193
m_4               1.5693      4.146      0.379      0.706      -6.662       9.801
m_5               3.4523      4.152      0.831      0.408      -4.792      11.697
m_6              -1.9781      4.108     -0.482      0.631     -10.135       6.178
m_7              -5.6862      4.108     -1.384      0.170     -13.842       2.470
m_8               0.3590      4.127      0.087      0.931      -7.835       8.553
m_9               0.6586      4.111      0.160      0.873      -7.503       8.820
m_10             -9.2494      4.105     -2.253      0.027     -17.401      -1.098
m_11             -9.0786      4.120     -2.203      0.030     -17.259      -0.898
m_12             -7.0455      4.112     -1.713      0.090     -15.211       1.120
==============================================================================
Omnibus:                        0.776   Durbin-Watson:                   1.865
Prob(Omnibus):                  0.678   Jarque-Bera (JB):                0.381
Skew:                          -0.097   Prob(JB):                        0.827
Kurtosis:                       3.216   Cond. No.                         74.3
==============================================================================
```

Figure 14 Model explaining the difference in the gasoline price with the change in WTI price and its one-period lagged values. The m_x variables are calendar month dummy variables.

Some of the month dummies are again not significant, but we decide to keep them in order to be consistent with the RLI model. Nevertheless, the WTI price variables are highly statistically significant and have expected positive coefficients. Apart from that, the contemporaneous change in crude price has larger coefficients and thus is more influential for the gasoline dynamic. This model explains 69% of the variance of changes in retail gasoline prices.

Having a model for historical gasoline prices, we use it in the same way as the WTI crude price model to forecast future changes in gasoline prices and reconstruct them by summing from the latest observed value (December 2018). Figure 15 then shows how well the model uses our predicted WTI prices and subsequently fits the realized gasoline prices. Again, we observe shortcomings of the prediction at the beginning of the predicted period and during the Covid crisis and recovery in 2020.

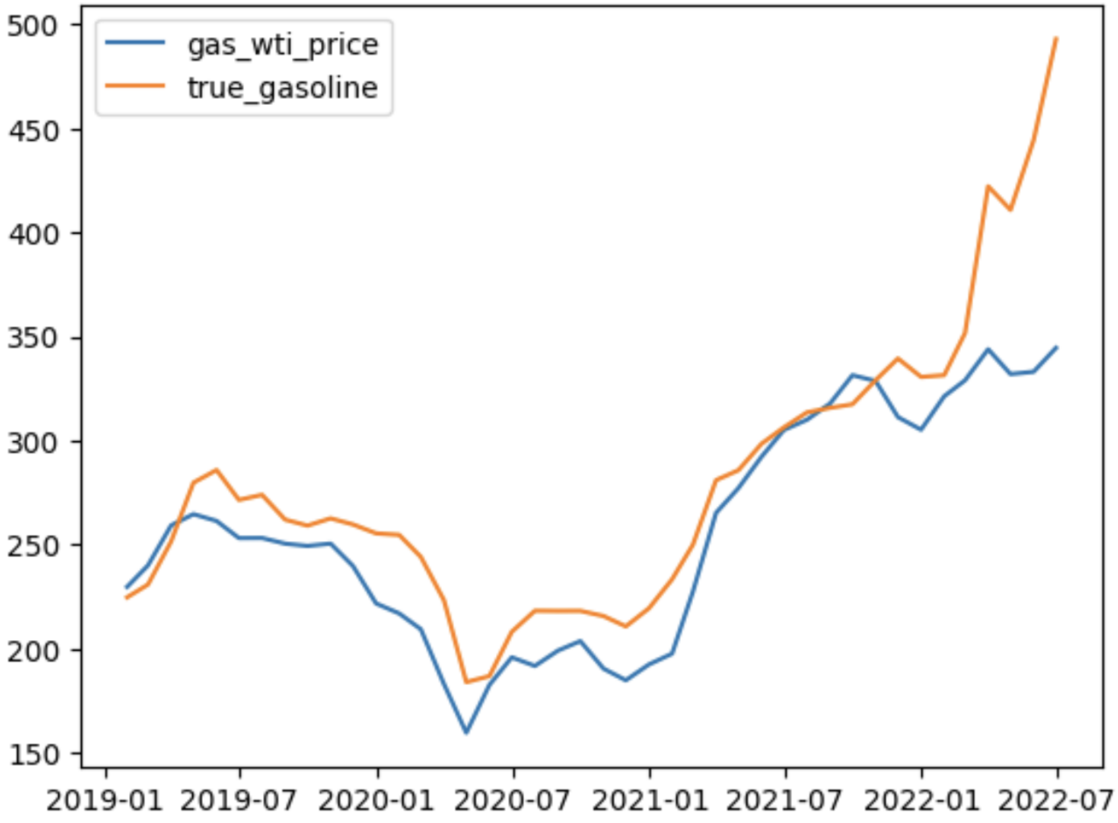


Figure 15 Performance of the model forecasting the gasoline prices compared to realized values. The series gas_wti_price is the gasoline price predicted with our forecast of the WTI prices using the model from Equation 15 and the orange series true_gasoline is the actual value recorded.

Finally, we use the predicted series for *WTI price* and WTI price with the RFS mandate terminated in December 2018, while we let the model forecast the U.S. retail gasoline prices. Figure 16 then shows the difference between the gasoline price based on model-predicted WTI prices with and without the ethanol policy in place. We observe that the no ethanol scenario is almost always markedly higher across the predicted sample.

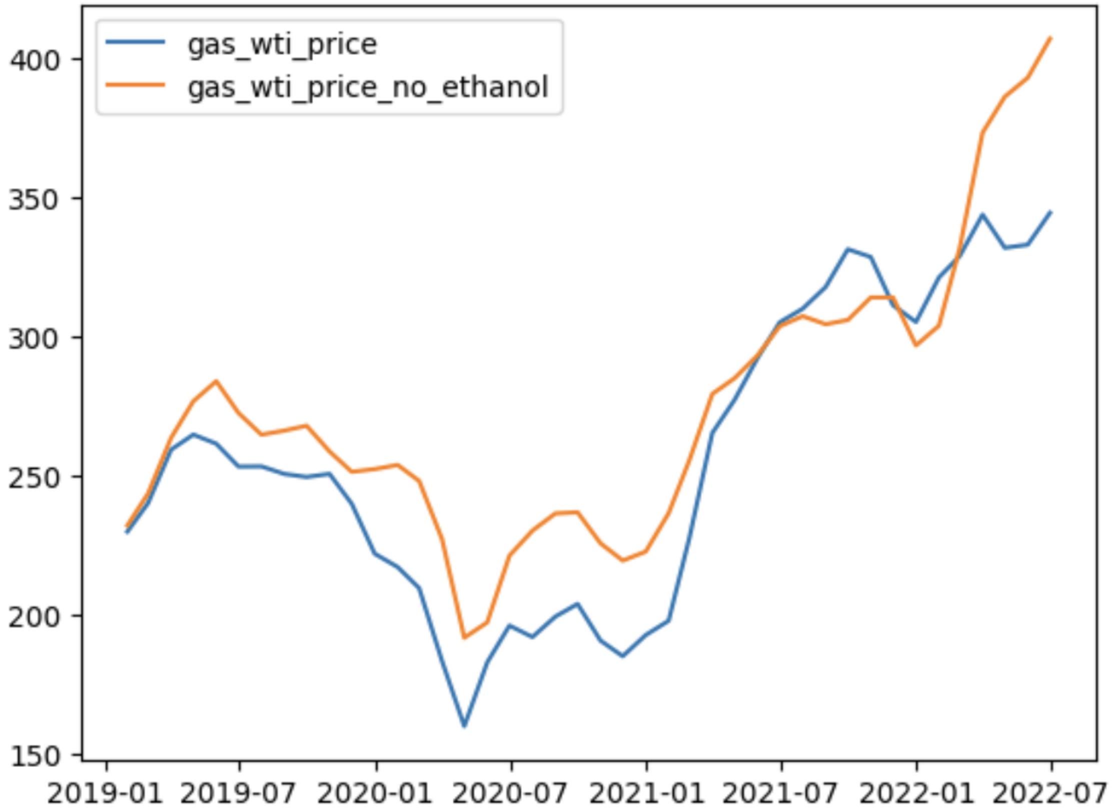


Figure 16 **Out of sample forecasts of the gasoline prices with ethanol deducted from the supply**

The mean of the ethanol discount is \$0.185/gallon and the monthly median is \$0.170/gallon. This difference is statistically significant with a t-test value of the sample mean differences being zero of -1.712. More detailed yearly estimates are in Table 5.

We estimate consistent ethanol discounts for the years 2020 and 2022, while the model predicts almost no effect in 2021. The model is rather straightforward, and the Covid shock

year	gasoline discount
2019	13.3
2020	33.2
2021	2.2
2022	32.0

Table 5 This table summarizes the average monthly discount of retail gasoline prices in USD cents due to ethanol blending average per calendar year.

and subsequent recovery was a so-called black-swan event, where the linear specification has naturally limited options to account for it. We assume a constant effect of WTI prices and monthly seasonal components based on the realization of the prices before 2019. We hypothesize that they would be markedly different should we include this period in the estimation period, yet it would limit our forecast inference.

4.4. Discussion of the numerical results

The estimates we provide in the preceding section vary and depend on the model used and other factors. Their average from 2019 to 2022 is an estimated discount in retail gasoline prices of $0.77 due to the use of ethanol, which we consider the principal result of this report. Compared to some of the results we refer to, ours describe a more recent period in which market conditions evolved substantially, not only with respect to the RFS program's size but also with respect to the volatility of crude oil prices and recent inflationary pressures in the economy. The volatility of major components of the gasoline price, crude oil and ethanol blending volume, changes its impact depending on the gasoline demand and supply elasticities. In periods of fuel scarcity and high prices, the price impact of ethanol policies is high due to relatively lower elasticities. This effect is well captured by the structural Partial equilibrium model (PEM) introduced in Section 4.2 and Figure 17 shows this relationship over time.

While in periods when the market is saturated, and fuel prices are lower, demand and supply elasticities are higher, then the price impact of the RFS program would be lower. Rajagopal et al. (2007) derive such a stylized model of supply and demand in energy and food markets and find the relationships inelastic, particularly in the short run. Those

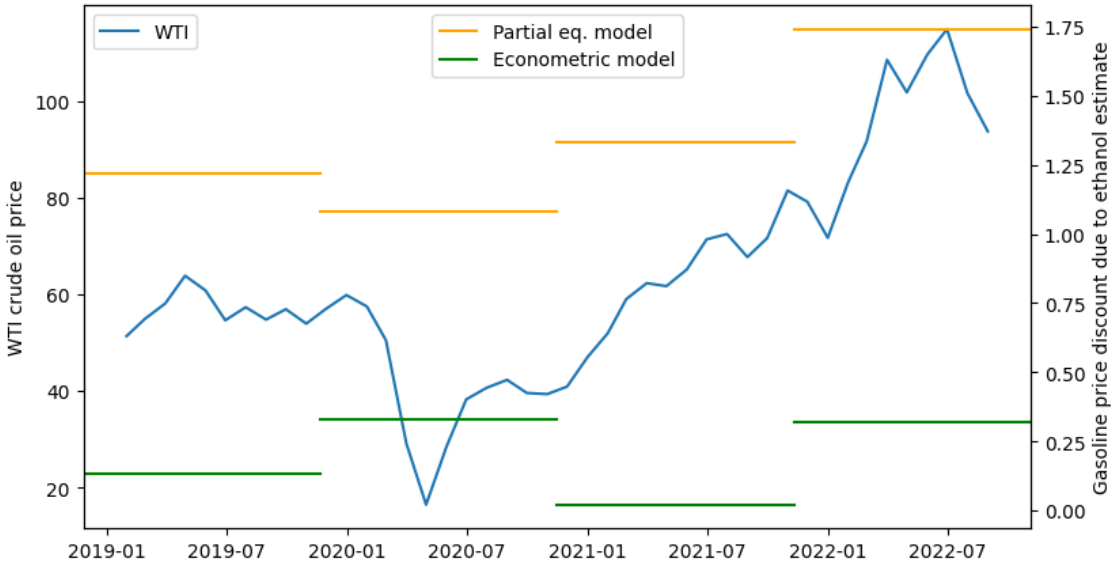


Figure 17 **This figure compares the WTI price (left axis) and estimated yearly gasoline price discount due to the ethanol policies (right axis). Particularly, the Partial equilibrium model (orange) estimates a higher discount at the relatively higher price level of the WTI crude.**

results are then considered in a broader context by Khanna et al. (2021). More recently, Hochman and Zilberman (2018) provide a more detailed discussion of demand and supply elasticities and their meta-analysis in the literature. Hochman and Tabakis (2020) then investigate such relationships in the South Korean market. The role of elasticities between ethanol demand, ethanol production, and gasoline is also discussed in Luchansky and Monks (2009).

Our results averaged from the two models suggest that the RFS program provides an average discount between 2019 and 2022 of \$0.77. Considering just the PEM model from Section 4.2, its average suggests the discount is \$1.34. On the other hand, the Econometric model (EM) is more conservative and estimates the effect to be \$0.20 on average over time.

The higher end of the discount interval is based on the PEM values. If we hypothesize that a certain level of ethanol would have been used as a gasoline oxygenate anyway, say 5%, then the same model suggests the savings are more conservative, in fact, around \$0.66 per gallon on average. More concretely, in 2022, the average savings for U.S. drivers due

	2019	2020	2021	2022	Average
E0% PEM	$1.22	$1.08	$1.33	$1.74	$1.34
EM	$0.13	$0.33	$0.02	$0.32	$0.20
Average	$0.68	$0.71	$0.68	$1.03	$0.77

Table 6 This table compares estimates from 2019 to 2022 of the ethanol-driven discount from the Partial equilibrium model from Section 4.2 and the econometric model from Section 4.3. The Average column average values from the model in the row, respectively, per year in the last row. The value $0.77 in the bottom-right cell is the average across years and models.

to ethanol are between $0.32 and $1.74 per gallon, or $0.32 and $0.86 when we consider a minimum of 5% of ethanol as an oxygenate regardless of the RFS program. Table 7 summarizes those results. However, from the point of view of the retail consumer, what matters is the total price decrease due to ethanol without regard to the decomposition of gasoline oxygenate and pure RFS effects.

	2019	2020	2021	2022	Average
E5% PEM	$0.59	$0.53	$0.66	$0.86	$0.66
EM	$0.13	$0.33	$0.02	$0.32	$0.20
Average	$0.36	$0.43	$0.34	$0.59	$0.43

Table 7 This table compares estimates from 2019 to 2022 of the ethanol-driven discount from the Partial equilibrium model from Section 4.2 and the econometric model from Section 4.3. The Average column average values from the model in the row, respectively, per year in the last row. The value $0.43 in the bottom-right cell is the average across years and models.

5. Qualitative findings

In this part, we report on qualitative findings, which follow rich literature on describing relationships between biofuels through several methodologies. Unlike the previous section, where we quantify numerical estimates of the effects of ethanol on gasoline prices in the U.S., here we describe how ethanol production interacts with other important commodities and financial variables.

5.1. Structural model approach

Similarly to McPhail (2011), we construct a structural model of biofuels and fossil fuels, where it is possible to dissect between ethanol demand and supply shocks. We consider a joint model of the global crude oil market, the U.S. gasoline market, and the U.S. ethanol market.

While the demand side is driven primarily by U.S. policies, such as tax credits and blending mandates, supply is mainly driven by changes in feedstock, primarily comprised of corn prices and yields. In this part, we illustrate how those shocks influence average gasoline prices as well as crude oil prices from 2010 to June 2022. We construct a system modeling the energy market, which includes the price and supply of crude oil, global economic activity (Kilian 2009), the real price of gasoline and the growth rate of its consumption in the U.S. and the real price of ethanol and U.S. ethanol production.

Considering an average response over our sample, we find a statistically significant response of gasoline price to shocks to ethanol supply. This response is also persistent for up to 8 months. On the contrary, a shock to the real price of ethanol does not have a direct effect on gasoline or crude oil price. Nevertheless, we expected this effect.

Using a straightforward VAR, we observe that gasoline responds to ethanol supply and demand shocks only after several months when it is firstly driven only by itself and the price of oil (rpo), when ethanol supply (es) and ethanol price (rpe) begin to drive about 40% of the shocks dynamic to gasoline.

However, this model does not take into account varying parameters and rather estimates constant effects across the inspected sample. Considering the increasing ethanol mandate through the RFS program, we turn to model the propagation of the shocks dynamically in time.

5.2. Dynamic Network evidence

Using the novel methodology of Dynamic Networks introduced in (Barunik and Ellington 2020, Ellington and Barunik 2020), we model the network structure forming around shocks to the supply and demand of biofuels and their propagation through the system. The directed network topology reflects the nature of shock propagation and allows us to understand the relative strength and direction of relationships between the considered variables. Since the methodology is based on TVP-VAR, we are able to obtain a full set of parameters and shock transmission strength across the sample, and we are able to capture time-varying properties of the relationship. We define the shocks as movements in the

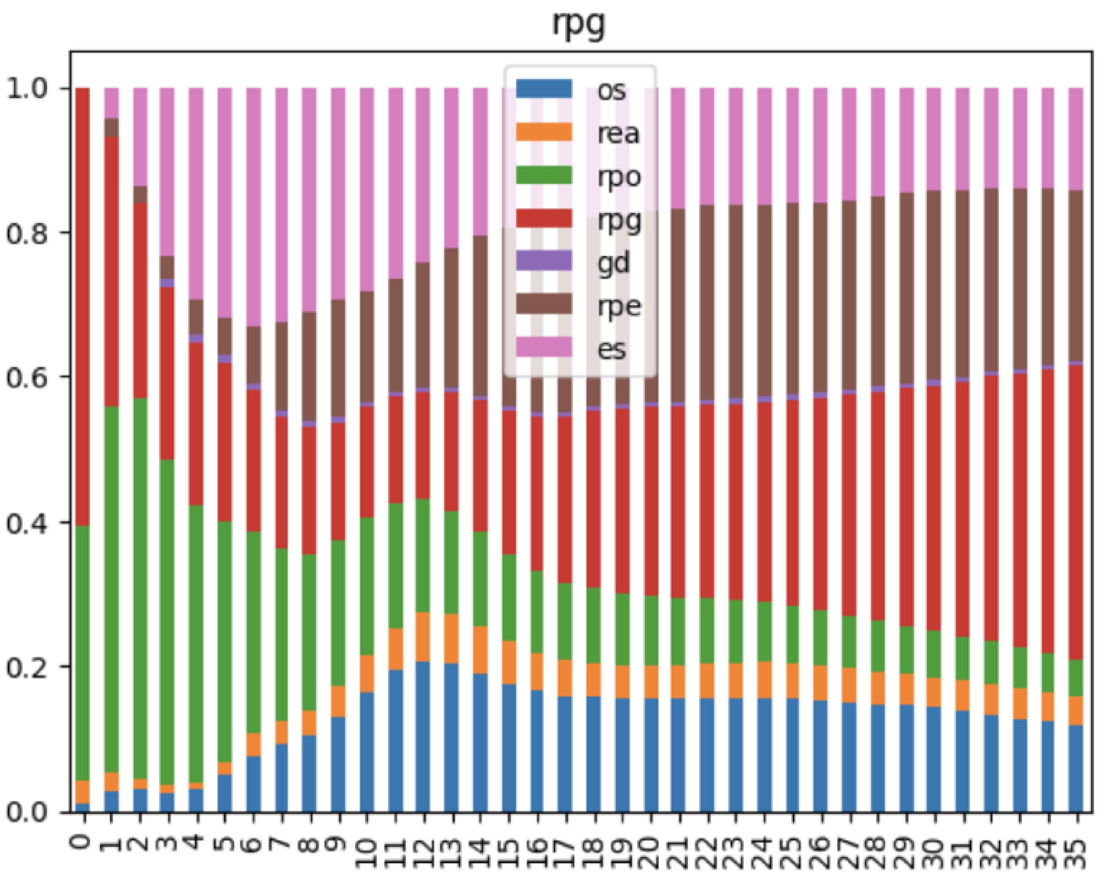


Figure 18 **Origins of price shocks to price of gasoline.** Os **is the supply of oil,** rea **is the index of real economic activity,** rpo **is the real price of crude oil,** rpg **is the real price of gasoline,** gd **is the demand of gasoline,** rpe **is the real price of ethanol and finally** es **is the supply of ethanol**

respective time series which cannot be directly explained by their own dynamics or values of other variables that are present in the system.

Dynamic Network is also able to separate contemporaneous correlation from the connectedness to construct a network with causal interpretation. This is useful since the considered time series are significantly correlated. If we remove the contemporaneous correlation, we can think of it as if the shocks, although not explained by the system itself, have a common driver. Thus they are correlated. If we remove that, we infer a more clear quantification of the strength and importance of pairwise and total relationships.

We turn to the interpretation of causal relationships shown in Figure 19. The total connection between the markets is quite low, mainly when compared to results in the stock market. We see that besides the food crisis in 2008 and 2019, the causal connectedness is quite low, and those spikes are rather short-lived. Only recently, the variable began to exhibit a significant and consistent period of causal shock propagation.

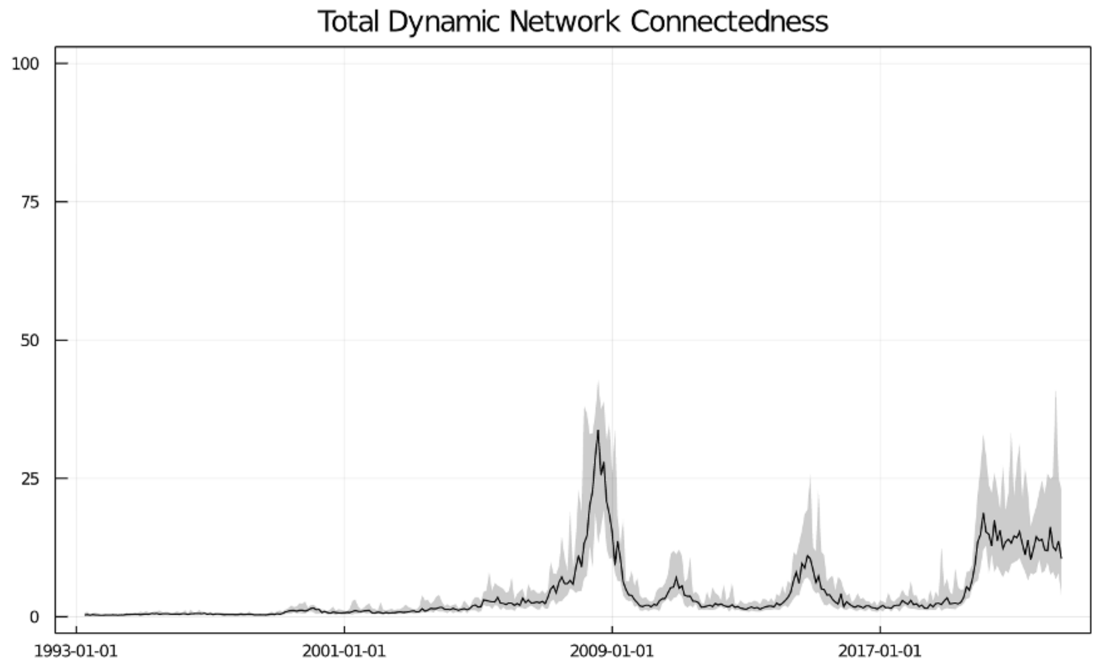


Figure 19 Total connectedness of price shocks to the system with subtracted contemporaneous correlation.

We observe a significant tightening of the markets during the Covid crisis in March 2020 and during the food crisis in 2008. That means that shocks to prices and supply spread to the other parts of the system very quickly. Thus, market crashes strengthen connections. We are able to understand what components have the highest contribution to the increased risk when it comes to market crashes.

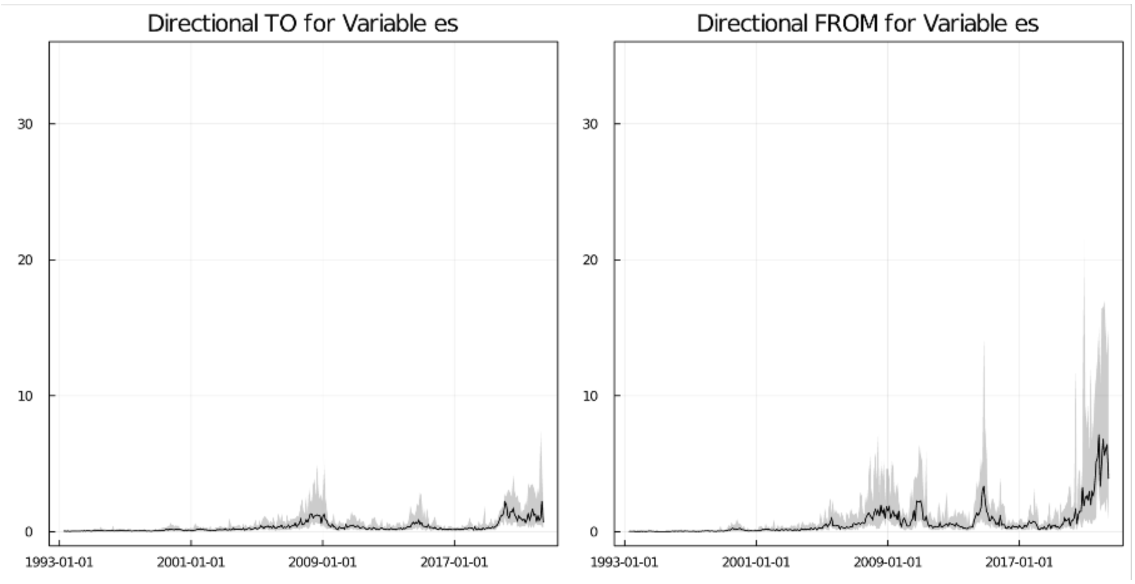


Figure 20 **Directional effects of shocks to the supply of ethanol to the system. The importance of ethanol supply shocks grows with the volume of the RFS program and is statistically significant.**

We pay particular attention to ethanol production in Figure 20 and observe that ethanol production emits shocks in cases of a market downturn. The importance of shocks emitting from ethanol supply has increased consistently after the Covid crash in 2020.

6. Conclusion

The role of biofuel is controversial in the literature yet still expanding due to public policy and is thus an important research topic. The broad discussion revolves around environmental and ecological impacts as well as economic implications, more specifically, the prices of food and other commodities. This report restricts its focus narrowly to ethanol's impact on gasoline prices in the United States.

We find that ethanol blending driven by the Renewable Fuel Standard (RFS) program has a direct and statistically significant negative (i.e. lowering) effect on gasoline prices at the pump. We estimate the savings to be between 2019 and 2022 on average \$0.77 per gallon of gasoline. Those translate to the total savings in the U.S. economy of roughly \$95.1 billion, representing about 0.41% of the U.S. nominal GDP. If we consider that those savings can be reinvested in the economy with a multiplier effect, the net benefit to the U.S. consumer is, in fact, even higher. The \$0.77 estimate is based on a structural Partial equilibrium model (PEM) and an Econometric model (EM) and summarizes the central tendency of their results over time. The models calculate scenarios ranging from the lowest savings of \$0.32 to the highest savings of \$1.74 per gallon. Those results are consistent with the findings in the reported literature, which report a wide impact of ethanol on gasoline prices in the U.S.; while the EM is rather conservative, the PEM generally reports larger savings.

The size of the ethanol effect is also highly dependent on the overall market conditions. One of the prominent drivers of the variability in our results is the higher volatility of energy prices in recent years, specifically crude oil. Although the EM estimates a constant effect of ethanol on gasoline through a constant impact of ethanol on crude oil prices, this relationship is, in reality, dynamic, as the global economy operates differently in regimes of high and low cruder oil prices. Just in the last decade, we witnessed crude oil prices going over \$100 per barrel and also as low as \$20 per barrel. In periods of higher volatility and prices, the impact of RFS is higher due to relatively low elasticities of demand and supply. This is supported by the literature and well captured by the PEM. In periods of lower volatility and crude prices, the market is saturated, and the effect of the ethanol policy is estimated to be lower since elasticities tend to be higher.

Quantifying the role ethanol has on U.S. gasoline prices is a difficult task, as it depends on many factors which vary greatly over time, as well as the specifications and assumptions of the used models. Other important factors are global economic activity or the technology which produces the fuel ethanol and is poised to become more effective over time, rather than not.

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7. Appendix

7.1. Systematic Literature Review

Following section 3.1, Figure 21 represents the thematic mapping, allowing the visualization of different types of themes (Caust and Vecco 2017). In the thematic map, we use keywords of the articles in the sample, where the keywords are defined by a semi-automated algorithm under the responsibility of Thomson Reuter's specialists, which is capable of capturing the content of an article with greater variety and depth (Della Corte et al. 2019).

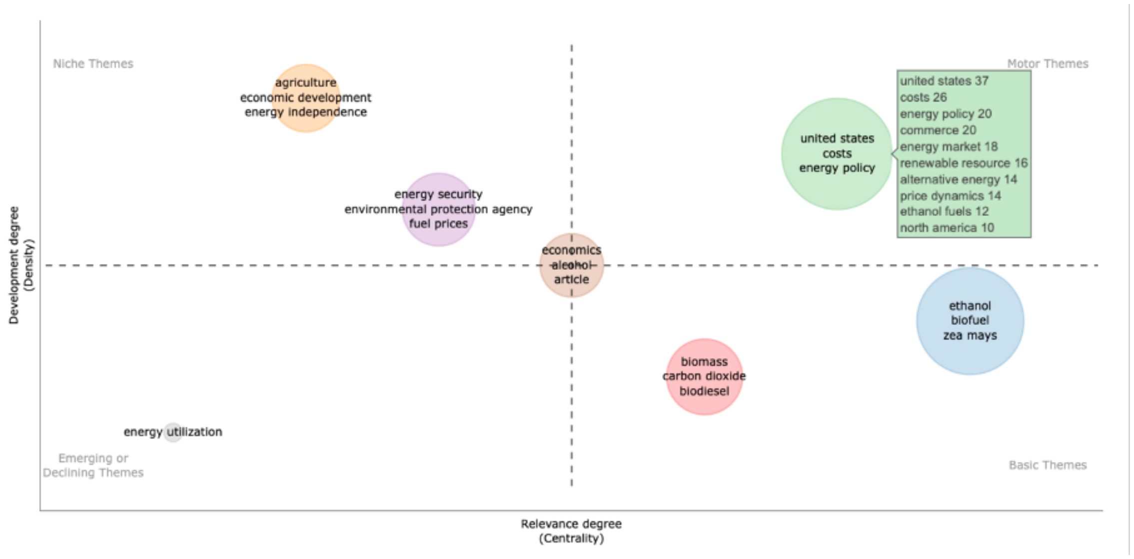


Figure 21 **Thematic map (Development degree x Relevance degree)**

The upper right quadrant of Figure 21 represents themes with a higher degree of development (density) and relevance (centrality), seen as key themes in the literature, among which "Energy Policy" and "costs" stand out. As expected, another key theme found in this analysis was "United States", defined as one of the keywords in the search strings. Apart from those, other driving themes are "price dynamics", "commerce" and "energy market". Declining or emerging themes are located in the lower left quadrant. In this research, the results suggest that the topic "energy utilization" is an emerging topic. The lower right quadrant shows sample basic themes. These themes refer to general themes in the different areas of investigation. They include “ethanol”, “biofuel”, “zea mays”, “biomass”, “carbon dioxide” and “biodiesel” from our sample. Finally, the upper left quadrant shows themes of high density, but of lesser importance to the sample or limited importance to the field (low centrality). Within these themes, “agriculture”, “economic development”, “energy independence”, “energy security”, “Environmental Protection Agency”, and “fuel prices” are the ones that stand out.

In sequence, we created Figure 22 using the VOSviewer software and it is based on the co-occurrence information of the authors’ keywords (van Eck and Waltman 2010). In this figure, the node sizes represent the number of times these keywords were used by the articles in the sample; the connecting lines indicate that these keywords were used in the same publication, while the colors are related to the year of publication. The relevance of the topics “Renewable Fuel Standard” and “policy” protrudes, even though they were not included in the search strings. This network also allows the identification of trending topics for the area, as they represent interests in recent research, such as “retail fuel spreads”, “pass-through”, “fuel markets”, “E85”, or even “energy prices” and “meta-analysis”.

Finally, Figure 23 was elaborated from a Multiple Correspondence Analysis, an exploratory multivariate technique of the keywords and the articles that make up the sample. The conceptual structure map identifies clusters from articles that express interrelated concepts (Aria and Cuccurullo 2017).

The results of this figure are to be interpreted based on the distribution of points and their position along the dimensions. The closer the keywords are represented in the figure, the greater their similarities in distribution. The figure allows the identification of new latent variables from the formation of clusters in a set of categorical variables. In this way, we identify two distinct clusters. The first cluster (in red), seems to be more relevant due to its size and centrality in relation to dimensions. The red cluster contains important keywords such as “price dynamics”, “commodity price”, “gasoline prices”, “blending”, “taxation” and “subsidy system”, which are terms associated with the price and market dynamics of biofuels in the U.S. In the second cluster (in blue), keywords such as “economics”, “energy security”, “public policy” and “gas emissions” are highlighted as terms associated with the development of public policies for the implementation of biofuels and

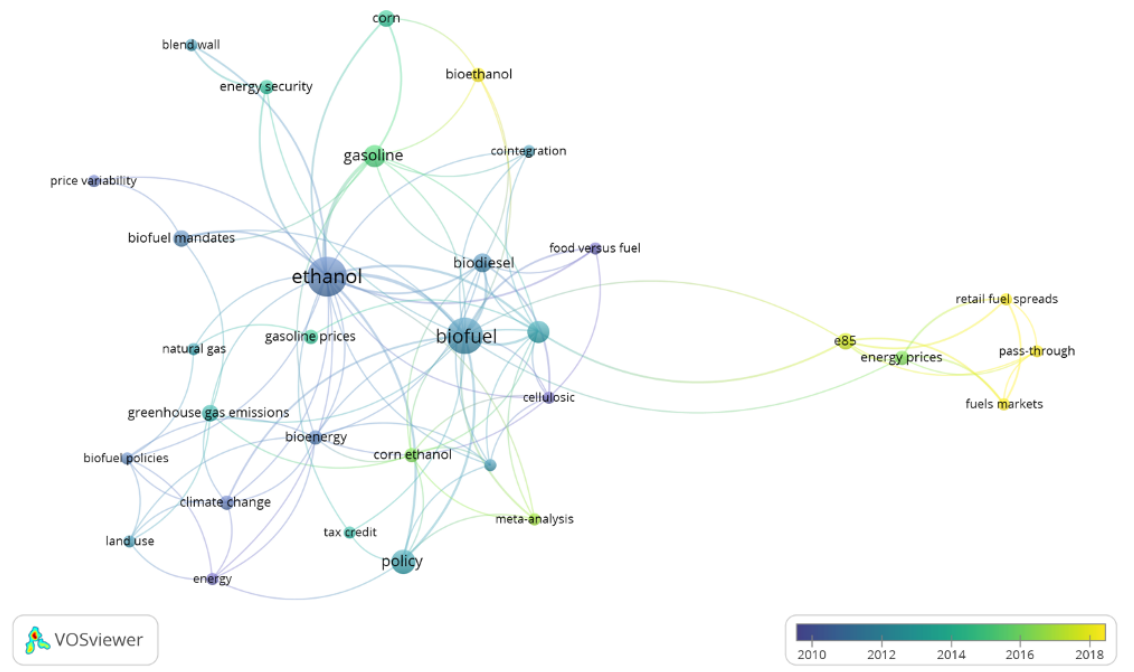


Figure 22 **Keyword co-occurrence map**

their environmental impact. This split corresponds to the exploratory and introductory review we provide in the Introduction.

7.1.1. Predominant cluster structure In order to answer RQ2 (what are the main article clusters identified in the evaluated literature), content analysis and mapping and clustering techniques were used, as they are frequently used in SLR studies (Perianes-Rodriguez et al. 2016, Rotella Junior et al. 2021).

Through the use of clustering techniques, it is possible to present a map that highlights areas corresponding to the clusters of nodes identified. Using the VOSviewer software, we calculate a bibliographic coupling network (for more, see (Perianes-Rodriguez et al. 2016)), whose graphical results are shown in Figure 24. In this analysis, the relationship between studies is determined based on the degree to which these articles are cited in the same publication.

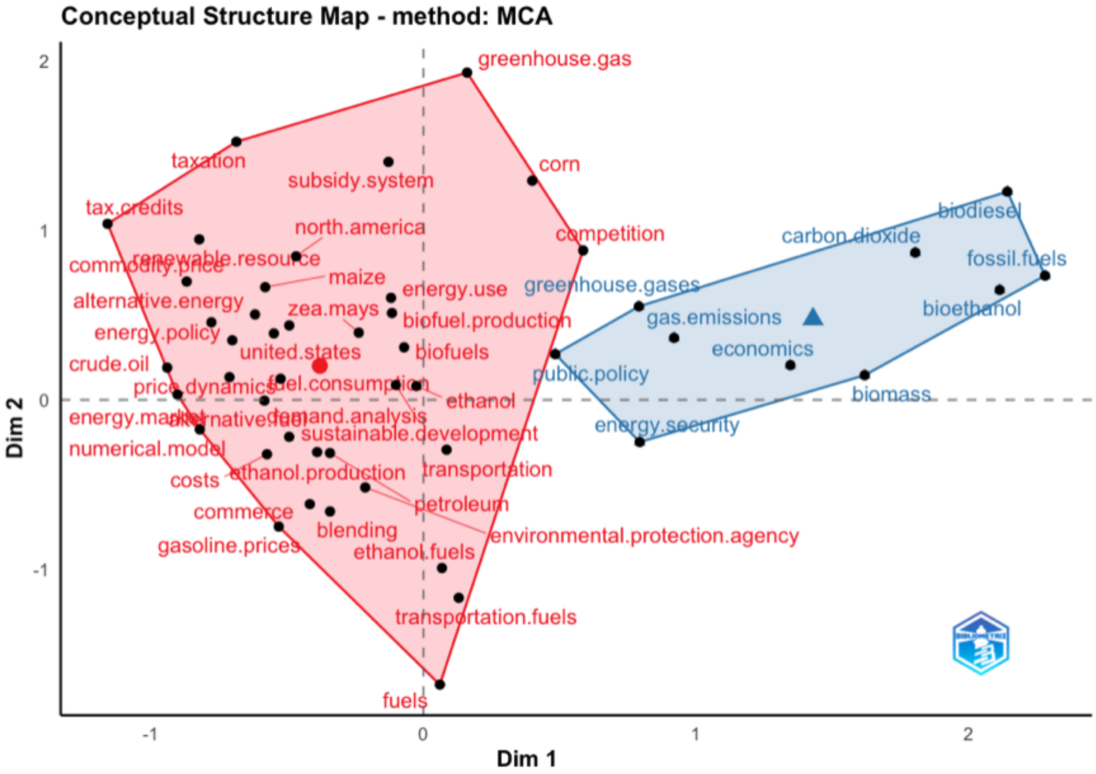


Figure 23 **Conceptual structure map**

Upon establishing the clusters, we analyze the content of the articles and focus on the title, abstract, introduction, and conclusion. This analysis aims to identify common interests and themes, from which the following predominant clusters are identified:

i. Impacts of biofuels on commodity prices and overall price dynamics;
ii. Impact of public policies on the implementation of ethanol and flexibility in the formulation of fuel blending;
iii. Impact of biofuels on environmental aspects.

It is important to note that, as the clustering technique was elaborated from the use of coincidental references, articles located in the transition region between the main clusters can be dedicated to evaluating themes inherent to more than one cluster.

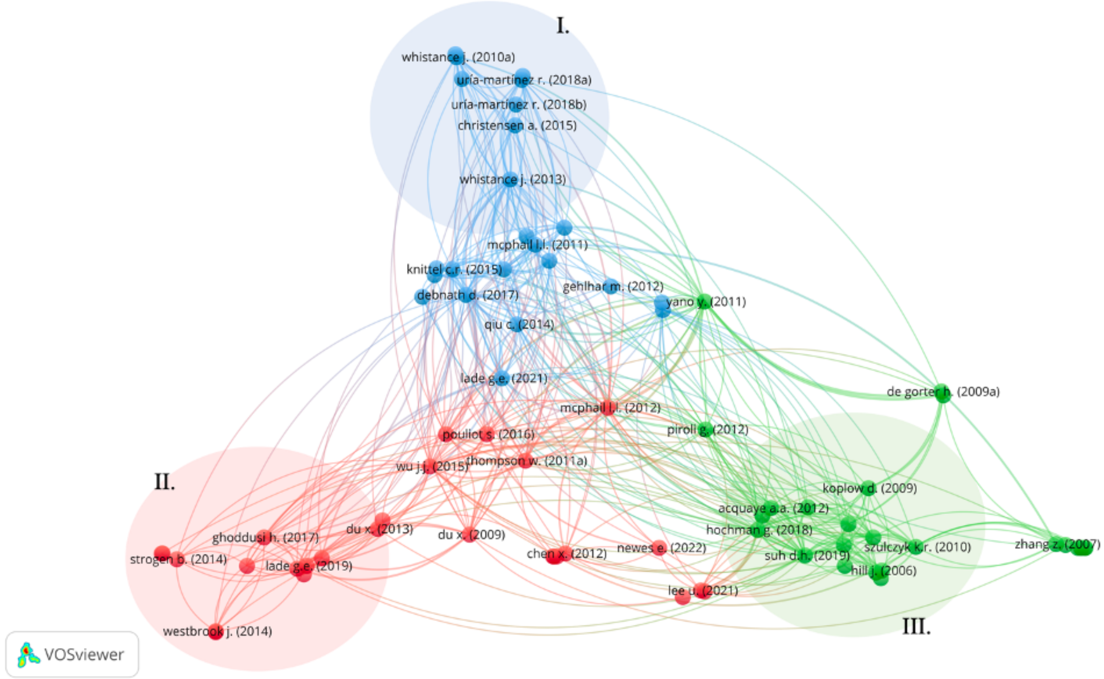


Figure 24 **Predominant clusters identified through bibliographic coupling**

7.1.2. Impacts of biofuels on commodity prices and overall price dynamics

Among the authors of the first cluster, Whistance and Thompson (2010) consider the North American scenario and evaluate how the increase in corn ethanol production impacts natural gas prices. The authors present a two-stage least squares structural model for projecting two scenarios: (i) current policies, including tariffs, tax credits, and mandates, were disregarded; (ii) established the production of ethanol only for the use of mandatory additives. The results indicate that the price of natural gas can be increased by up to 0.25% and 0.5% for the first and second scenarios, respectively.

In another study, Whistance et al. (2010) analyze the effects of the ethanol policy on the prices and quantity of natural gas, especially focusing on the impacts of the ethanol tariff, mandates, and tax credits. The results indicated an increase in corn production, which will consequently tend to raise natural gas prices.

Zilberman et al. (2013) investigate the relationship between food and fuel markets. According to the authors, the ethanol market provides a strong link between the corn and energy markets, and the price of ethanol increases as corn and gasoline prices increase. Finally, the study concludes that ethanol prices are positively related to sugar and oil prices.

Whistance and Thompson (2014) also analyze the price relationship between ethanol and gasoline and between corn and gasoline in the scenarios of a mandatory and non-mandatory (RFS). The authors find evidence that price relationships are weaker when RFS is mandatory.

Another example of a study that makes up this cluster is that of Christensen and Siddiqui (2015), which assesses the impacts on fuel prices and compliance costs associated with the RFS. In this article, a regional market model is proposed to quantify the impacts of prices for several market variables. Among the results, Christensen and Siddiqui (2015) identify that the RFS does not have a substantial impact on the retail prices of gasoline and diesel.

7.1.3. Impact of public policies for the implementation of ethanol and flexibility in the formulation of fuel blending. Based on the second cluster identified, Liu and Greene (2014) argue that a good understanding of the factors that affect demand for E85 is needed in order to develop effective policies for promoting E85 and to develop models that predict sales of this product in the United States. In this way, the authors estimate the sensitivity of aggregate demand for E85 to the prices of E85 and gasoline, as well as the relative availability of E85 versus gasoline, and conclude that the latest data allow for a better estimation of demand and indicate that the price elasticity of E85 is substantially higher than previously estimated.

Lade and Bushnell (2019) study the pass-through of the E85 subsidy to US retail fuel prices. The authors argue that the RFS relies on taxes and subsidies to be passed on to consumers to stimulate demand for biofuels and decrease demand for gasoline and diesel. The study concludes that between 50% and 75% of the E85 subsidy is passed on to consumers and that the pass-through takes approximately 6 to 8 weeks, with retailers' market structure influencing both the speed and level of pass-through.

(Ghoddusi 2017), through a quantitative assessment, measured the risks of price changes for biofuel producers in a deregulated market. The authors present a set of risk management strategies fully applicable to the protection of the biofuels sector.

In a different perspective, Westbrook et al. (2014) assess whether the U.S is able to meet the RFS targets without an enforcement mechanism. The authors proposed a parametric analysis of ethanol use for the domestic vehicle sector. The results indicate that the RFS program's goals to reduce fossil fuel consumption and, consequently, GHG emissions can be achieved by improving vehicle efficiency.

7.1.4. Impact of biofuels on environmental aspects Allocated in the third cluster, Sexton et al. (2009) analyze the impact of increased production of biofuels on food and fuel markets. They argue that the current production of biofuels generates a conflicting relationship between food and fuel, as it generates an increase in the cost of food and a reduction in the cost of gasoline. In this way, the study concludes that agriculture has to provide food and fuel, generating a need for constant improvement in its productivity. They argue that biotechnology has a fundamental role in allowing the achievement of this improvement.

Acquaye et al. (2012) use four scenarios to analyze the potential of biofuels to reduce UK emissions. The authors used a hybrid lifecycle assessment developed in a multi-regional input-output (MRIO) framework and concluded that in order to achieve the emission reduction determined by the Low Carbon Transition Plan (LCTP), it would be necessary that 23.8% of the transport fuel market would be served by biofuels by the year 2020.

Piroli et al. (2012) applied a time series analysis for the five main agricultural commodities, the cultivated area and the price of crude oil in order to study the impacts of changes in land use caused by the production of biofuels in the US. The authors conclude that the markets for crude oil and cultivated agricultural land are interdependent. Apart from that, the authors claim that the increase in biofuel production causes changes in land use which subsequently cause food commodities to be replaced by crops intended for biofuel production.

More recently, Suh (2019) examines the effects of replacing fossil fuels with biofuels on carbon dioxide emissions in the U.S transportation sector. The author proposes that ethanol is a substitute for oil and a complement to natural gas, while natural gas is a substitute for oil. Furthermore, the author concludes that the price-induced substitution of fossil fuels for biofuels is a critical factor in predicting biofuel-related carbon dioxide emissions.

7.1.5. Research Agenda To answer **RQ4** (what are the main trends and research opportunities for this literature?), we propose a possible open research agenda based on the results of our SLR. We notice that the term bioethanol has been present in the analyzed sample since 2012, remaining until now, especially when associated with the use of the terms ”commerce” and ”energy market”, which shows that this type of study is still interesting to the current research. Corroborating this statement, Figure 21 (Thematic map) presented the driving themes of the studied area, which include, in addition to the terms “commerce” and “energy market” already mentioned, “costs”, “energy policy”, “price dynamics” and “renewable resource”. In this way, it is possible to mention some research topics that have been little explored and that have started to draw attention more recently, standing out as hot-topics for future research. It is possible to propose the development of research focused on advanced biofuels, biofuels supply chains, and transportation biofuels, as well as issues of budget control and cost management, both in production and in the management of the biofuels supply chain. Also, an analysis of the thematic evolution allows the identification of research opportunities that involve the control of greenhouse gas emissions, and other environmental and climatic aspects.

Still discussing research trends, Figure 22 (Keyword co-occurrence map) corroborates previous discussions and opens horizons for new research opportunities on retail fuel spreads and on the e85 composition.

Moreover, Figure 23 (Conceptual structure map) points out opportunities for research in public policies related to climatic and environmental issues, energy security, while topics such as sustainable development, price dynamics, blending, demand analysis and biofuel production have greater centrality, that is, they tend to continue to be study opportunities.

Finally, Figure 25 shows the evolution of the representativeness of each cluster over time. We note that at the beginning of the research on the subject, the most influential cluster was the one that addressed the impact of biofuels on environmental aspects (cluster (iii)). However, this scenario has changed, and the figure makes it possible to identify that studies that assess the impacts of biofuels on commodity prices and overall price dynamics (cluster (i)) have been of greatest recent interest, followed by the assessment of the impact of public policies on the implementation of ethanol and flexibility in the formulation of fuel blending (cluster (ii)). In this way, the topics associated with clusters (i) and (ii) will represent the greatest opportunities for future research.

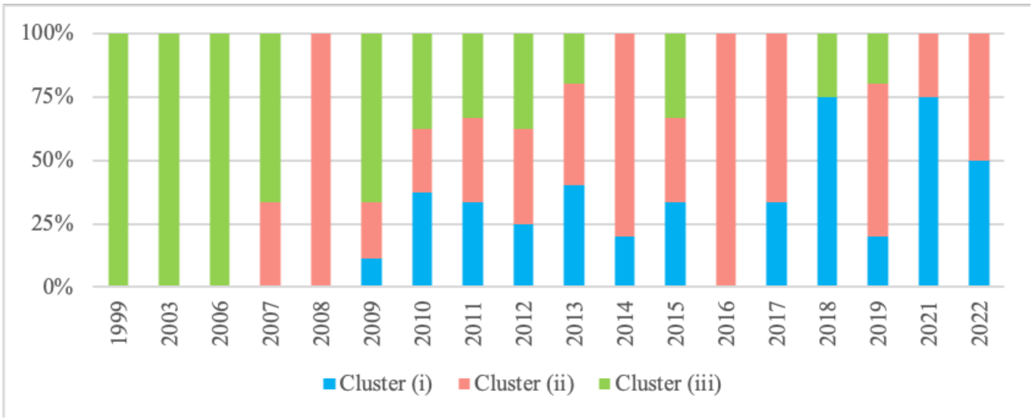


Figure 25 Evolution of the number of publications by clusters

7.2. Supplementary material

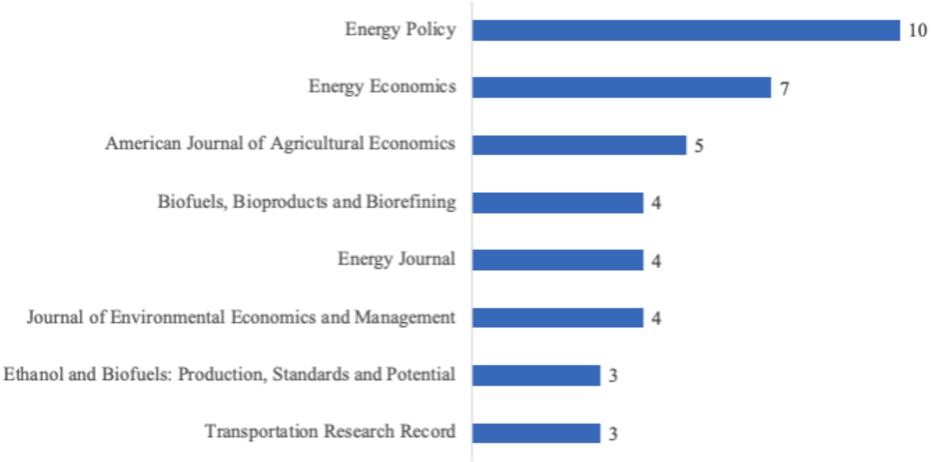


Figure 26 Most frequent journals in the SLR sample

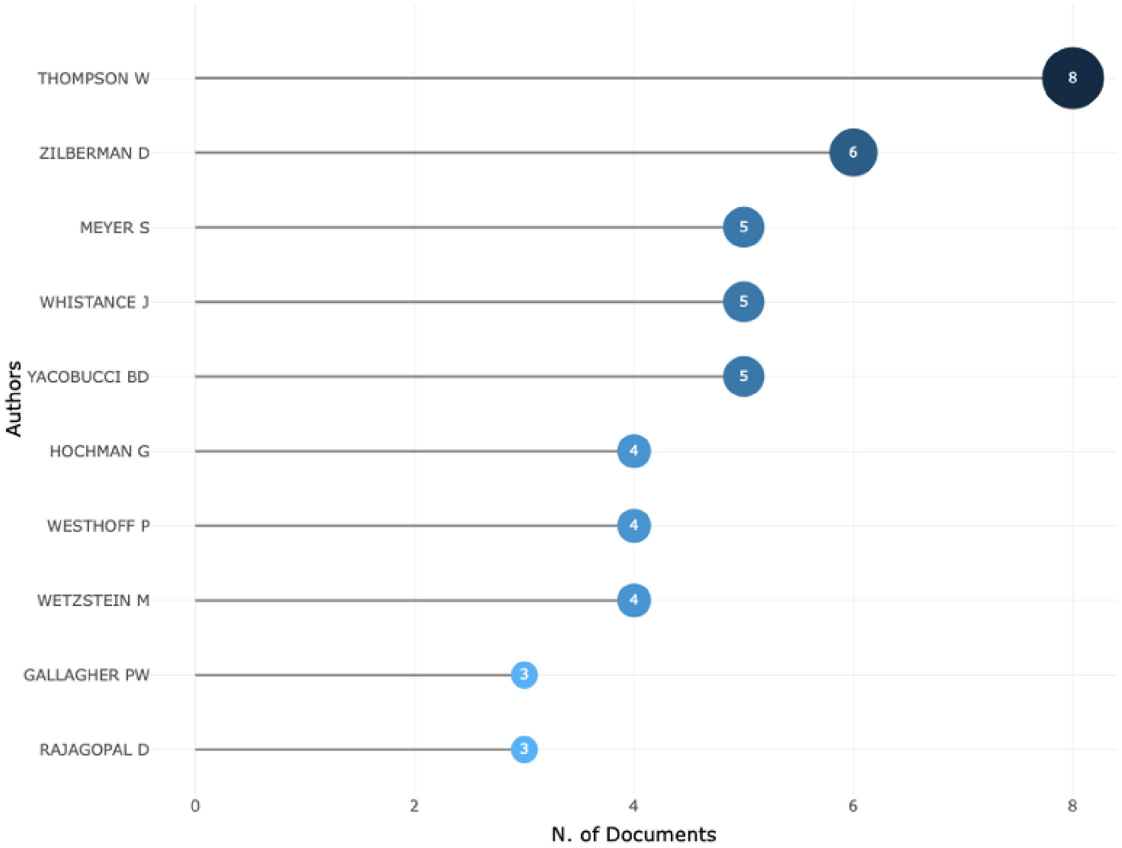
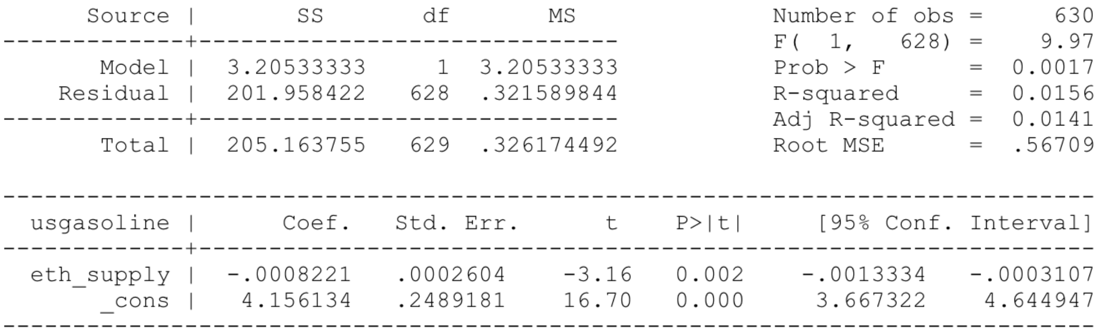


Figure 27 Distribution of citations over time for ten of the most cited articles in the sample



```
      Source |       SS       df       MS              Number of obs =     630
-------------+------------------------------           F(  1,   628) =    9.97
       Model |  3.20533333     1  3.20533333           Prob > F      =  0.0017
    Residual |  201.958422   628  .321589844           R-squared     =  0.0156
-------------+------------------------------           Adj R-squared =  0.0141
       Total |  205.163755   629  .326174492           Root MSE      =  .56709

------------------------------------------------------------------------------
  usgasoline |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
  eth_supply |  -.0008221   .0002604    -3.16   0.002    -.0013334   -.0003107
       _cons |   4.156134   .2489181    16.70   0.000     3.667322    4.644947
------------------------------------------------------------------------------
```

Figure 28 Full sample OLS estimate of the role of ethanol in gasoline prices based on weekly data from June 2010 to June 2022

variable	abb	value	unit	source
US fuel demand elasticity	ηDH	-0.37	unit free	Drabik et al. (2016)
Foreign fuel demand elasticity	ηDF	-0.40	unit free	Drabik et al. (2016)
US gasoline supply elasticity	ηSH	0.20	unit free	Drabik et al. (2016)
Foreign gasoline supply elasticity	ηSF	0.71	unit free	Drabik et al. (2016)
Gasoline price	PG	4.78	USD/GEEG	EIA
Ethanol market price (volume)	Pe	2.61	USD/gallon	Bloomberg
US motor fuel consumption (volumetric)	DF US	367.19	Mil gallons/day	EIA
US domestic corn demand as food/feed	DNY US	19.20	Mil bushels/day	USDA
US gasoline supply	SH	122.54	MilGEEG/day	EIA
Foreign fuel supply	SF	1 453.00	MilGEEG/day	EIA
US production of yellow corn	SC	39.34	Mil bushels/day	USDA
US corn exports	X	6.51	Mil bushels/day	USDA
Fuel tax in the ROW	tROW	0.00	USd/gallon	Drabik et al. (2016)
Fuel tax	tUS	0.49	USD/gallon	EIA
Corn ethanol blender's tax credit	tc	0.00	USD/gallon	NY Times (2012)
Miles per gallon of ethanol relative to gasoline	λ	0.70	unit free	Drabik et al. (2016)
Ethanol yield per bushel of corn	β	2.80	gallons/bushel	Drabik et al. (2016)

Table 8 **Variables in the elasticities model due to Drabik et al. (2016)**