The Biofuels Blueprint: Understanding the U.S. Renewable Fuel Standard

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Abstract: *This article provides a comprehensive review of the U.S. Renewable Fuel Standard (RFS), synthesizing nearly two decades of program evolution, market outcomes, and economic analysis. The RFS mandates minimum renewable fuel blending volumes through a nested structure based on lifecycle greenhouse gas reductions, enforced via tradeable Renewable Identification Numbers (RINs). Actual implementation diverged substantially from statutory targets, reaching only 20 billion gallons in 2022 versus the intended 36 billion, primarily due to cellulosic biofuel production failures. RIN prices exhibit extraordinary volatility but follow rational economic fundamentals rather than speculative excess. Total inflation-adjusted compliance costs are estimated to be $201.1 billion over 2011 through 2023, with full pass-through of these costs through competitive fuel markets at the bulk wholesale level. The RFS experience demonstrates both the potential and limitations of mandate-based renewable energy policies.*

Keywords: biofuels, biodiesel, ethanol, mandate, renewables, RFS, RIN

JEL Categories: Q02, Q11, C3

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Introduction

The U.S. Renewable Fuel Standard (RFS) represents one of the most ambitious and complex biofuel policies ever implemented, fundamentally reshaping American energy markets over the past two decades. The RFS mandates the blending of minimum volumes of renewable fuels into the nation's surface transportation fuel supply. With three core policy objectives—enhancing energy security through domestic biofuel production, promoting advanced low-greenhouse gas transportation fuels, and supporting rural economies—the program has influenced agricultural commodity markets, fuel pricing, investment decisions across multiple sectors, and the environment (Carter, Rausser, and Smith 2017; Burkhardt 2019; Lark et al. 2022).

Despite its economic significance and policy prominence, the RFS remains one of the most misunderstood federal programs in the energy sector. The program's complexity stems from its nested mandate structure based on lifecycle greenhouse gas emission reductions, its unique compliance mechanism using tradeable Renewable Identification Number (RIN) credits, and the frequent exercise of various waiver authorities that have dramatically altered implementation from statutory intentions. The original legislation envisioned a transition from 9 billion gallons of renewable fuels in 2008 to 36 billion gallons by 2022, with increasing reliance on advanced biofuels, particularly cellulosic ethanol. However, actual implementation has diverged substantially from these statutory targets, with total mandates reaching only 20 billion gallons in 2022, just over half the originally intended level.

This divergence between statutory ambition and practical implementation has generated significant market volatility and policy uncertainty (Lade and Smith 2025). RIN prices have exhibited extraordinary volatility, creating compliance cost swings that translate to billions of dollars annually across the petroleum refining sector. The emergence of the "E10 blend wall"—the practical constraint limiting ethanol blending to 10 percent of gasoline consumption—combined with the failure of cellulosic biofuel production to achieve commercial scale, has fundamentally altered the program's economic dynamics and distributional impacts.

Understanding the RFS is important for economists, market participants, and policymakers because the program does not sunset and will continue indefinitely. In addition, the interaction of the RFS with other policies has become more important over time. These include a changing menu of federal biofuel credits and the rise of state climate policies, with the California low carbon fuel standard being the most prominent example (Whistance, Thompson, and Meyer 2017). Moreover, sustainable aviation fuel (SAF) has emerged as a potentially major new source of demand for biofuels as arguably the most viable near-term option for decarbonizing aviation (Wu et al. 2025).

The purpose of this article is to provide a comprehensive review of the RFS, synthesizing nearly two decades of program evolution, market outcomes, and economic analysis. Our objective is to explain foundational concepts and principles, similar to Pindyck's (2001) widely cited primer on commodity spot and futures markets. We examine the program's institutional framework, including the nested mandate structure and RIN compliance system, explore the economic fundamentals driving RIN price formation and market behavior, and the passthrough of RIN costs through the fuel supply chain. The article draws on extensive price data, regulatory rulemakings, and market developments through 2025, providing much-needed clarity about the operation and impact of this critical energy policy.

We contribute to economic literature in several ways. First, we provide comprehensive documentation of RFS implementation and market outcomes, updating previous reviews (e.g., Stock 2015 2018) with recent developments including the program's post-2022 reset authority and emerging market dynamics. We also focus on how the RFS operates in practice, unlike reviews that take a more policy-oriented approach (Lade, Lin Lawell, and Smith 2018a; Khanna, Rajagopal, and Zilberman 2021; Lade and Smith 2025). Second, we demonstrate that RIN pricing follows rational economic fundamentals despite frequent claims of speculative excess or market manipulation. Third, we document full passthrough of RIN compliance costs through competitive fuel markets at the bulk wholesale level. Finally, we identify emerging structural changes in surface biofuel markets, particularly the growing importance of renewable diesel relative to traditional biodiesel, which have significant implications for future RIN price behavior and program effectiveness. Moreover, as state and national governments around the world pursue additional renewable fuel policies, the lessons learned from RFS implementation in the U.S. provide valuable insights for future policy design.

Overview of the U.S. Renewable Fuel Standard

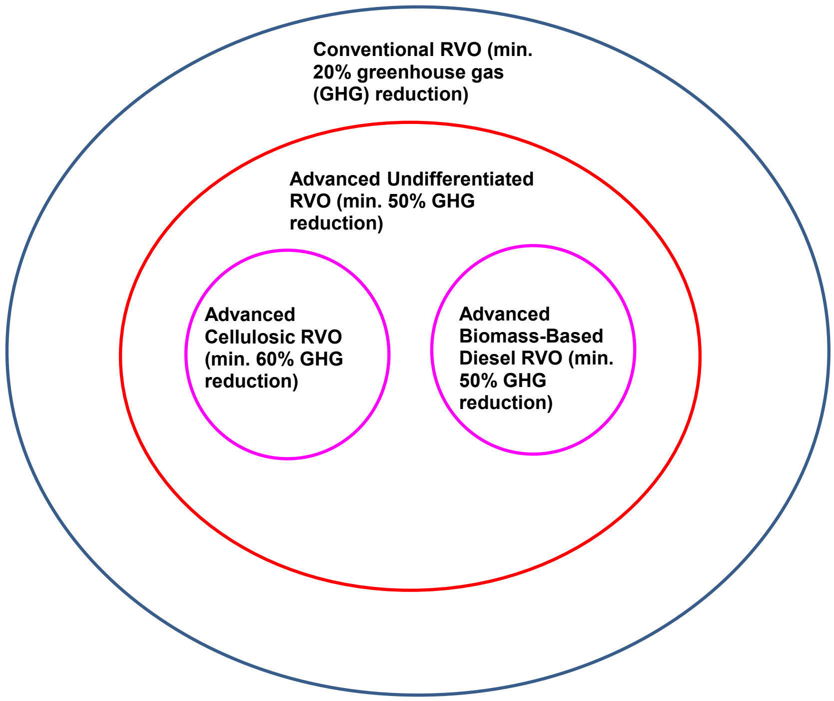
The U.S. Renewable Fuel Standard (RFS) was introduced in the Energy Policy Act of 2005 and expanded in both scope and duration in the Energy Independence and Security Act of 2007. The RFS program has three primary policy goals (Stock 2018): i) enhance energy security through additional domestic production of biofuels, ii) expand the development and production of second-generation low-greenhouse gas transportation fuels, and iii) support rural economies by expanding the demand for agricultural products.

The RFS specifies volumetric mandates, called renewable volume obligations (RVOs), for biofuels to be blended into U.S. surface transportation vehicle fuels. RVOs are specified for four categories of renewable fuels: cellulosic biofuel, biomass-based diesel, advanced biofuel, and conventional biofuel. Biofuels are defined by three attributes: i) feedstock, ii) production process, and iii) fuel type. Feedstock must be biological in nature, such as corn starch or soybean oil. Production of biofuel uses a combination of chemical and physical processes (e.g., Gerveni, Hubbs, and Irwin 2023a). Specific examples of biofuels include ethanol, biodiesel, and renewable diesel. Although the RFS only regulates the fuel content of surface transportation fuels, renewable fuels can qualify for the RFS program if they are used as jet fuel or heating oil.

The U.S. Environmental Protection Agency (EPA) is responsible for administering all aspects of the RFS. The EPA is required by the RFS statutes to issue annual rulemakings to set the RVOs. Through 2022, annual RVO rulemakings were required to be finalized by November 30th of the year prior. Thereafter, the annual standards were to be finalized 14 months before the compliance year begins. The deadlines for annual RVO rulemakings have been routinely missed, and this has been allowed by courts so long as the EPA provides reasonable justification.

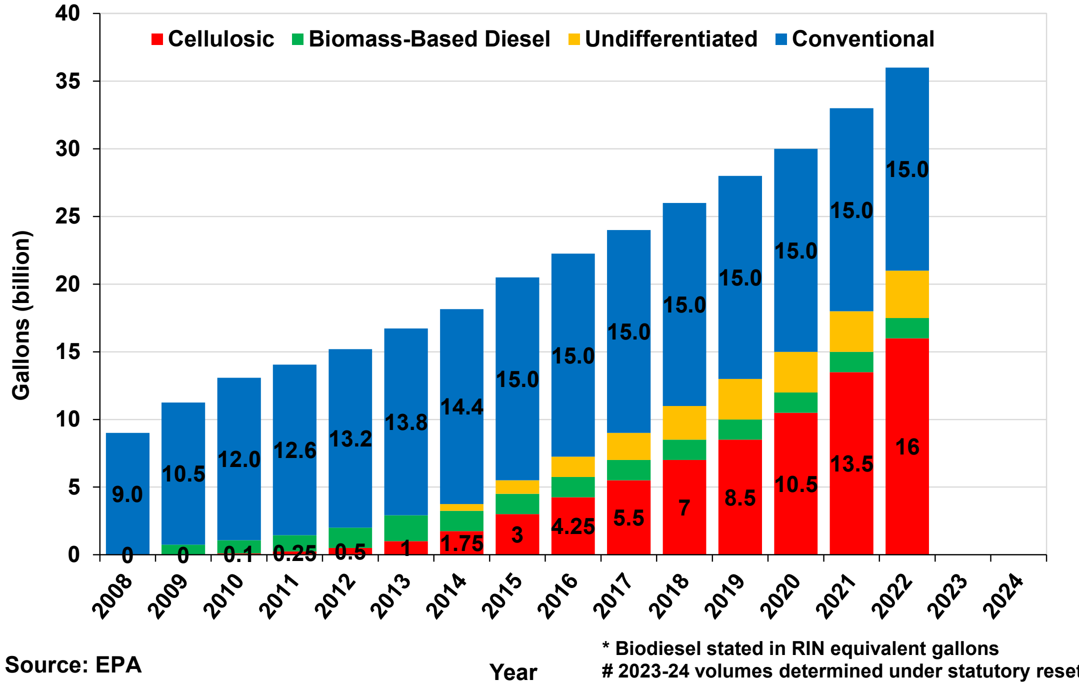
An important feature of the RFS standards is that they are nested based on lifecycle greenhouse gas (GHG) emission reductions relative to petroleum fuels. In contrast to fossil fuels, the carbon in biofuels is at least partially recycled because crops used as feedstock convert carbon dioxide from the atmosphere into biomass, which is then converted into transportation fuel. Biofuels with the largest GHG reductions have the highest rank, and this is reflected in the ordering from the inner to the outer rings in Figure 1. The two highest ordered biofuels are cellulosic and biomass-based diesel, with minimum GHG reductions of 60 and 50 percent, respectively. Cellulosic biofuels are eligible to meet their own RVO, the overall advanced RVO, and the (implied) conventional RVO, but not the biomass-based diesel RVO. Similarly, biomass-based diesel is eligible to meet its own RVO, the overall advanced RVO, and the conventional RVO, but not the cellulosic RVO. Other advanced biofuels must reduce GHG by at least 50 percent and can meet the overall advanced RVO as well as the conventional RVO. Conventional biofuels must reduce GHG by at least 20 percent and can only meet the conventional RVO and none of the other RVO categories. In practice, the conventional RVO is often referred to as the corn ethanol RVO because ethanol made from corn starch is the most common biofuel used to fill this implied RVO.

Figure 1. The RFS Biofuel Nesting Scheme



The 2007 RFS statute specified the level of volumetric standards through 2022 for each of the categories except for biomass-based diesel. Specific volumes for biomass-based diesel were specified through 2012. A minimum of one billion gallons of biomass-based diesel was required for 2013 through 2022, with larger amounts subject to EPA approval. The standards for each of the categories are presented in Figure 2. The basic logic behind the standards was to rely almost entirely on "first generation" conventional biofuels in the early years and then transition to greater reliance on "second generation" advanced biofuels in later years. This is seen in the cap on conventional biofuels at 15 billion gallons starting in 2015 and the increase in cellulosic from 1 billion gallons in 2013 to 16 billion gallons in 2022. The total RFS mandate for biofuels reached a maximum in 2022 of 36 billion gallons. Specific volumetric standards were not provided in the 2007 RFS statute after 2022. However, a "reset" process was included in the statute for setting standards starting in 2023, and this will be discussed in more detail later in this section.

Figure 2. Statutory U.S. Renewable Fuel Standard Volume Obligations (RVOs), 2008 - 2024*,#



The statutory volumes shown in Figure 2 are only the starting point for the EPA in annual rulemakings. The RFS provides three separate authorities to modify or waive the statutory RVOs:

1. The cellulosic waiver authority allows the EPA to reduce the cellulosic RVO by the amount of a projected shortfall of cellulosic production below the statutory cellulosic RVO. The statute authorizes EPA to reduce the total advanced and total renewable RVOs by up to the amount of the cellulosic shortfall.

2. The general waiver authority allows EPA to waive any of the volumes if it finds either that failing to do so would "severely harm the economy or environment of a State, a region, or the United States," or if there is "inadequate domestic supply" of the relevant biofuel (Coppess and Irwin 2017a).

3. The biomass-based diesel waiver authority allows the EPA to waive the biomass-based diesel RVO by up to 15 percent of the applicable annual requirement for up to 60 days (Coppess and Irwin 2017b). The EPA must determine that there is a significant renewable feedstock disruption or other market circumstances that would make the price of biomass-based diesel increase significantly to invoke this temporary waiver.

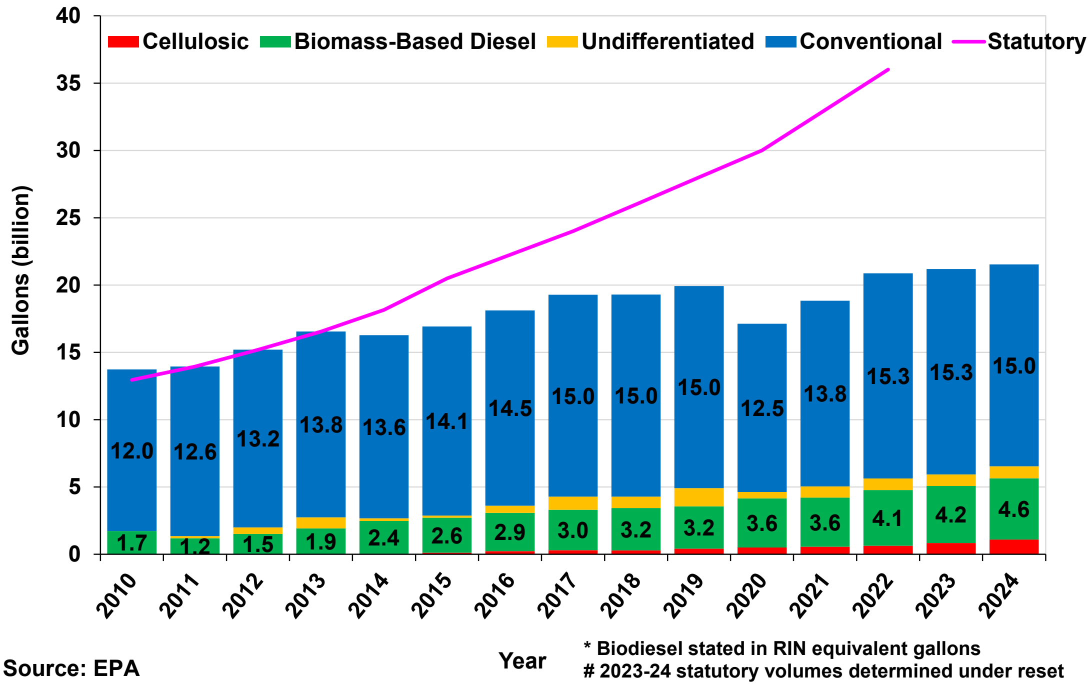
While not directly impacting statutory volumes like the waiver provisions discussed above, the RFS also includes a provision for granting temporary exemptions from RFS compliance for small refineries (Coppess and Irwin 2017c). Small refineries are defined as those with less than 75,000 barrels of crude oil throughput in a calendar year. The RFS initially included a blanket exemption for all small refineries through 2011, which was subsequently extended through 2013 by the EPA. In addition, the RFS statutes provided EPA with the authority to grant an extension of the blanket exemption to individual small refineries. An exemption is based upon petition and must demonstrate that the refinery experienced "disproportionate economic hardship."[1]

Figure 3 presents the final RFS RVOs for 2010 through 2024, along with total statutory RVOs. The RVOs shown in this chart were drawn from the final EPA rulemakings for each calendar year. It is evident that total final RVOs for the RFS fell far short of the ambitious goals set in the RFS statutes. For example, the total RVO in 2022 was a little more than 20 billion gallons when the statutory target was 36 billion gallons. The biggest reason for the shortfall can be traced to cellulosic biofuel production. The mandated targets for cellulosic biofuels were extremely aggressive from the outset, given that industrial-scale production was virtually non-existent when the second RFS legislation was passed in 2007. While several plants were subsequently built, production of liquid cellulosic fuels struggled to reach even a few million gallons. Until recently, nearly all the production in this category has been in the form renewable natural gas ("biogas") from landfills and anerobic manure digesters.[2] In the last year, cellulosic ethanol production has increased from corn kernel fiber conversion at ethanol plants. The low cellulosic production totals from all sources caused the EPA to use its cellulosic waiver authority to write down the cellulosic RVO to very low levels every year over 2007 to 2022. The total renewable and advanced RVOs have also been written down in conjunction with the write-down in the cellulosic RVO.

The implementation of the annual RFS standards has been complicated by two additional factors. The first is the E10 "blend wall," which arises because regulation in the U.S. has historically limited the ethanol content of gasoline blends to a maximum of 10 percent by volume (Lade and Smith 2025). Consequently, the theoretical maximum amount of ethanol that can be consumed is 10 percent of total gasoline consumption. At the time the RFS was passed in 2005 and 2007, it was commonly projected that U.S. gasoline consumption by 2015 would be around 150 billion gallons. So, it is no surprise that the cap on the conventional RVO in 2015 was set to 15 billion gallons, exactly 10 percent of projected gasoline consumption. The problem is that actual gasoline consumption began falling almost as soon as the RFS was passed due to the combined effects of high real crude oil prices and the onset of the Great Recession. Consequently, the conventional

RVO as specified in the RFS statutes began to surpass the E10 blend wall in 2013. This in turn caused compliance costs to increase sharply (Irwin and Good 2013). The second complicating factor was the global COVID-19 pandemic that started in March 2020. This caused gasoline and diesel consumption in the U.S. to plunge dramatically (Irwin and Hubbs 2020). Considering this emergency, the EPA reduced the annual RVOs in 2020 and 2021, with the largest reductions falling on the conventional RVO.

Figure 3. Final U.S. Renewable Fuel Standard Volume Obligations (RVOs), 2010 - 2024*,#



EPA rulemakings on the RFS have been subjected to a long series of legal challenges, with much of the litigation dealing with issues related to the conventional RVO surpassing the E10 blend wall. Examples include challenges to the EPA's interpretation of "inadequate domestic supply" (Irwin and Good 2017c) and the awarding of small refinery exemptions (Coppess and Irwin 2020). Other cases have dealt with the level of the cellulosic RVO (Endres and Endres 2013) and the point of obligation for compliance. Some of the cases have reached all the way to the U.S. Supreme Court.[3]

An important aspect of the RFS is that it does not "sunset." In other words, the EPA is required to continue issuing annual RVOs even though the statutes no longer specify volumetric mandate levels after 2022. Annual RVOs will continue indefinitely until the U.S. Congress repeals or revises the RFS. The EPA was granted broad discretion in determining RVOs after 2022, using a "reset" process following these specific steps:

1. EPA gathers data on current biofuel production capacity, feedstock availability, consumption patterns, and market conditions. The agency also reviews implementation of the prior year's standards to assess program performance.
2. The EPA determines the reset volumes by the analysis of six statutory factors: i) the impact of the production and use of renewable fuels on the environment, including air quality, climate change, conversion of wetlands, ecosystems, wildlife habitat, water quality, and water supply, ii) the impact of renewable fuels on the energy security of the United States, iii) the expected annual rate of future commercial production of renewable fuels, including advanced biofuels in each category (cellulosic biofuel and biomass-based diesel), iv) the impact of renewable fuels on the infrastructure of the United States, including deliverability of materials, goods, and products other than renewable fuels, and the sufficiency of infrastructure to deliver and use renewable fuels, v) the impact of the use of renewable fuels on the cost to consumers of transportation fuel and on the cost to transport goods, and vi) the impact of using renewable fuels on other factors, including job creation, the price and supply of agricultural commodities, rural economic development, and food prices.
3. Based on the analysis of the previous factors, EPA determines appropriate volume targets for each biofuel category, ensuring compliance with statutory constraints such as the nested structure of RVOs and minimum biomass-based diesel requirements.

In June 2023, the EPA announced final RVOs for 2023, 2024, and 2025 based on the reset criteria for the first time.[4] That final rulemaking established biofuel volume requirements and associated percentage standards for cellulosic biofuel, biomass-based diesel, advanced biofuel, and total renewable fuel. The rulemaking also responded to a court remand of the 2016 annual rule by establishing a supplemental volume requirement of 250 million gallons of renewable fuel that was added on top of the total renewable fuel RVO for 2023. The 2023 through 2025 final U.S. RFS volume targets are presented in Panel A of Table 1. EPA set progressively increasing volume targets across most biofuel categories, with total RVOs rising from 21.19 (20.94 + 0.25) billion gallons in 2023 to 22.33 billion in 2025. Notably, the implied conventional RVO remained capped at 15 billion gallons for 2024 and 2025, reflecting the persistent E10 blend wall constraint. The biomass-based diesel RVO shows steady growth from 2.82 to 3.35 billion gallons, while the cellulosic RVO increases from 0.84 to 1.38 billion, representing EPA's cautious but optimistic assessment of emerging cellulosic production in recent years.

Table 1. Final U.S. RFS Volume Targets and Fractional Mandates, 2023 - 2025

	Calendar Year		
Category	**2023**	**2024**	**2025**
Panel A: Final U.S. RFS Volume Targets (Billion RINs)			
(1) Renewable fuel	20.94	21.54	22.33
(2) Advanced biofuel	5.94	6.54	7.33
(3) Cellulosic	0.84	1.09	1.38
(4) Biomass-based diesel	2.82	3.04	3.35
(5) Implied Conventional (1) + (6) - (2)	15.25	15	15
(6) Supplemental standard	0.25	n/a	n/a
Panel B: Fractional Mandates (%)			
(1) Renewable fuel	11.96	12.5	13.13
(2) Advanced biofuel	3.39	3.79	4.31
(3) Cellulosic	0.48	0.63	0.81
(4) Biomass-based diesel	2.58	2.82	3.15
(5) Implied Conventional (1) + (6) - (2)	8.71	8.71	8.82
(6) Supplemental standard	0.14	n/a	n/a

Notes: The volumes in Panel A are shown as billion ethanol-equivalent RIN gallons except biomass-based diesel, which is shown in billion physical gallons.

It is important to understand that compliance with annual RVOs is enforced via percentages rather than absolute volumes. More specifically, the volume targets are converted into percentage standards using projections from the Energy Information Agency (EIA) of the U.S. Department of Energy for petroleum gasoline and diesel consumption in the lower-48 states plus Hawaii (Alaska opted out of RFS requirements). In addition, the amount of biofuels blended into gasoline and diesel and expected small refinery exemptions are included in the computations. The specific formula for a given compliance year is:

$$FRVO_i = \frac{RVO_i}{(G + D - R) - SRE} \ X \ 100, \tag{1}$$

where $FRVO_i$ is the fractional percentage RVO for the i^{th} biofuel (i = total, advanced, biomass-based diesel, and cellulosic), RVO_i is the mandated volume for the i^{th} biofuel, G is the 49-state projected total gasoline consumption for the U.S., D is the 49-state projected diesel consumption for the U.S., R is the projected volume of biofuels in total gasoline and diesel consumption in the U.S., and SRE is the projected volume of small refinery exemptions. Notice that the denominator in the computation of percentage standards in equation (1) is combined petroleum and gasoline consumption net of biofuels, which means that every (obligated) gallon of petroleum gasoline and diesel transportation fuel in the U.S. is subject to the same set of fractional obligations. This provides both certainty and flexibility. The certainty is the result of percentage requirements being fixed for a calendar year regardless of market fluctuations in petroleum gasoline and diesel demand. The flexibility is due to total compliance volumes automatically adjusting based on actual petroleum gasoline and diesel fuel consumption levels.

Obligated parties under the RFS are domestic petroleum refiners and importers as well as some foreign producers. These parties use fractional mandates to calculate firm-specific RVOs. This is done by multiplying the applicable percentage standard by an obligated party's fuel production and/or imports. Consider the fractional RVOs for 2023 through 2025 shown in Panel B of Table 1. A refiner producing 1 billion gallons of petroleum gasoline and diesel in 2025 would need to demonstrate that 131.3 million gallons of renewable fuel in total was blended into the transportation fuel supply (1 billion gallons x 13.13%). Within this total, obligated parties must ensure compliance with each biofuel category.[5] So, they would need to demonstrate the blending of 8.1 million gallons of cellulosic biofuel (1 billion gallons x 0.81%) and 31.5 million gallons of biomass-based diesel (1 billion gallons x 3.15%). The "undifferentiated" RVO is implied as the difference between total advanced and cellulosic and biomass-based diesel RVOs. Hence, obligated parties would need to demonstrate blending of 3.5 million gallons of undifferentiated advance biofuel (1 billion gallons x (4.31% - 0.81% - 3.15%)). Finally, the conventional RVO is also implied and computed as the difference between the total renewable fuel and advanced RVOs. This implied conventional RVO would be 88.2 million gallons (1 billion gallons x (13.13% – 4.31%)).

The RIN Compliance System

Once RVOs are known and obligated parties compute firm-specific mandates, a mechanism is needed for demonstrating compliance. The RFS legislation established a system of compliance based on Renewable Identification Numbers (RINs). A RIN is a 38-digit identifier generated upon production or import of a qualifying biofuel.[6] As biofuel moves through the fuel supply chain, the RIN must remain attached to the biofuel. The RIN can be separated (detached) only when the biofuel is blended into motor vehicle fuel. Detached RINs are tradable, so an obligated party can acquire RINs for compliance either by purchasing renewable fuel with the RIN attached or by purchasing RINs in the secondary market. Once obtained via blending or purchase, obligated parties can turn RINs in to the EPA to demonstrate compliance ("retire" the RIN). Finally, RINs attached to biofuel that is exported must be retired within 30 days because the fuel is not used for U.S. domestic surface transportation.

Five categories of biofuel RINs are specified under the RFS:

- D3 RINs represent cellulosic biofuel made from switchgrass, miscanthus, crop residue, food waste, cover crops, tree residue, manure, and landfill gas.
- D4 RINs represent biomass-based diesel biofuel made from vegetable oil and waste oil and fats. D4 RINs represent a variety of biofuels, including FAME (fatty acid methyl ester) biodiesel, renewable diesel, jet fuel, and renewable heating oil. A common industry shorthand is to refer to D4 RINs as biodiesel RINs.
- D5 RINs represent undifferentiated advanced biofuel, such as sugarcane ethanol, grain sorghum, biogas from waste digesters, and non-cellulosic portions of food waste and cover crops. A common industry shorthand is to refer to D5 RINs as advanced RINs.
- D6 RINs represent conventional biofuel, mainly corn starch ethanol. A common industry shorthand is to refer to D6 RINs as ethanol RINs.
- D7 RINs represent cellulosic diesel that is produced using crop residue, switch grass, yard waste, cellulosic food waste and cellulosic cover crops.

The RIN categories are nested based on the hierarchy shown in Figure 1. Each RIN category meets its own biofuel type: D3 and D7 for cellulosic, D4 for biomass-based diesel, D5 for undifferentiated advanced (total advanced – (cellulosic + biomass-based diesel), and D6 for conventional (total renewable fuel – total advanced). Given the nesting hierarchy based on GHG reductions, excess D3, D4, and D7 RINs can be used to satisfy the undifferentiated advanced and conventional RVOs, and excess D3, D4, D5, and D7 RINs can be used to satisfy the conventional requirement. D6 RINs can only be used to satisfy the conventional RVO.

Biofuels cannot generate RINs unless officially approved by the EPA. Each “biofuel pathway” consists of a feedstock, production process, and fuel type, mirroring the definition of biofuels provided earlier. The pathway approval process includes a detailed analysis of lifecycle GHG emissions. Based on the feedstock, fuel type, and lifecycle GHG reduction relative to petroleum fuel, the EPA evaluates the petition. If the petition is approved, a D RIN code is assigned, and RIN generation can proceed under the pathway.

An important feature of the RIN credit system is that the number of RINs generated per physical gallon of biofuel is based on the energy equivalence value with ethanol. Because biofuels differ by energy content, it does not make sense to add together gallons across different biofuel types. For this reason, the EPA adjusts all physical biofuel gallons by energy value when determining RIN generation. Specifically, blending one gallon of ethanol generates one RIN, blending one gallon of FAME biodiesel generates 1.5 RINs, and blending one gallon of renewable diesel generates 1.6 or 1.7 RINs. Accordingly, it is necessary to distinguish between “wet” (physical) gallons of a biofuel and RIN-equivalent gallons. For example, one wet gallon of FAME biodiesel generates 1.5 RIN gallons.[7]

Another important characteristic of RINs is their storability. Specifically, a RIN created in a given year can be used for compliance in the calendar year the RIN was produced or the next year. For example, RINs generated in 2025 can be used to meet compliance obligations in 2025 or 2026. Being able to bank RINs provides a buffer to fluctuations in fuel supply and demand. However, banking of RINs by obligated parties cannot exceed 20 percent of the subsequent year’s RVO. This limit prevents large surpluses of RINs from being rolled over year-after-year.

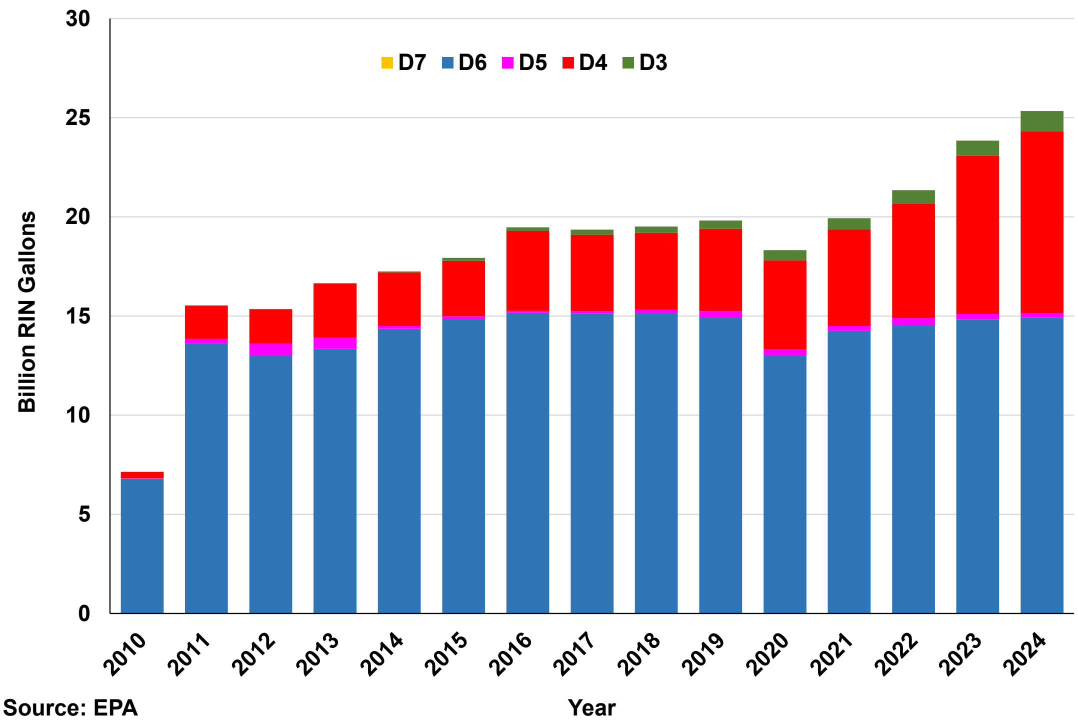
In a parallel fashion, an obligated party may incur a RIN compliance deficit up to 20 percent of their RVO in any given year. However, any deficit incurred in a given compliance year must be made up in the following compliance year. This rule prevents obligated parties from rolling deficits indefinitely into the future.

Lastly, because of uncertainty surrounding cellulosic ethanol production, the RFS statutes require that the EPA make cellulosic waiver credits available to obligated parties whenever the cellulosic waiver authority is used to reduce the cellulosic RVO. The formula for the price of cellulosic waiver credits is also specified in the statutes, and the credit can be combined with a D5 advanced RIN to satisfy the cellulosic RVO.[8]

Figure 4 presents annual RIN generation by category over 2010 through 2024.[9] While RIN generation is obviously related to the RVOs presented in Figure 2 and Table 1, it is important to recognize that RIN generation generally differs from RINs used for compliance in a given year. There are several reasons for this difference: i) RINs must be retired for biofuels that are exported; ii) some small errors may occur in reported RIN generation; iii) RINs can be banked from one compliance year to the next; and iv) obligated parties have flexibility in which RIN categories are used to comply with some of the RVOs (e.g., D4 vs. D6 for meeting the conventional RVO). With that caveat in mind, there are several broad trends in the RIN generation data that are notable. The first is that D6 conventional RIN generation has been at or slightly below 15 billion gallons every year except for 2010, the first year of the program, and 2020, the COVID year. This is no accident given that conventional RVO has been set near 15 billion gallons for most years. The second is the growing level of D4 biomass-based diesel RIN generation. In 2019, D4 RIN generation was 4.1 billion gallons. This more than doubled to 9.2 billion in 2024. The growth of

D4 RIN generation reflects increases in the biomass-based diesel and overall advanced RVOs. The third is the appearance of substantial volumes of D3 cellulosic RIN generation starting in 2021. D3 generation in 2024 topped a billion gallons for the first time.

Figure 4. Annual RIN Generation by Category, 2010 - 2024

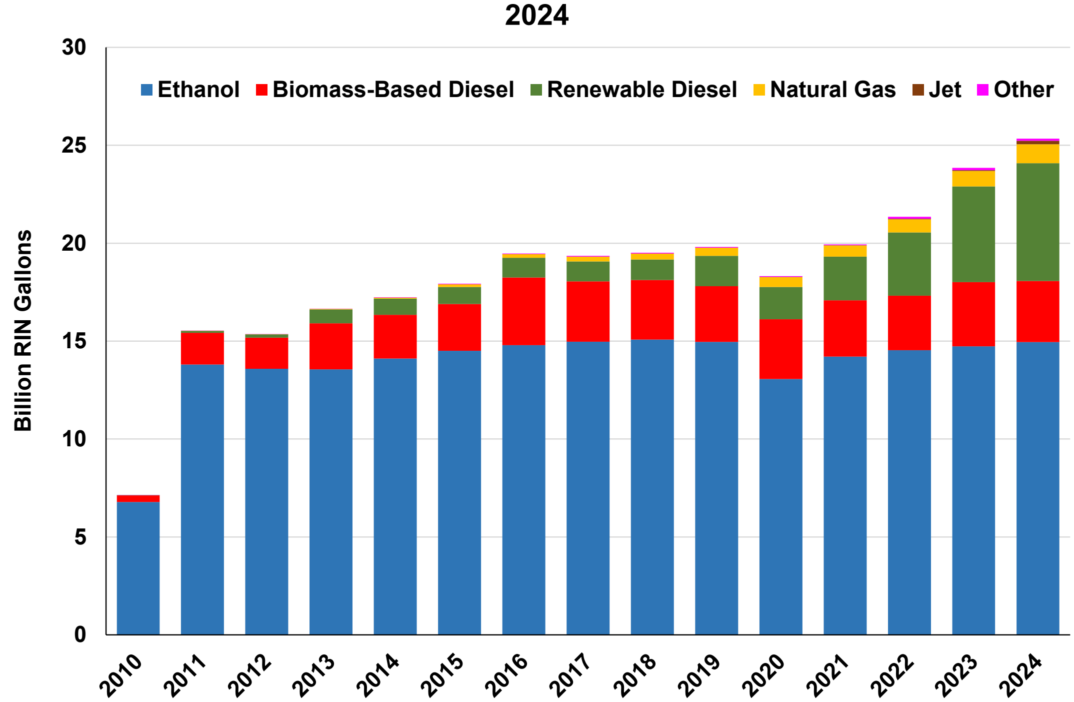


Source: EPA

Further insights are provided in Figure 5, which breaks out RIN generation by type of biofuel over 2010 through 2024. This breakout requires aggregating generation data across RIN categories for some biofuels. For example, renewable diesel pathways have been approved by the EPA for generating D4, D5, and D6 RINs. The breakout indicates that ethanol RIN generation has been slightly less than 15 billion gallons in most years, which reflects the fact that the vast majority of D6 RINs are associated with ethanol production. That data also highlights the increase in FAME biodiesel RIN generation over time. Biodiesel generation, which was 1.6 billion gallons in 2011, expanded to 3.1 billion gallons by 2020, almost exactly doubling over the decade. Since 2020, biodiesel RIN generation has been more or less flat around 3 billion gallons. There was also a substantial increase in renewable natural gas RIN generation in recent years, which rose to nearly a billion gallons in 2024. This is primarily associated with growth in natural gas production from landfills and dairy manure anaerobic digesters.

The most striking feature of Figure 5 is the explosion in renewable diesel RIN generation that started in 2021.[10] Renewable diesel generation was 1.6 billion gallons in 2020, roughly half the level of biodiesel generation that year. By 2024, renewable diesel RIN generation reached 6 billion gallons, a nearly four-fold increase in only four years and more than twice that of biodiesel. The 2024 generation total for renewable diesel represented nearly a quarter of all 2024 RIN generation. The factors driving the renewable diesel boom include increases in RVOs, especially biomass-based diesel, federal tax credits, and state-level low-carbon fuel program credits. This illustrates the interconnected nature of the biomass-based diesel "policy stack," which cannot be fully understood one policy at a time (Whistance, Thompson, and Meyer 2017; Mazzone, Smith, and Witcover 2022; Gerveni, Irwin, and Hubbs 2023b; Lade and Smith 2025). In particular, credits generated through the LCFS program in California played a crucial role in incentivizing the expansion of renewable diesel capacity in the U.S. (Gerveni, Irwin, and Hubbs 2023c). However, total consumption of biomass-based diesel in the U.S. is still determined by the RFS RVOs. LCFS tax credits offset part of the RIN cost of complying with the national standard, but do not change the level of the national standard. LCFS credits also direct the flow of renewable diesel towards California (Gerveni, Irwin, and Hubbs 2023d).

Figure 5. Annual RIN Generation by Type of Biofuel, 2010 - 2024

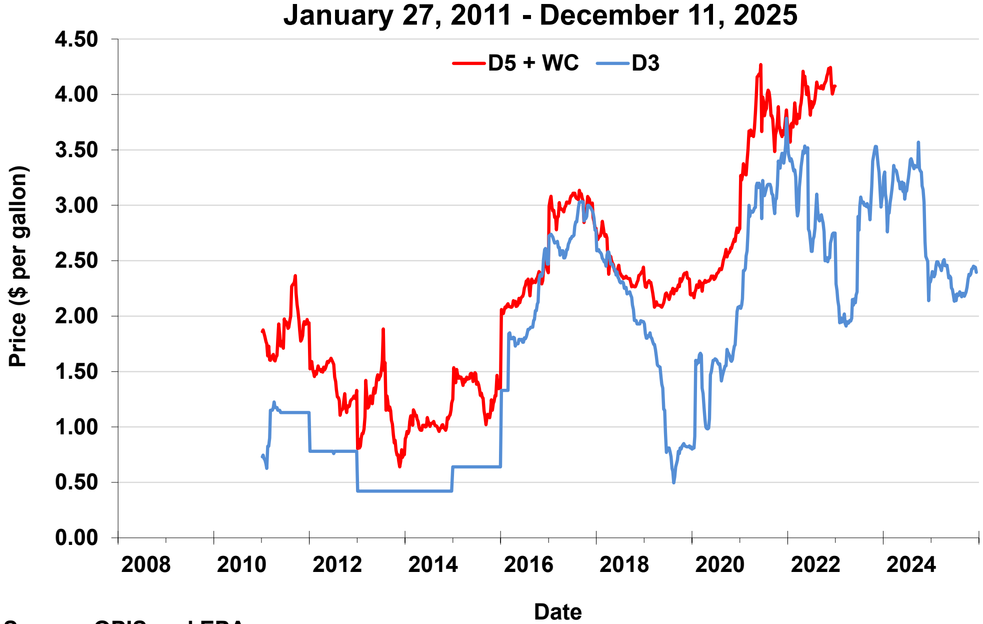


Source: EPA

Historical RIN Prices

RINs trade in an active secondary market and there is now a long history of prices to examine. We begin with D3 prices, which, as noted above, represent a special case because the RFS statute allows the possibility of satisfying the cellulosic RVO with a waiver credit combined with a D5 RIN in place of a D3 RIN. What this means in practice is that the price of a D3 RIN should never trade above the price of a D5 RIN plus the waiver credit amount. Figure 6 shows the history of D3 prices and the D5 RIN price plus waiver credit from January 2011 through December 2025. As expected, the D3 RIN price is always below the D5 RIN price plus waiver credit. Note that waiver credits were not initially offered during 2023 through 2025. A waiver credit for 2024 was offered starting in June 2025 but is not included here because the credit value was not known to RIN traders in real-time during 2024. The D3 price has fluctuated over a wide range, with lows near $0.50 per gallon and highs above $3.50. In recent years, prices have fluctuated between roughly $2.00 and $3.50.

Figure 6. Weekly (Thursday) Sum of D5 Advanced RIN Price and Cellulosic Waiver Credit and D3 Cellulosic RIN Price, January 27, 2011 - December 11, 2025

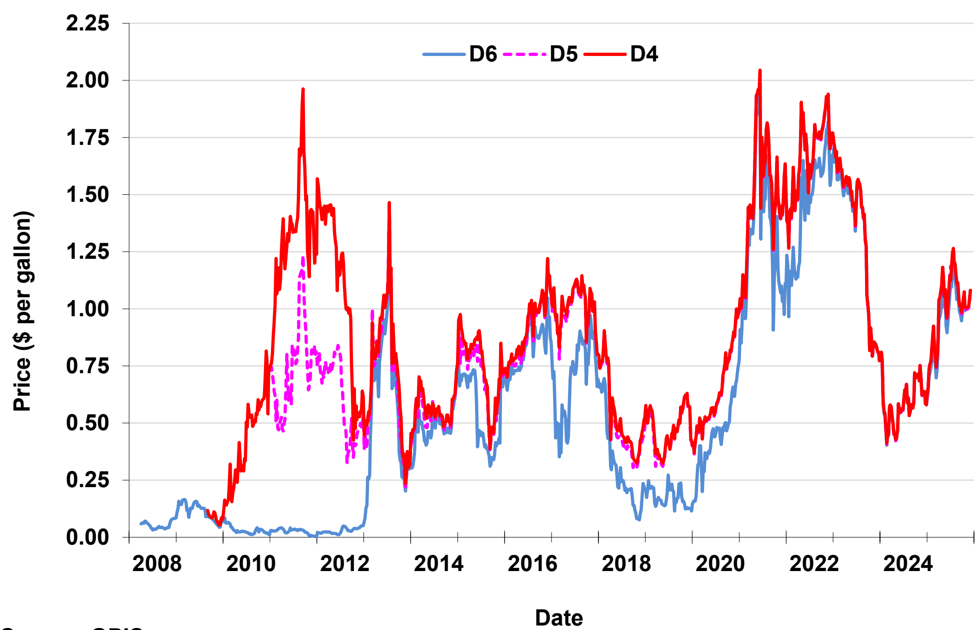


Source: OPIS and EPA

Figure 7 shows the available history of D4, D5, and D6 RIN prices since April 2008. There are several notable features of the prices for these RIN categories. The first is that D6 RIN prices generally traded for extremely low values, only a few cents, for the first five years of the available market history. It is reasonable to think of these low prices as largely reflecting administrative and overhead costs of compliance for obligated parties under the RFS (Thompson, Meyer, and

Westhoff 2010 2011; Whistance and Thompson 2014).[11] The implication is that blending ethanol into gasoline through 2012 required little if any incentive through the RIN mechanism. In other words, ethanol was a competitive blend component in E10 gasoline without the RFS mandate. This was due to several factors, including the availability of federal and state ethanol tax credits, historically high crude oil prices, the transition from MTBE (methyl tert-butyl ether) as the primary source of octane and oxygenate in gasoline blends to ethanol providing these components, and the development of petroleum gasoline blendstocks better matched to the properties of ethanol (Tyner 2008; Irwin and Good 2012; Abbott 2013; Babcock 2013; Anderson and Elzinga 2014; Taheripour, Baumes, and Tyner 2022; Newes et al., 2022; Irwin 2025).

Figure 7. Weekly (Thursday) D4 Biodiesel, D5 Advanced, and D6 Ethanol RIN Prices, April 3, 2008 - December 11, 2025



Source: OPIS

The second feature is the explosion in D6 RIN prices to over $1 per gallon that occurred in the first half of 2013. While highly controversial at the time, there is a relatively simple explanation for the meteoric rise in D6 prices (Irwin and Good 2013). Importantly, it is not because ethanol lost its position as a competitive blend component in E10 gasoline. Instead, as noted earlier, regulations on the volatility properties of gasoline had long imposed a 10 percent constraint on the total amount of ethanol that could be consumed in the U.S. gasoline pool (Lade and Smith 2025), and the conventional RVO began to exceed the E10 blend wall in 2013. Skyrocketing D6 RIN prices in the first half of 2013 were associated with the recognition by market participants that the gap between the conventional RVO and the E10 blend wall would have to be filled by D4

RINs, the cheapest alternative for filling the conventional RVO. This is possible because of the nesting hierarchy of RINs illustrated earlier in Figure 1. In short, D4 RINs assumed the role of the "marginal" gallon for filling the conventional RVO, which forced the price of D6 RINs to rise to the level of D4 RINs (Lade, Lin Lawell, and Smith 2018b). As we will see in the next section, the fundamental value of D4 RINs is driven by the price of biomass-based diesel, which tends to be much more expensive to produce than the petroleum diesel it displaces.

The third notable feature of D4, D5, and D6 RIN prices is high volatility. D4 and D6 prices have fluctuated between a few cents and more than $2 per gallon. D5 prices have not been quite as volatile but have ranged from under $0.50 to over $2 per gallon. It is not surprising, then, that the coefficient of variation (standard deviation/mean) is 49, 47, and 87 percent for D4, D5, and D6 prices, respectively. A prominent recent example of volatility is the "RIN cliff" that occurred in the second half of 2023 and the first half of 2024 due to expansion of renewable diesel production beyond what was needed to fulfill the biomass-based diesel RVO (Gerveni, Hubbs, and Irwin 2023e). Since RINs can be banked from year-to-year, the current RIN price depends not only on market conditions today but also expected conditions in the future. As a result, one of the major sources of RIN price uncertainty is the level of future RVOs. RIN prices are especially sensitive to releases of proposed and final annual rulemakings by the EPA, as well as rumors about the rulemakings. When these rulemakings are perceived by the market as increasing demand for biofuels, RIN prices tend to increase and *vice versa* (Irwin 2013; Lade, Lin Lawell, and Smith 2018b; Avileis, Swanson, and Irwin 2025).

The fourth feature is that for extended periods the price of D4, D5, and D6 RINs have essentially been the same. During these periods, D4 RINs have been the marginal gallon for filling both the advanced and conventional RVOs (Irwin and Good 2017b). In other words, D4 RINs were produced in excess of the amount needed to fulfill the biomass-based diesel RVO and these excess RINs were used to "top off" the advanced and conventional RVOs. In theory, for a D4 RIN to be substituted for a D5 or D6 RIN, the price of the D4, D5, and D6 RINs must be the same.

RIN Bundle Prices and Compliance Costs

While the price of individual RIN categories is obviously important to the operation of the RFS program, obligated parties are ultimately interested in what is known as the price of a RIN "bundle." Compliance with the RFS requires obligated parties to retire a combination of D3, D4, D5, and D6 RINs for each gallon of obligated petroleum gasoline and diesel fuel.[12] Hence, it is convenient to think of the obligated party as needing to retire a bundle of RINs per gallon of obligated fuel, where the composition of the RIN bundle is determined by the percentage fractional standards (Stock 2015). The cost of this RIN bundle is the price that an obligated party must pay per gallon of petroleum fuel to comply with the annual RVOs.

A simple example will help illustrate the concept. Assume that: i) annual petroleum gasoline consumption is 150 billion gallons, ii) petroleum diesel consumption is 50 billion gallons, iii) the mandated volume of ethanol is 15 billion gallons, and iv) the mandated volume of biodiesel is 2 billion gallons. These are the only two types of biofuels in this example. Total gasoline and diesel consumption in the example is 150 + 15 + 50 +2 = 217 billion gallons. The ethanol mandate represents 7.5 percent of total petroleum gasoline and diesel consumption (15/(150+50), whereas the biodiesel mandate represents 1 percent (2/(150+5)). Each obligated party must turn into the EPA 0.075 ethanol RINs for each gallon of gasoline and diesel they produce (or import) and 0.01 biodiesel RINs for each gallon of gasoline and diesel. Obligated parties can simply multiply 0.075 and 0.01 times the number of gallons of gasoline and diesel they produce to compute their total RIN obligation. Finally, assume that the price of an ethanol RIN is $0.50 per gallon and a biodiesel RIN is $1 per gallon. The price of a RIN bundle for obligated parties can then be computed as,

$$\text{Price of RIN bundle} = 0.075 \text{ X } 0.50 + 0.01 \text{ X } 1 = \$0.0475. \tag{2}$$

In this example, obligated parties spend $0.0475 per gallon of gasoline and diesel to comply with the ethanol and biodiesel mandates. The cost of the RIN bundle is a function of both the fractional RIN obligation per gallon and the price of the two types of RINs.

Some assumptions are necessary to compute RIN bundle prices in practice because RINs used for compliance do not necessarily track precisely with fractional RVOs due to the nesting provisions of the RIN system.[13] In the previous example these were assumed to be the same. In our computation of RIN bundle prices, we follow Stock (2015) and Irwin (2018) and assume that: i) only D5 RINs are used to meet the difference between the advanced RVO and the sum of the cellulosic and biodiesel RVOs, and ii) only D6 RINs are used to meet the conventional RVO. Given these assumptions, weekly RIN prices are multiplied by the fractional RVOs for a given year. Note that the fractional RVOs only change once a year while the RIN prices change weekly. It is also important to emphasize that the results of the computations are only an estimate of the price of a RIN bundle. The true price depends on the vintage of RINs actually used for compliance by obligated parties and the types of RINs used for compliance with higher nested categories (e.g., D4 for D6 compliance).

Our estimates of the weighted-average price of a RIN bundle from January 2011 through December 2025 are presented in Figure 8. Since the conventional RVO is the largest of the RVOs, it is not surprising that the price of a RIN bundle is highly correlated with D6 RIN prices. In December 2012, the cost of a RIN bundle was around one cent per gallon. Seven months later the cost of a bundle peaked at 14 cents per gallon. This is an enormous increase in the cost of RIN obligations, and since the cost must be applied to every gallon of petroleum gasoline and diesel produced in the U.S. (or imported), it is not surprising that it was so controversial. The price did crash in the second half of 2013, reaching as low as 2 cents per gallon. From 2014 through 2017, the price of a RIN bundle bounced between roughly 5 and 10 cents per gallon. This was followed in 2018 and 2019 by a dip back under 5 cents. Starting in late 2020, the price of a RIN bundle increased very rapidly, peaking at 23 cents per gallon in July 2021. This reflected market expectations of RVOs being set by the new Biden Administration that would be more robust than what had been set in the first Trump Administration. Since that spike, the price of a RIN bundle has mainly ranged between 10 and 20 cents per gallon.

Figure 8. Weekly (Thursday) Price of RIN Bundle, January 27, 2011 - December 11, 2025

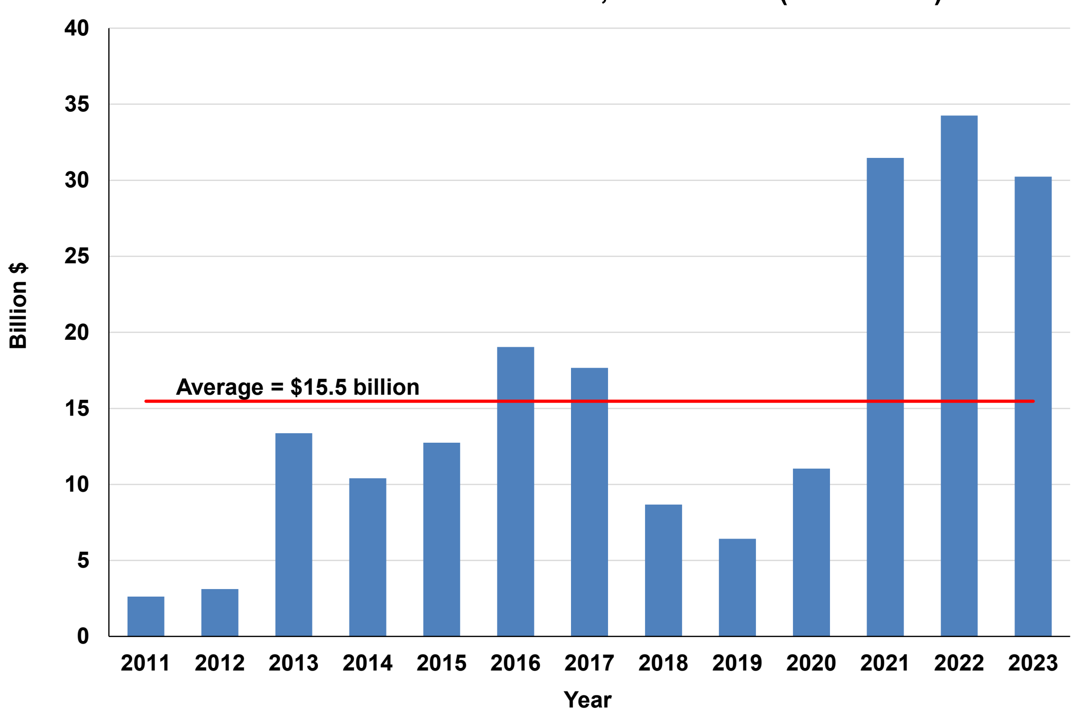
Source: OPIS and EPA

We can use the RIN bundle prices to estimate compliance costs associated with the RFS. This requires four steps. First, we collect data on obligated gasoline and diesel volumes under the RFS reported to the EPA for 2011 through 2023.[14] The last available year is 2023 since compliance for 2024 was extended and did not close until December 1, 2025. Second, we compute average annual

RIN bundle prices for 2011 through 2023 using the prices shown in Figure 8. The annual averages match the frequency of the reported obligated volumes from the EPA. Third, we multiply obligated volumes by average annual RIN bundle prices. Fourth, the estimated nominal compliance costs are converted to inflation-adjusted terms using the annual average CPI for all urban consumers. The base year for the inflation adjustment is 2023.

Figure 9 shows that real (inflation-adjusted) compliance costs estimated in this manner are large in economic terms, averaging $15.5 billion over 2011 through 2023.[15] The range in RIN compliance costs is also very large, ranging from $2.6 billion in 2011 to $34.2 billion in 2022. Since fractional obligations vary far less than RIN bundle prices, the pattern of compliance costs in Figure 9 mirrors that of bundle prices. The surge in RIN compliance costs in recent years is also notable, exceeding $30 billion in each year over 2021 through 2023. Finally, real compliance costs over 2011 through 2023 total $201.1 billion. By 2025, total RFS compliance costs could easily surpass $250 billion. It is important to emphasize that actual compliance costs will likely differ from those presented in Figure 9 because the compliance strategies followed by obligated parties may differ from those assumed here in the computation of RIN bundle prices. Even considering the possibility of such estimation errors, the point remains that RIN compliance costs over the life of the RFS is in the hundreds of billions of dollars.

Figure 9. Inflation-Adjusted Annual RIN Compliance Costs for the U.S. Renewable Fuel Standard, 2011 - 2023 (2023 = 100)



It is interesting to consider the role of the "conventional gap"—the difference between the conventional RVO and the E10 blend wall—in determining the level of RIN compliance costs. As noted earlier, the conventional gap since 2013 has been filled by D4 RINs, the next highest ordered RIN in terms of RFS compliance. When this occurs, the price of a D6 RIN is forced to equal the price of a D4 RIN because biomass-based diesel becomes the marginal gallon for filling the conventional RVO. This dramatically increases overall compliance costs for two reasons. The first is that the conventional RVO is by far the largest RVO, ranging from about 70 to 90 percent of the total RVO over 2010 through 2023. The second is that biomass-based diesel (FAME biodiesel and renewable diesel) is relatively expensive to produce compared to the petroleum diesel that it replaces, which, as shown in Figure 7, makes D4 RIN prices relatively high. The net result is that high D4 RIN prices are applied to not only the biomass-based diesel RVO when computing the RIN bundle price, but also to the conventional RVO, which has the largest weight in the calculations.

In order to illustrate the impact of the conventional gap on RIN compliance costs we re-estimate costs under a counterfactual scenario where the gap is set to zero over 2013 through 2023. First, we compute the E10 blend wall each year and set the conventional RVO to this volume. Second, we recompute the percentage conventional RVO based on the lower E10 volumes each year. Third, we set D6 RIN prices over 2013 through 2023 to $0.05 per gallon, the average price over 2008 through 2012 when the conventional gap was zero. Fourth, we re-compute RIN bundle prices based on the same data and assumptions as before, except for the lower conventional RVOs and D6 RIN prices. Fifth, the estimated nominal compliance costs are converted to inflation-adjusted terms again using the annual average CPI for all urban consumers.

The impact on RIN compliance costs under the counterfactual scenario is striking, with total inflation-adjusted costs over 2013 through 2023 falling from $182.0 to $67.0 billion, a decline of nearly two-thirds.[16] We can then allocate the difference in costs to the conventional gap, which totaled 6.3 billion gallons over 2013 through 2023. The resulting estimate is $18.30 per gallon of conventional gap volume, an extraordinarily high cost by any standard. This highlights once again the pivotal impact that the E10 blend wall has on the implementation of the RFS mandates. If gasoline and diesel usage had grown at the rate expected in 2005 and 2007 when the RFS statutes were originally passed, the conventional gap would never have existed, and RIN compliance costs would have been substantially lower.

Lastly, it is important to note that the compliance costs estimated here should not be considered total compliance costs of U.S. biofuels policy. The reason is that we do not consider the offsetting impact of the non-RFS parts of the biofuel policy stack, namely federal tax credits and California's low carbon fuel standard (LCFS) credits. For example, if the biomass-based diesel blenders tax credit had never been introduced, the theory and evidence presented in the next section shows that D4 RIN prices would have been $0.67 per gallon higher during much of the sample and our estimate of RFS compliance costs would be correspondingly higher. Similarly, consideration of the credits available through the California LCFS in the last decade would cause the estimated RFS compliance costs to be even higher (Whistance, Thompson, and Meyer 2017).

Economic Fundamentals and RIN Pricing

RIN credits play two roles within the RFS. First, RINs are the accounting mechanism whereby obligated parties demonstrate compliance. Second, because RINs can be bought and sold, their price serves to equate supply and demand for biofuels so that the RFS obligations are, in fact, met. Understanding this second role—how RIN prices are determined—is critical to understanding how the RFS works in practice.

There is no doubt that RIN prices have been volatile from the outset of the RFS program. This volatility has led some to question the rationality of RIN prices. Charges of market manipulation and speculative excess have arisen repeatedly (e.g., Reuters, 2013; Voegele 2013; Blewitt and Mider 2016). Given the large size of total compliance costs, mispricing in the RIN market could have substantial economic impacts.

As noted above, RIN prices equate the supply and demand of biofuels so that the fraction of biofuel blended and consumed equals the fraction specified by the annual RVO. In principle, RIN prices can serve to stimulate supply by subsidizing high-cost biofuels, or they can serve to stimulate demand by allowing retailers to discount fuels with a higher biofuel content that might not otherwise be sold. For fuels like biomass-based diesel that are more expensive than their petroleum counterpart and do not have a binding blend wall, RIN prices serve to stimulate supply. This requires a supply price that is high enough to elicit production at the mandated quantity. At the same time, consumers are only willing to pay the competitive market price for biofuel. The result is a wedge between the supply price and demand price of the biofuel, which, in theory, equals the market value, or price, of the RIN. For biofuels that are generally cost-competitive with their petroleum counterpart, such as ethanol in E10, RIN prices do not need to stimulate supply, but rather the RIN system stimulates consumer demand for fuel blends with higher ethanol content, such as E15 and E85.

With this background, we turn our attention to a detailed discussion of the pricing of D4 RINs. As noted earlier, biomass-based diesel has often been the marginal gallon for filling three different "buckets" in the RFS. In addition to its own mandate, biomass-based diesel has been used to fill the advanced and conventional RVOs. This means that D4 RINs have played a central role in RFS compliance for much of its history.

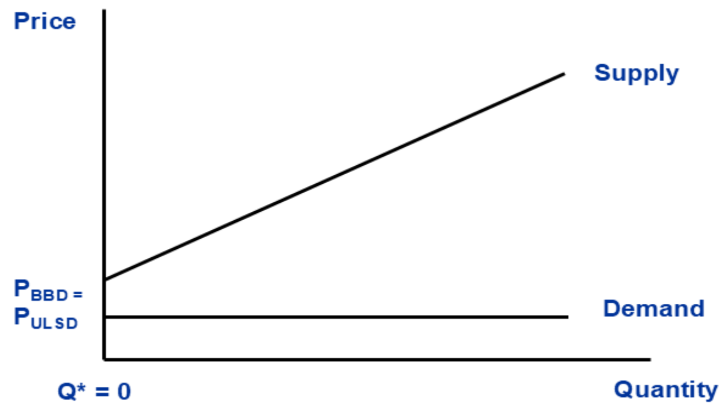
Our analysis is based on a partial equilibrium economic model used in several previous analyses of the RFS and RIN pricing (e.g., Irwin and Good 2017d; Gerveni, Hubbs and Irwin 2023b). The model shown in Panel A of Figure 10 represents the supply of biomass-based diesel producers and demand from diesel blenders at the bulk wholesale level in a competitive market. It is important to note that supply represents the total of domestic and imported production. The supply curve is upward sloping to reflect the increasing marginal cost of biomass-based diesel as the quantity supplied increases. Retail demand at the consumer level is implicitly represented by a simple percentage markup of the wholesale demand shown in Figure 10. This implies complete pass-through of wholesale price changes to the retail level.

The model in Panel A of Figure 10 also assumes that biomass-based diesel demand is perfectly elastic (horizontal) at the price of ultra-low sulfur diesel (ULSD). This reflects an assumption that biomass-based diesel and petroleum diesel are perfect substitutes (after adjusting for the lower energy value of biomass-based diesel) and that biomass-based diesel is a small enough part of the diesel market that changes in its price do not impact the overall demand for diesel fuel.[17] The implication is that the biomass-based diesel price must be the same as the energy-adjusted ULSD price in order for there to be a positive demand for biomass-based diesel. If the biomass-based diesel price is above the energy-adjusted ULSD price, then no biomass-based diesel will be demanded. Finally, the model does not consider the impact of carryover RIN stocks. While the model is obviously a simplification of the factors that influence the supply and demand of biomass-based diesel, it has proven to be a useful representation.

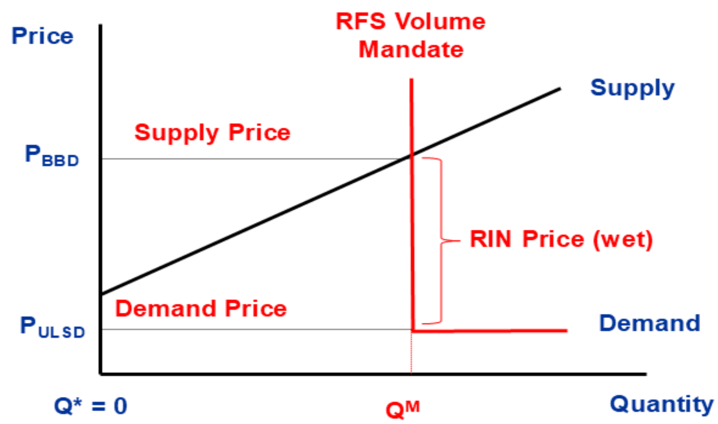
The most notable feature of the biomass-based diesel market in Panel A of Figure 1 is that the equilibrium market quantity (Q*) is zero. In other words, there is no intersection of the supply and demand curves in the positive quadrant of price and quantity. This unusual outcome reflects the fact that the production cost of biomass-based diesel is almost always substantially higher than that of ULSD. This does not mean there can never be a positive equilibrium quantity of biomass-based diesel. This could happen when diesel prices are extremely high, which would shift the demand curve up, and/or feedstock prices (e.g., soybean oil) are very low, which would shift the supply curve down.

Figure 10. The Biomass-Based Diesel Market

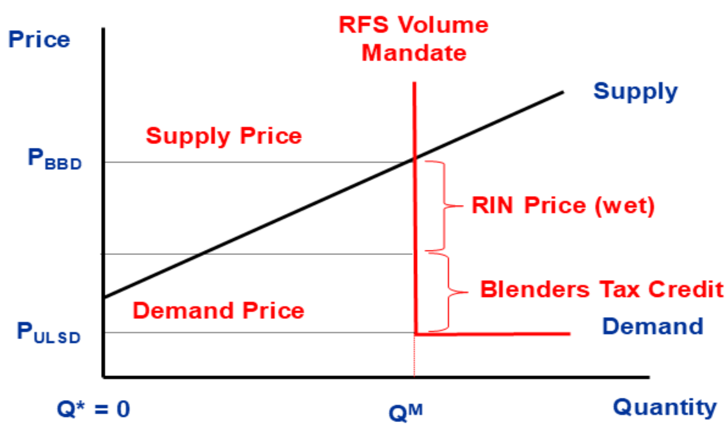
Panel A. No Policy Incentives



Panel B. Binding RFS Volume Mandate



Panel C. Binding RFS Volume Mandate and Blenders Tax Credit



The first policy scenario we consider with the model is a binding RFS volume mandate. In Panel B of Figure 10, the mandate is assumed to be binding because it requires a higher level of biomass-based diesel production than without the mandate ($Q^M > Q^* = 0$).[18] This means that the demand for biomass-based diesel becomes perfectly inelastic at the mandated quantity. The entire demand curve becomes L-shaped, with the vertical and perfectly inelastic portion equal to the volume mandate and the horizontal perfectly elastic portion above the mandated quantity equal to the energy-adjusted ULSD price. To incentivize production at the mandated quantity, biomass-based diesel producers must be paid a higher supply price than the energy-adjusted ULSD price. At the same time, consumers must be offered a lower demand price—the energy-adjusted ULSD price—to incentivize consumption at the mandated quantity. The result is a wedge between the supply and demand prices ($P_{BBD} - P_{ULSD}$) that equals the market value, or price, of a RIN. The RIN price represents the incentive needed to enforce production and consumption at the mandated quantity. In this simple model, the cost of the RIN is ultimately borne by consumers through higher diesel prices at the pump.

The second policy scenario we consider is a binding RFS volume mandate and a blenders tax credit. This scenario reflects the situation for most of the last 15 years when both an RFS mandate and the $1 per gallon blenders tax credit for biomass-based diesel have been in place in the U.S.[19] As shown in Panel C of Figure 10, the effect of the tax credit under this scenario is purely distributive because the biomass-based diesel supply price and quantity are unaffected by the blenders tax credit. The only change is that the effective demand price of blenders is increased by the amount of the tax credit, and consequently, the RIN price is reduced by the same amount. Under this scenario, consumers and taxpayers share the cost of the RFS volume mandate.

The market model in Panel C of Figure 10 shows that the D4 RIN price for a wet (physical) gallon of biomass-based diesel is the difference between the biomass-based diesel supply price at the mandated quantity and the ULSD demand price plus the tax credit. This can be expressed in mathematical terms as follows,

$$\text{Wet D4 RIN Price} = \max\left[(P_{BBD} - (0.927 * P_{ULSD} + BTC)), 0\right]. \quad (3)$$

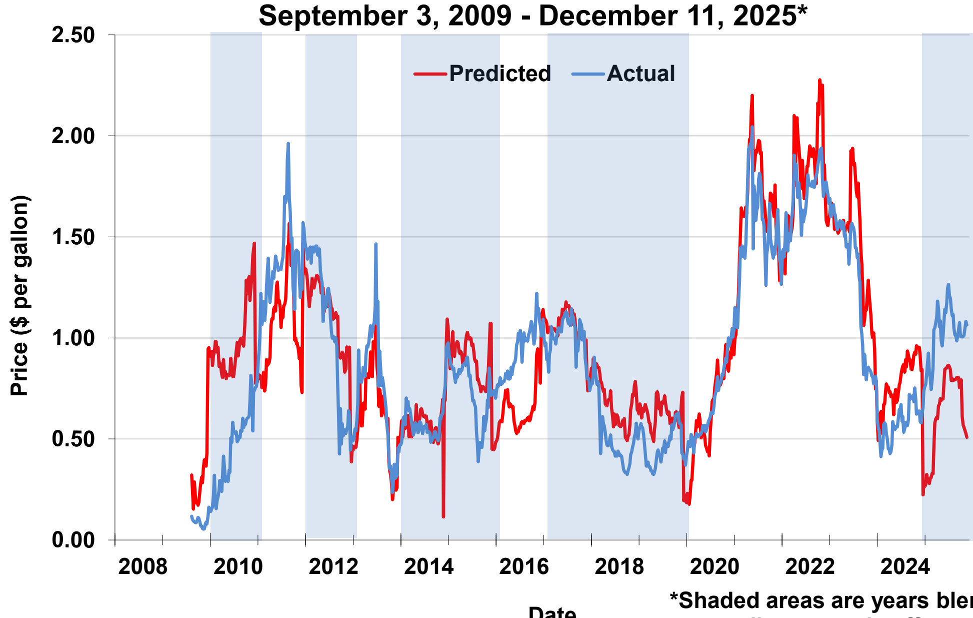
Since biomass-based diesel contains less energy than petroleum diesel, the ULSD price is multiplied by 0.927 in order to compare the two prices on an energy equivalent basis. BTC represents the blenders tax credit, which as mentioned earlier, is $1 per gallon when it is in effect. The maximum operator is necessary because RIN prices are bound from below by zero. Since the dominant biofuel used to fill the biomass-based diesel RVO during most of the history of the RFS has been FAME biodiesel, the wet (physical) D4 RIN price can be converted into RIN gallons by dividing by 1.5, the RIN conversion factor for biodiesel,

$$\text{D4 RIN Price} = \max\left[(P_{BBD} - (0.927 * P_{ULSD)} + 1)), 0\right]/1.5. \tag{4}$$

Irwin, McCormack, and Stock (2020) consider this to be the "fundamental" in the D4 RIN market.[20]

We use the theoretical model represented by equation (4) to predict actual D4 RIN prices over January 2011 through December 2025.[21] FAME biodiesel prices at the U.S. Gulf are used as a proxy for biomass-based diesel prices because, as noted above, FAME has been the dominant biofuel used to comply with the biomass-based diesel RVO for most of the history of the RFS, and FAME prices are available since the start of the RFS. Bulk wholesale ULSD prices are also measured at the Gulf. One complicating factor is that there are several years when the blenders tax credit expired and was not retroactively reinstated until near the end of the year or later. We set the blenders tax credit to zero in these years. The blue line in Figure 11 is the actual D4 price and the red line is the predicted price. The predictions from this simple model track actual D4 market prices reasonably well. The R^2 from a regression of the predictions on actual D4 prices is 74 percent. Our point is not that this is the best possible D4 RIN pricing model, but rather it demonstrates that D4 RIN prices follow a rational pricing process that can be easily understood. This also implies that D4, D5, and D6 RIN prices follow the same pricing fundamental as long as biomass-based diesel is the marginal gallon for complying with the advanced and conventional RVOs.

Figure 11. Weekly (Thursday) Predicted D4 RIN Price Based on Biodiesel Fundamental and Actual D4 RIN Price, September 3, 2009 - December 11, 2025*



Source: OPIS

*Shaded areas are years blenders tax credit was not in effect

There are several periods where the predicted D4 price in Figure 11 is above the actual price. As the shading indicates, this corresponds in most cases to years when the blenders tax credit expired and was not retroactively reinstated until later. Traders in the RIN market are aware of the potential for the tax credit to be reinstated retroactively and take this into account by pricing into D4 RINs some probability that the tax credit will be restored. The simple pricing model we use here assumes the probability is zero during these periods, which results in a prediction that tends to be higher than the market price. Irwin, McCormack, and Stock (2020) develop a sophisticated D4 pricing model that incorporates uncertainty about the status of the blenders tax credit.

Careful inspection of Figure 11 also reveals that predicted D4 prices tended to be too high relative to actual prices from 2022-2024 and then unusually low in 2025. The upward bias in predictions over 2022-2024 likely reflects the omission of California LCFS credits from the pricing model during the renewable diesel boom years. The downward bias in 2025 appears to have more complicated roots. For example, FAME biodiesel prices dropped by about $1 per gallon shortly after January 1st but D4 RIN prices did not change appreciably. A possible explanation is uncertainty over implementation of the new 45Z tax credit, which was passed as part of the Inflation Reduction Act of 2022 under the Biden Administration. The 45Z credit varies based on carbon intensity scores (Buffie 2023), whereas the old blenders tax credit (which 45Z replaces) was a flat $1 per gallon of biomass-based diesel. The new credit was scheduled to go into effect on January 1, 2025 but final rules from the U.S. Treasury Department on 45Z had not been released at that point, and there was considerable uncertainty whether the new Trump Administration would try to repeal, modify, or replace the new credit. The combination of the expiration of the blenders tax credit, which led to FAME prices dropping by a dollar a gallon, and uncertainty regarding the future of the 45Z credit, caused a substantial amount of FAME biodiesel production to go offline (Barnett 2025). At the same time, renewable diesel prices and production were not as severely impacted. This may signal that D4 prices now track renewable diesel prices more closely than FAME biodiesel prices.[22]

The same principles can be applied to D6 RIN prices. Since the bulk of the conventional RVO is filled by ethanol, we first consider ethanol prices in relation to petroleum gasoline prices. Specifically, we define the D6 RIN price fundamental as follows,

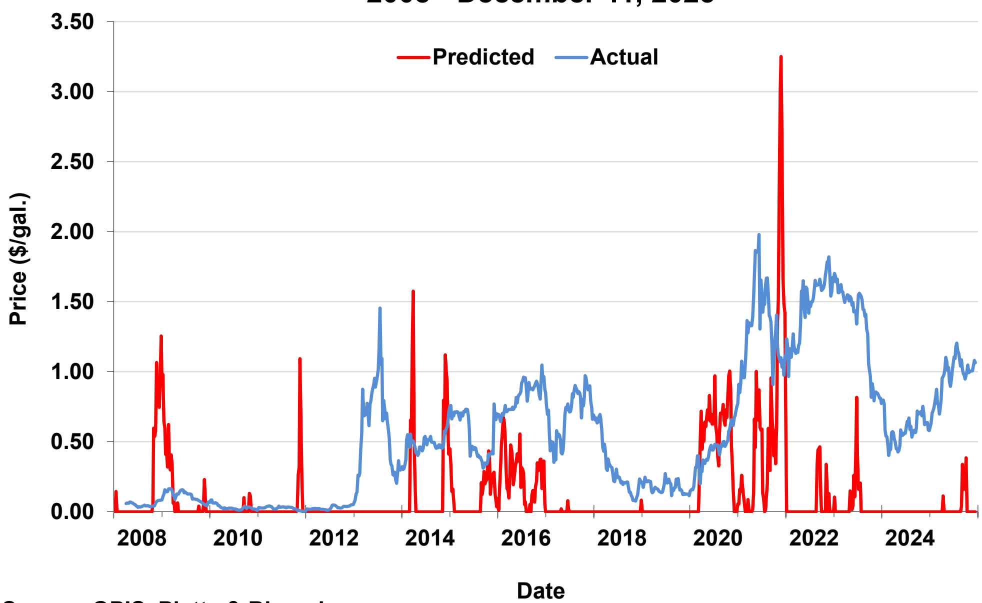
$$\text{D6 RIN Price} = \max\left[(P_E - (0.667{*}P_{CBOB} + \text{VEETC}) - (P_{AR} - P_E), 0\right], \tag{5}$$

where P_E is the price of ethanol, P_{CBOB} is the price of CBOB gasoline blendstock, VEETC (volumetric ethanol excise tax credit) is the blenders tax credit for ethanol, and P_{AR} is the price of aromatics. Since ethanol has approximately two-thirds of the energy value as petroleum gasoline, the CBOB gasoline price is multiplied by 0.667 in order to compare ethanol and CBOB prices on an energy equivalent basis. Between 2008 and 2011, VEETC was either $0.45 or $0.51 per gallon of ethanol. The credit expired permanently at the end of 2011. We assume full passthrough of VEETC from gasoline blenders to ethanol producers in years when the credit is in place.[23] Aromatic compounds have octane ratings similar to ethanol and have been routinely used as octane enhancers in gasoline blends. Irwin and Good (2017a) provide evidence that ethanol and aromatics have functioned as octane substitutes in gasoline blends. All prices are measured at the spot wholesale level for the U.S. Gulf.

The ethanol fundamental represented by equation (5) can be divided into two components. The first is the term (P_E – (0.667*P_{CBOB} + VEETC), which represents the "energy penalty" for blending ethanol with gasoline blendstock after adjusting for the blenders tax credit. The second is the term (P_{AR} - P_E), which represents the "octane premium." Irwin and Good (2017a) and Irwin (2019) show that the energy penalty tends to be positive because the price of ethanol generally exceeds the energy-adjusted price of CBOB. The octane premium also tends to be positive since the aromatic price is generally higher than the ethanol price. The difference between these terms can therefore be positive or negative, depending on the relative magnitude of the energy penalty versus the octane premium. If the difference is positive, the predicted D6 RIN price will be positive. If the difference is negative, the predicted D6 RIN price will be zero.[24]

Figure 12 compares the predicted D6 RIN price based on equation (5) and actual D6 RIN prices over April 2008 through December 2025. There are only a few periods where the predictions and actual D6 prices track one another, which gives the overall impression that the two are not very closely related. This is confirmed by the regression of predicted on actual D6 prices, which only has an R^2 of 0.02. This could be seen as an indictment of pricing efficiency in the D6 RIN market. However, this ignores the key role that the E10 blend wall plays in determining D6 RIN prices. If the conventional RVO is below the E10 blend wall, then the D6 price should follow the ethanol fundamental predicted by equation (5). However, if the conventional RVO is set above the E10 blend wall, then biomass-based diesel becomes the marginal gallon for filling the conventional RVO and D6 RIN prices should be determined by the biodiesel fundamental predicted by equation (4). In other words, we should expect D6 RIN prices to track the ethanol fundamental only when the conventional RVO is non-binding. We have previously discussed that the conventional RVO first exceeded the E10 blend wall in 2013 and generally continued to do so through 2025.[25] The implication is that the ethanol fundamental should only be valid previous to 2013 when the E10 blend wall clearly exceeded the conventional RVO. In fact, predicted D6 RIN prices track observed prices reasonably well over 2008-2012. The most frequently observed prediction over this period is zero, corresponding to the very low actual RIN prices. The average predicted D6 price is $0.07 per gallon, only slightly more than the average observed price of $0.05. In addition, the spike in predicted D6 prices in late 2008 and 2009 corresponds to the increase in actual D6 prices that accompanied the onset of the Great Recession. Finally, it is interesting to observe that 74 percent of predicted D6 RIN prices over the entire sample equal zero, which indicates that the octane premium is larger than the energy penalty most of the time.

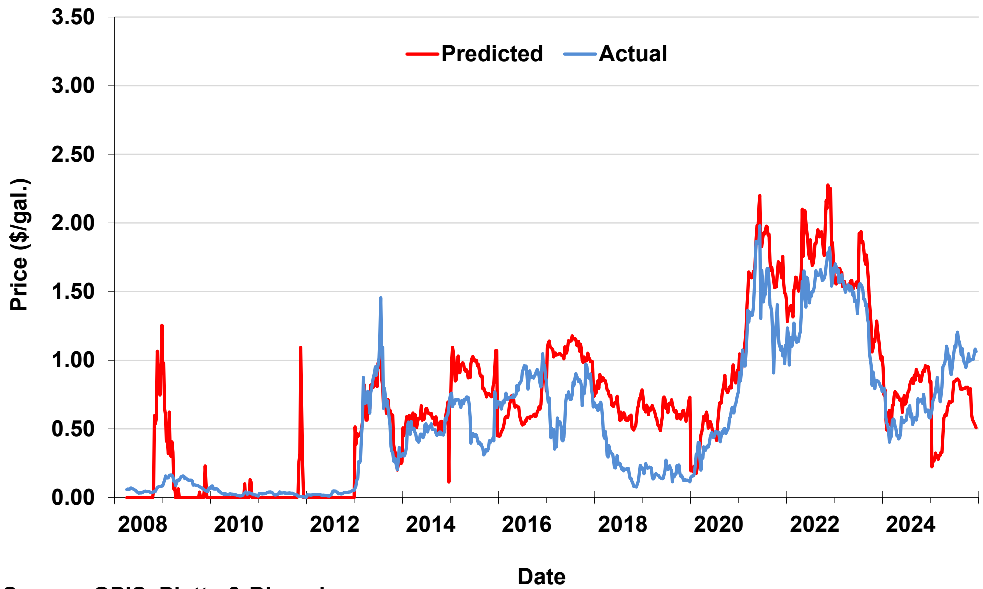
Figure 12. Weekly (Thursday) Predicted D6 RIN Price Based on Ethanol Fundamental and Actual D6 RIN Price, April 3, 2008 - December 11, 2025



Source: OPIS, Platts & Bloomberg

We provide an alternative analysis of D6 RIN prices in Figure 13 where the fundamental changes depending on whether the conventional RVO is above or below the E10 blend wall. Specifically, D6 prices are predicted using the ethanol fundamental from equation (5) over 2008-2012 and the biodiesel fundamental from equation (4) over 2013-2025. One can see that the predicted and actual D6 series now track one another reasonably closely for the entire period. The R^2 jumps to 0.78 using the combined model, providing strong evidence that D6 RIN prices can be explained by economic fundamentals, so long as the fundamentals are correctly specified. This is exemplified by the close fit of predicted and actual D6 prices in the huge spike that occurred in 2013.

Figure 13. Weekly (Thursday) Predicted D6 RIN Price Based on Ethanol/Biodiesel Fundamental and Actual D6 RIN Price, April 3, 2008 - December 11, 2025

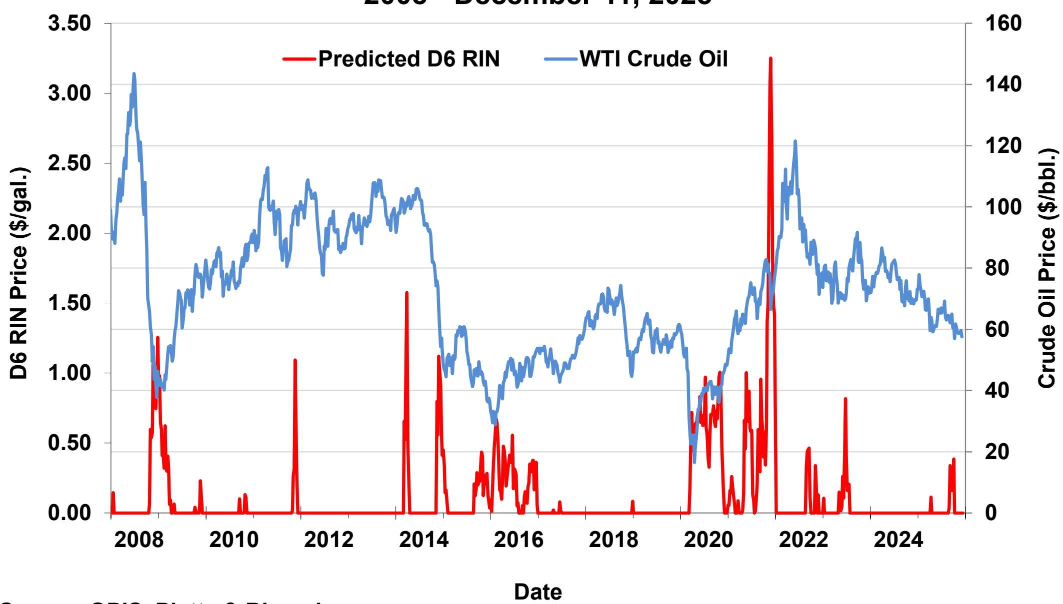


Source: OPIS, Platts & Bloomberg

The analysis of D6 RIN prices highlights the crucial role that octane value plays in the ethanol market. We can provide further evidence of this market value by: i) only considering the 2008-2012 period, when the conventional RVO is non-binding, and hence, there is no uncertainty whether the ethanol fundamental provided by equation (5) is applicable; and ii) omitting the octane premium from the ethanol fundamental. The predicted D6 RIN price for 2008-2012 averages $0.34 per gallon without the octane premium, nearly seven times higher than the actual average RIN price for the period of $0.05. Limiting the sample to 2012, when the VEETC blenders tax credit is not in place, removes any uncertainty regarding passthrough of the credit from blenders to ethanol producers. The predicted D6 RIN price for 2012 averages $0.51 per gallon without the octane premium, more than 15 times higher than the actual average RIN price of $0.03. [26] These differences are too large to be explained by anything other than the octane value of ethanol.

It is also interesting to consider the role of crude oil prices in D6 RIN pricing. The price of crude oil is the main driver of both the CBOB and aromatics price in the ethanol fundamental provided by equation (5). If the price of crude oil decreases, the price of CBOB and aromatics will tend to decrease, which, all else constant, will cause the energy penalty to increase and the octane premium to decrease. If the price changes are large enough, the energy penalty can become larger than the octane premium, which implies a positive D6 RIN price. Figure 14 plots the predicted D6 RIN price based on the ethanol fundamental given by equation (5) and the WTI crude oil price over April 2008 through December 2025. Note that the nearby futures price for WTI crude oil is used to measure crude prices. There is clearly a relationship, albeit imperfect, between low crude oil prices and predicted D6 RIN prices. Each time that the crude oil price approached roughly $40 per barrel, the predicted D6 RIN price spiked upward. This happened during the Great Recession of late 2008 and 2009, the sharp decline in crude prices in 2015 and 2016, and during the early phase of the COVID pandemic. This indicates that the conventional RVO was binding during the Great Recession and would have been binding during the latter two episodes if biomass-based diesel had not been the marginal gallon for filling the conventional RVO. The aggregate ethanol blend rate for gasoline in the U.S. fell sharply during the Great Recession and the early months of the COVID pandemic and then recovered quickly. There was no discernable decline in the blend rate during 2015 or 2016. This provides mixed evidence whether blending disincentives signaled by the D6 ethanol fundamental are reflected in the physical market demand for ethanol. Nonetheless, this comparison highlights the important result that while ethanol is generally a competitive blend component in gasoline, this is not always the case. In particular, the conventional RVO provides a safety net for ethanol demand when crude oil prices are very low.[27]

Figure 14. Weekly (Thursday) Predicted D6 RIN Price Based on Ethanol Fundamental and WTI Crude Oil Price, April 3, 2008 - December 11, 2025



Source: OPIS, Platts & Bloomberg

To summarize, the results presented in this section indicate RIN price volatility has a rational foundation, consistent with the findings reported by Whistance and Thompson (2014) and Irwin, McCormack, and Stock (2020). While there is always the possibility that market manipulation and speculation could temporarily move RIN prices away from fundamental values, this appears to be the exception rather than the rule. RIN price volatility is related to the structure of the RFS, political uncertainty about the implementation of the mandates, and supply and demand uncertainty in U.S. biofuel and petroleum markets (Lade, Lin Lawell, and Smith 2018b). At the same time, there is surprisingly little academic research on this important question and limited information is available on the operation of the secondary RIN market.

Passthrough of RIN Prices

By any reasonable standard, the estimated RIN compliance costs under the RFS are large. Refiners and importers of petroleum gasoline and diesel initially absorb the cost of RIN credits because they are the obligated parties under the RFS. However, this does not necessarily mean that refiners and importers ultimately bear the costs. This raises the important question of RIN price passthrough, one of the most controversial aspects of the RFS.

It is helpful to begin with a simple example to demonstrate how RIN price passthrough is designed to work in the fuel supply chain. Assume there are only four participants in the supply chain: biodiesel producers, diesel refiners, blenders, and truckers. Blenders purchase biodiesel and diesel, blend the two, and sell the blends to truckers. Biodiesel producers generate a RIN when biodiesel is produced, which remains attached when the biodiesel is sold to blenders. The blenders can detach the RIN once the biodiesel is blended with petroleum diesel and sold to truckers. Once the RIN is detached, blenders can then sell the detached RIN to refiners, who retire the RIN with the EPA since they are the obligated party under RFS rules. Assuming perfect competition in this circular system, refiners raise the price of diesel sold to blenders by the cost of the RIN obligation per gallon to recoup the RIN expense. In parallel, blenders lower the price of biodiesel in the diesel sold to truckers to reflect the revenue earned by selling the RIN. The impact on truckers is the net of these two effects. This is the essence of the tax and subsidize incentive mechanism that is at the heart of the operation of the RFS.[28]

The effect of the two RIN passthrough effects on retail gasoline and diesel prices under perfect competition can be stated formally on a per gallon basis as:

$$PT = (1-\propto) \cdot RB - \propto \cdot D \cdot E \quad (6)$$

where PT is the net passthrough impact, $\propto$ is the proportion of biofuel in the retail fuel blend, RB is the price of a RIN bundle, D is the price of the relevant RIN for the biofuel, and E is the RIN equivalence value of the biofuel (e.g., E = 1 for ethanol and E = 1.5 for FAME biodiesel). The term $(1-\propto)\cdot RB$ is the RIN tax and the term $-\propto\cdot D\cdot E$ is the RIN subsidy.[29] For a given set of RIN prices, the higher the proportion of biofuel in the retail fuel blend ($\propto$), the higher the RIN subsidy is in relation to the RIN tax and the greater the incentive provided for the biofuel. For example, assume the D6 RIN price for ethanol is $0.50 per gallon and the RIN bundle price is $0.05 per gallon. If the fuel is 100 percent petroleum gasoline, or E0, the RIN tax is $0.05 per gallon and the RIN subsidy is zero because the blend does not contain any ethanol. At the other extreme, if the fuel is 100 percent ethanol, or E100, the RIN tax is zero and the RIN subsidy is $0.50 per gallon. The net passthrough impact on E10 is predicted to be 0.9 X $0.05 – 0.1 X $0.50 = -$0.005 per gallon. The RIN tax on the gasoline component and the RIN subsidy on the ethanol component nearly offset one another, so there is a small negative impact on the retail price of E10 at the pump. In other words, consumers save one-half cent per gallon at the pump with full passthrough of the RIN tax and subsidy.

Figure 15 shows predicted net retail price impacts of RIN passthrough on E10 gasoline blends over January 2011 through December 2025. We use actual weekly RIN prices (Figure 7), estimated weekly RIN bundle prices (Figure 8), and equation (6) to compute the predicted retail price impacts. The figure shows net RIN passthrough as well as separate RIN tax and RIN subsidy components. The predicted net passthrough impact on E10 retail prices is quite small, ranging from about -2 to +3 cents per gallon. On average, the E10 passthrough impact is only +1 cent. The average passthrough impact increases to 2 cents per gallon after 2021, coinciding with higher RIN prices during the renewable diesel boom.[30] The small net passthrough impacts for E10 mask large variations in the magnitude of the RIN tax and subsidy over time. During periods when D6 RIN prices are low, such as 2011-2012 and 2018-2019, all three components are small. In contrast, during periods when D6 RIN prices are high, like 2021-2023, the magnitude of the RIN tax and subsidy increase to as much as $0.20 per gallon. This is another manifestation of periods when D4 biomass-based diesel RINs serve as the marginal gallon for filling the conventional RVO.

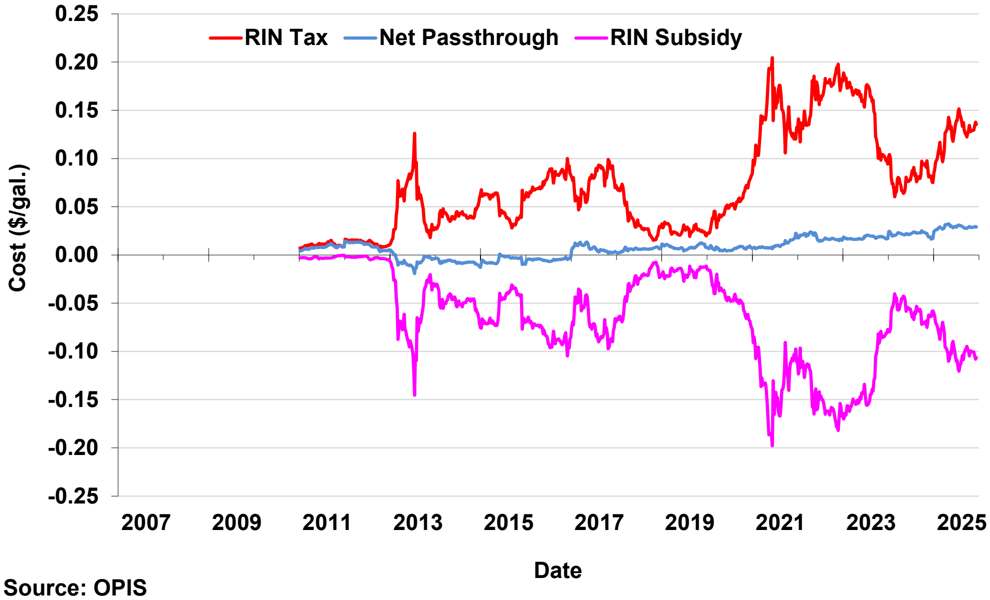
Figure 16 shows predicted net retail price impacts of RIN passthrough for B5 diesel, which is a blend of 5 percent FAME biodiesel and 95 percent petroleum diesel. This is a common biodiesel blend. The figure shows that predicted net passthrough impacts for B5 tend to be about the same as E10, on average. Specifically, the predicted B5 passthrough impact averages +1.0 cents. While average net passthrough is similar for B5 and E10, net passthrough for B5 is much more volatile.

For example, 2011-2012 was a period with low D6 RIN prices, which resulted in low RIN bindle prices and low RIN tax levels for B5. However, this was also a period with high D4 biomass-based diesel RIN prices, which led to relatively large subsidies for B5. The end result was a net passthrough subsidy to diesel consumers that averaged +8 cents per gallon for this two-year period. When D4 and D6 RIN prices are similar, which is the case when biomass-based diesel is the marginal gallon for complying with the conventional RVO, net passthrough will be larger for B5 compared to E10 because the biofuel content of B5 is lower than E10. This is precisely what happened during the renewable diesel boom years, when the net passthrough for B5 averaged +5 cents per gallon and the net for E10 averaged only +2 cents per gallon.

The natural question to ask at this point is how closely RIN price passthrough in the fuel supply chain matches the predictions of theory. This boils down to answering three specific questions: i) Do refiners raise the price of gasoline and diesel in wholesale markets enough to fully offset the cost of RIN obligations? ii) Are the wholesale price increases fully passed through to retail fuel prices? and iii) Do blenders lower the price of biofuels at the retail level to fully reflect the revenue earned from the sale of RINs? With respect to the first question, smaller merchant refiners have repeatedly voiced concerns about their ability to fully pass through RIN costs at the wholesale level, arguing that this puts them at a competitive disadvantage in fuel markets and justifies exemptions from compliance (e.g., Brown 2020). It is possible that some segments of the fuel supply chain depart from competitive conditions, perhaps because of geographic isolation or special local features of fuel markets. On top of this, the fuel supply chain is complex, and the RIN market is complicated. [31] Thus, the extent to which RIN prices are passed through the fuel supply chain ultimately is an empirical question.

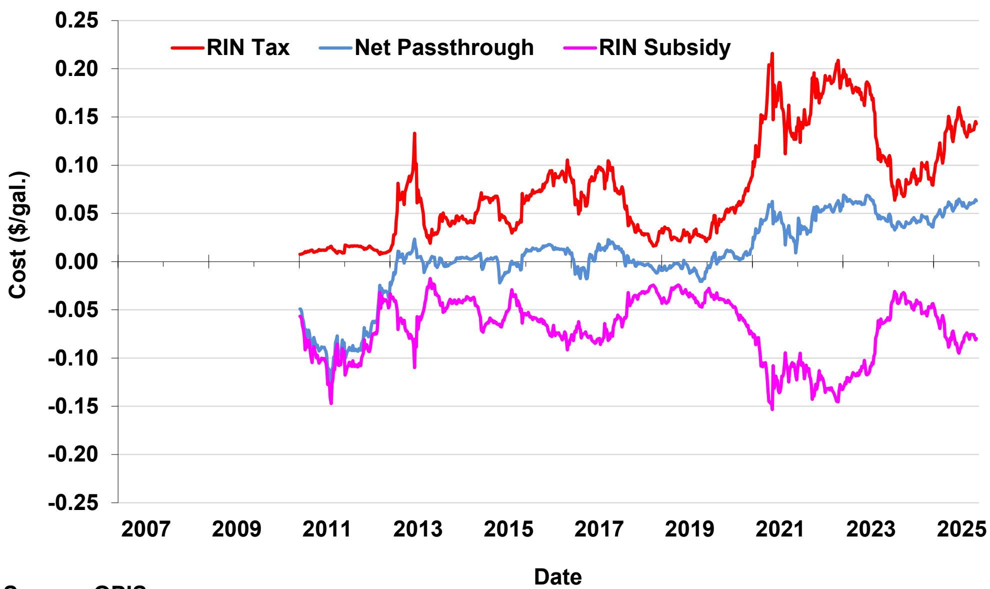
The basic strategy used in the literature to examine RIN price passthrough at the bulk wholesale stage is to compare prices for pairs of petroleum fuels, where the two fuels are as similar as possible in composition and location, but one is obligated under the RFS and the other is not (Burkholder 2015). This isolates the RIN price impact by holding constant other factors that drive petroleum gasoline and diesel prices. If passthrough is complete, the difference in the prices of the two fuels should vary one-for-one with the cost of the RIN obligation.

Figure 15. Predicted Passthrough of RIN Prices to Weekly (Thursday) Retail Price of E10 Gasoline Blend, January 6, 2011 - December 11, 2025



Source: OPIS

Figure 16. Predicted Passthrough of RIN Prices to Weekly (Thursday) Retail Price of B5 Diesel Blend, January 6, 2011 - December 11, 2025



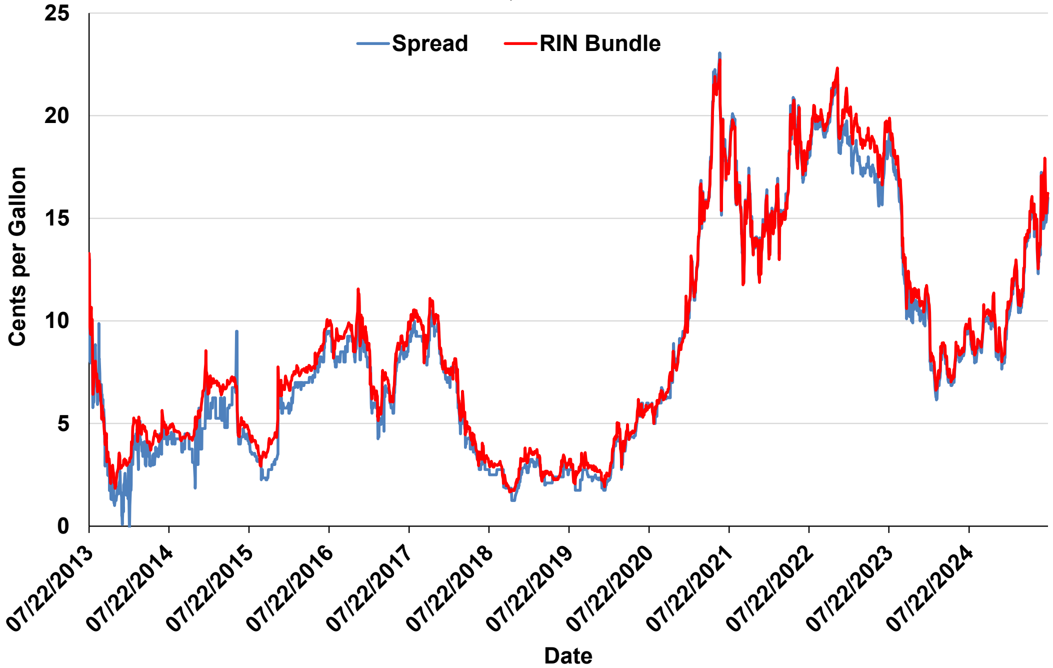
Source: OPIS

Here, we compare daily spot prices of ULSD and ultra-low sulfur heating oil (ULSHO) at the U.S. Gulf. These two fuels have virtually the same chemical compositions, with the only difference being the addition of a few fuel additives to ULSD and red dye to ULSHO. The fuels are traded in large bulk volumes, so price quotations should be an accurate reflection of daily market transactions for one of the biggest fuel markets in the world. Since the prices are quoted for the same location, the spread between the prices should hold constant supply and demand factors that jointly move these two fuel prices, such as crude oil prices, interest rates, and exchange rates. Crucially, refiners and importers that sell ULSD in this market incur an obligation under the RFS, while sellers of ULSHO do not. If the bulk wholesale market is competitive, refiners should be able to fully pass through RIN costs to buyers in this market. More specifically, the spread between the two fuel prices should equal the price of a RIN bundle, which, as shown earlier, is a measure of the cost of RIN obligations per gallon of obligated petroleum gasoline and diesel.

Figure 17 compares the daily spread between spot ULSD and ULSHO prices at the Gulf and the price of a RIN bundle over July 2013 through July 2025. The sample begins in July 2013 because this is the first date for which we were able to obtain the ULSD and ULSHO prices. The RIN bundle prices are the same as those presented earlier in Figure 8. While there are some periods where the two series deviate, the spread between the ULSD and ULSHO prices tends to closely track the price of the RIN bundle. More specifically, the R^2 for a regression of the RIN bundle on the spread is 0.99 and the estimated intercept and slope are quite close to zero and one, respectively, consistent with complete passthrough at the daily horizon. It is also interesting to observe how closely the spread tracks the RIN bundle price after 2014. It may be that market participants took some time to adjust to the spike in D6 RIN prices, and consequently the RIN bundle price, which occurred in 2013.

The results in Figure 17 are consistent with previous studies showing that RIN bundle costs are fully passed through by obligated parties at the bulk wholesale level in the form of higher gasoline and diesel prices (Burkholder 2015; Knittel, Meiselman, and Stock 2017; Burkhardt 2019; Mazzone, Smith, and Witcover 2022). There is a large literature that indicates the bulk wholesale price of gasoline and diesel is passed through with a lag to the retail level (e.g., Borenstein, Cameron, and Gilbert 1997; Bachmeier and Griffin 2003; Lewis 2011). If the passthrough of bulk wholesale gasoline and diesel prices is complete, then the passthrough of the cost of the RIN bundle from obligated parties at the wholesale level to the consumer should eventually also be complete. Of course, it is possible this competitive outcome may not hold for smaller market participants at the bulk wholesale level or for geographically isolated markets. Nonetheless, the empirical literature suggests that RIN price passthrough on the petroleum side of the fuel supply chain largely follows the predictions of theory.

Figure 17. Spread between Daily ULSD and ULSHO Prices at the U.S. Gulf and Daily RIN Bundle Price, July 22, 2013 - July 16, 2025



The third passthrough question is the extent to which the value created by detaching a RIN from a biofuel by blenders is fully passed through to consumers in the form of a reduced price for the blended fuel based on its biofuel content. Answering this question is complicated because of data requirements and the myriad arrangements used to sell fuel at the retail level. For example, longer-term contracts are often used with prices and terms that are not observable.

Several studies examine this third passthrough question. Pouliot, Smith, and Stock (2017) examine daily data on terminal ("rack") gasoline prices over 2012 through 2016 and estimate a 63 percent RIN price passthrough for branded E10 and 92 percent passthrough for unbranded E10 in 20 large cities. The authors conclude that fuel suppliers at some terminals exercise market power and retain some of the RIN value, and consequently, the RIN subsidy value is not fully passed through to consumers. Li and Stock (2019) examine the passthrough of D6 RIN prices to retail prices using monthly data at the gas-station level on E10 retail prices in Minnesota. They estimate that the rack price of E10 is passed through to the retail price of E10 with a passthrough coefficient close to one, that there is near-complete retail passthrough in the Minneapolis-St. Paul

E85 market, but outside the Twin Cities less than half the net RIN subsidy is reflected in pump prices. Lade and Bushnell (2019) examine RIN price passthrough to pump prices for higher ethanol blends using station-level data in the Midwest. They find that, on average, half to three-quarters of the E85 subsidy is passed through to consumers. However, passthrough takes 6–8 weeks and station-level pass-through rates exhibit substantial heterogeneity, with retailer market structure influencing both the speed and level of passthrough. Mazzone, Smith, and Witcover (2022) investigate RIN price passthrough for FAME biodiesel over 2015 through 2021 and find that the RIN subsidy is fully passed through in the Midwest, but is incomplete in the East Coast, West Coast, and Gulf Coast. Passthrough rates in California and Oregon are the lowest in the nation at 58 and 62 percent, respectively.

In sum, the available evidence is mixed regarding passthrough of the RIN subsidy to consumers. In some cases, passthrough is complete while in others it is less than complete, which raises concerns about the efficiency of the RIN mechanism for incentivizing biofuel consumption consistent with the design of the program. This conclusion should be tempered, however, by noting that the value of the net RIN subsidy obligation for E10 and B5 is small (see Figures 14 and 15, respectively) because the biofuel component of these fuel blends is small. Consider the net passthrough impact on E10 in the example earlier in this section, which was predicted to be 0.9 X \$0.05 – 0.1 X \$0.50 = -\$0.005 per gallon with full passthrough of the RIN subsidy. If the subsidy passthrough is assumed to be only 70 percent, the net passthrough is 0.9 X \$0.05 – 0.7 X 0.1 X \$0.50 = +\$0.01 per gallon, so there is a small positive net impact on the retail price of E10 at the pump that costs consumers one and one-half cents per gallon compared to full passthrough. The econometric evidence in the literature suggests such discrepancies exist, but their impacts are minimal for the vast majority of gasoline and diesel blends sold in the U.S. Only a small volume of fuels, in particular E15, E85, and high renewable diesel blends, generate large enough RIN subsidies that the net passthrough impact could be problematic. Li and Stock (2019) find that E15 and E85 markets are thin and typically have little competition. We are not aware of any passthrough studies for higher blends of renewable diesel, a topic on which further academic research is warranted.

Conclusions

This article provides a comprehensive review of the U.S. Renewable Fuel Standard (RFS), synthesizing nearly two decades of program evolution, market outcomes, and economic analysis. The RFS, established in 2005 and expanded in 2007, represents one of the most ambitious biofuel policies ever implemented, mandating the blending of minimum volumes of renewable fuels into the nation's transportation fuel supply with three core objectives: enhancing energy security, promoting advanced low-greenhouse gas fuels, and supporting rural economies (Stock 2015).

The RFS operates through a nested mandate structure based on lifecycle greenhouse gas emission reductions, with four categories of renewable fuels: cellulosic biofuel, biomass-based diesel, advanced biofuel, and conventional biofuel. The volume mandates are formally known as renewable volume obligations (RVOs). The 2007 legislation originally envisioned growth from 9 billion gallons in 2008 to 36 billion gallons by 2022, with increasing reliance on cellulosic ethanol. However, actual implementation diverged substantially from statutory targets. Total RVOs reached only about 20 billion gallons in 2022, just over half the intended level, due primarily to the failure of cellulosic biofuel production to achieve commercial scale. The EPA has used various waiver authorities to reduce RVOs below statutory levels, particularly for cellulosic biofuels.

Compliance with RFS mandates is enforced through Renewable Identification Numbers (RINs), tradeable credits generated when qualifying biofuels are produced or imported. We document substantial RIN generation growth, particularly for biomass-based diesel RINs, which increased from 4.1 billion gallons in 2019 to 9.2 billion by 2024. This growth reflects the boom in renewable diesel production that was driven by RFS mandates, federal tax credits, and state low-carbon fuel programs.

Two critical constraints have shaped RFS implementation. The "E10 blend wall"—the practical limit of 10 percent ethanol content in gasoline—became binding when the conventional RVO began exceeding this threshold in 2013, triggering a dramatic RIN price spike. This also resulted in biomass-based diesel RINs serving as the "marginal gallon" for filling multiple mandate categories due to the nested structure of the RFS. The COVID-19 pandemic provided another major disruption, causing the EPA to reduce 2020 and 2021 RVOs due to collapsed fuel demand.

RIN prices have exhibited extraordinary volatility, with prices for conventional RINs, the largest category, ranging from near zero to over $1.50 per gallon. Despite this volatility, RIN pricing generally follows rational economic fundamentals rather than being driven by speculative excess or market manipulation. We demonstrate strong correspondence between predicted and actual RIN prices, so long as the fundamentals are correctly specified. RIN price volatility is related to the structure of the RFS, political uncertainty about the implementation of the mandates, and supply and demand uncertainty in U.S. biofuel and petroleum markets (Lade, Lin Lawell, and Smith 2018b).

Total inflation-adjusted RIN compliance costs are estimated at $201.1 billion over 2011 through 2023, averaging $15.5 billion annually and ranging from $2.6 billion to $34.2 billion depending on RIN price levels. The economic impact of these costs depends on the passthrough of RIN prices through the fuel supply chain. Consistent with other studies, we find complete passthrough of the RIN price "tax" at the bulk wholesale level, with the spread between ultra-low sulfur diesel and heating oil prices tracking RIN bundle costs with near-perfect correlation. The available evidence is mixed regarding passthrough of the RIN price "subsidy" to retail fuel consumers. In some cases, passthrough is complete while in others it is less than complete. Any concerns that arise from this finding should be tempered, however, by noting that the value of the net RIN subsidy obligation for the most commonly sold gasoline and diesel blends in the U.S. is small.

The RFS experience demonstrates both the potential and limitations of mandate-based renewable energy policies. While successfully stimulating biofuel market development, the program has generated significant compliance costs, market volatility, and implementation challenges (Babcock 2020). The substantial divergence between original statutory ambitions and practical outcomes highlights the risks of technology-forcing policies that outpace market realities, particularly regarding cellulosic biofuels (Lade and Smith 2025). The lessons learned from RFS implementation provide valuable guidance for designing more effective, efficient, and equitable renewable energy policies. These lessons may be instructive across a wide array of green energy initiatives, with sustainable aviation fuel (SAF) an especially prominent example (Wu et al. 2025). The challenge for economists, policymakers, and market participants is to internalize these lessons while remaining adaptive to the rapidly evolving landscape of energy technologies and climate imperatives.

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Endnotes

[1] A detailed discussion of the process and criteria used to determine whether a small refinery has experienced economic hardship can be found in this August 2025 EPA rulemaking document: https://www.govinfo.gov/content/pkg/FR-2025-08-27/pdf/2025-16390.pdf.

[2] Biogas captured from landfills qualifies as a cellulosic biofuel due to the breakdown of paper lignin in landfill waste.

[3] See *Environmental Protection Agency v. Calumet Shreveport Refining, LLC* available here: https://www.supremecourt.gov/opinions/24pdf/23-1229_cone.pdf.

[4] See the EPA rulemaking available here: https://www.govinfo.gov/content/pkg/FR-2023-07-12/pdf/2023-13462.pdf.

[5] This example assumes that a given biofuel can only be used to fill its own RVO. The nesting structure of the mandates means that some biofuels can be used to fulfill multiple RVOs.

[6] See Table 1 in McPhail, Westcott, and Lutman (2011) for detailed information on RIN code definitions.

[7] In the preliminary rulemaking for 2026 and 2027 RVOs released in June 2025, the EPA proposed that imported biofuels and domestic biofuels made from imported feedstocks receive half RIN credits and that renewable diesel be limited to 1.6 RIN gallons. If finalized, this would represent the first substantial changes to the RIN equivalence system since it was first set up. Details can be found in the preliminary rulemaking available here: https://www.govinfo.gov/content/pkg/FR-2025-06-17/pdf/2025-11128.pdf.

[8] When a cellulosic waiver credit is offered to obligated parties, the RFS statute specifies that it must be "…at the higher of $0.25 per gallon or the amount by which $3.00 per gallon exceeds the average wholesale price of a gallon of gasoline in the United States, adjusted for inflation." See the 2024 EPA rulemaking available here: https://www.govinfo.gov/content/pkg/FR-2025-07-07/pdf/2025-11153.pdf.

[9] The RIN generation data were collected from the "Generation Summary Report" provided by the EPA at this link: https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rins-generated-transactions.

[10] Note that FAME biodiesel and renewable diesel RIN generation are presented here in RIN equivalent gallons rather than physical volumes.

[11] Compliance with the RIN system unquestionably entails substantial administrative costs, including operating a trading desk, contracting with a law firm for compliance issues, and requiring management to attend to RIN costs and RIN compliance instead of focusing on its normal physical fuels operation. Some of these costs are fixed while some scale with the size of the business. Because of the fixed cost component, administrative compliance costs can disproportionately burden small merchant refiners.

[12] The volume of D7 RINs generated historically is so small that it can be ignored in the computation of RIN bundle prices.

[13] This is due to the existence of RIN banking across compliance years. If there are no banked RINs and RIN prices follow D3≥D5≥D6 and D4≥D5≥D6, then the assumptions are not required because each RVO will be met using only RINs that correspond to each RVO. With positive banked RINs, obligated parties have flexibility in using D3, D4 or D5 RINs to meet the overall advanced mandate and D3, D4, D5, or D6 RINs to meet the conventional mandate.

[14] See Table 1 at this link: https://www.epa.gov/fuels-registration-reporting-and-compliance-help/annual-compliance-data-obligated-parties-and.

[15] Stock (2018, pp. 12-13) notes that this cost measure should be interpreted in light of its limitations, "…because RINs represent a transfer to RIN generators or separators, gross costs neglect the benefits to recipients, and gross costs provide no indication of who ultimately pays for or receives the value from a RIN." In addition, this measure does not consider any cost offsets due to: i) lower fuel prices associated with the octane value of ethanol in E10 gasoline (Irwin and Good 2017a; Irwin 2019); or ii) the social benefit of reductions in greenhouse gas emissions.

[16] Our estimate of the cost under a zero conventional gap is biased upwards because we do not consider the impact of lower demand on the price of D4 RINs.

[17] If additional biofuel supplies reduce the price of blended petroleum fuels, this may result in higher consumption of fuels as consumption responds to the lower price. Khanna, Rajagopal, and Zilberman (2021) review the literature on the "rebound effect" and conclude that the magnitude of this effect is likely to be small for the U.S.

[18] Mandates can be binding for economic and physical reasons. When a mandate binds economically, the competitive equilibrium quantity is less than the mandate level. When a mandate binds physically, there is a physical limitation to biofuel production or consumption. An example is regulations in the U.S. that have traditionally limited ethanol to no more than 10 percent of gasoline blends by volume.

[19] We do not consider the impact of other state-level tax credits in the policy stack for biomass-based diesel. The most important state-level credits are those available through the California LCFS program. We do not consider these credits in the analysis for two reasons. First, the credits are firm specific, and data are not available in the public domain to estimate a firm weighted-average credit value. Second, the impact of the credits is mainly limited to the renewable diesel boom period that began in 2021, which is a relatively small part of our sample. Nonetheless, consideration of LCFS and other similar state low carbon fuel credits (New Mexico, Oregon, and California) for D4 RIN pricing is an interesting area for future research. See Whistance, Thompson, and Meyer (2017), Mazzone, Smith, and Witcover (2022) and Gerveni, Hubbs, and Irwin (2023b) for further discussion of the role of LCFS credits in the biomass-based diesel market.

[20] Thompson, Meyer, and Westhoff (2010) refer to the fundamental represented by equation (4) as the "core" RIN value. They argue that observed RIN prices also include a transactions cost and speculative component, with the speculative component reflecting expectations about the future likelihood that an RVO will be binding. Along these lines, one can also conceptualize RIN prices as representing option values, where the RIN provides the right to the buyer of not blending an additional physical gallon of a biofuel. The fundamental value in equation (4) would then represent the "moneyness" of the RIN option. The time value of the RIN option would represent the likelihood that the RVO is binding in the future, which would drive the option into-the-money or even further in-the-money. This is the same as the speculative component proposed by Thompson, Meyer, and Westhoff. Since D4 RIN "options" would almost always be considered deep-in-the-money, the time value in practice should be minimal. See Afkhami and Ghoddusi (2022) for a detailed analysis of RIN prices using an option pricing framework.

[21] The factor for converting from wet to ethanol equivalent RIN gallons for biomass-based diesel has varied through time. Since 2021, renewable diesel production has risen dramatically, and conversion factors are 1.6 or 1.7 for this biofuel. We assume the conversion factor is 1.5 for 2011-2021 and 1.6 thereafter to reflect the rising levels of renewable diesel production.

[22] The 45Z tax credit was modified in the One Big Beautiful Bill Act (OBBA) passed in July 2025. The credit was extended through December 2029 with limitations on feedstock that could be used to produce eligible biofuels.

[23] Bielen, Newell, and Pizer (2018) use the expiration of VEETC in 2011 to estimate the incidence of the tax credit. They find that most of the credit—around 55 percent—was passed through from gasoline blenders to ethanol producers. Another 5 percent appeared to be passed on to corn producers, which implies that a total of about 60 percent of VEETC was passed from blenders to ethanol and corn producers. Changing the passthrough assumption from 100 to 60 percent has a modest impact on the predicted D6 RIN prices and does not change the overall conclusions of the analysis.

[24] It is important to keep in mind the limitations of the model represented by equation (5). In particular, the model only considers the energy and octane characteristics of ethanol relative to petroleum CBOB blendstock. Other characteristics, such as Reid vapor pressure (RVP) affect the value of ethanol in gasoline blends. A full refinery optimization model is needed to conduct a complete analysis of value of ethanol in E10 gasoline blends, and therefore, the model presented here should only be viewed as an approximation to the true marginal value of ethanol. A 2022 study by the EPA investigates the marginal blending value of ethanol using a detailed model of the U.S. refining sector and finds results that are broadly consistent with those generated here.

[25] The question of whether the conventional RVO exceeded the E10 blend wall over 2016-2020 is complicated by SRE policies. Final conventional requirements were set higher than the blend wall in final rulemakings during this period, but SREs awarded later had the effect of reducing effective conventional

requirements below the E10 blend wall (Coppess and Irwin 2018). However, this process was uncertain in real-time, and therefore, only partially reflected in D6 RIN prices.

[26] It is important to emphasize that the octane premium discussed here is only applicable to gasoline blends containing up to 10 percent ethanol (E10). The value of octane in higher ethanol blends, such as E15, has not been sufficient to date to incentivize widespread adoption of these blends.

[27] It is reasonable to expect high corn prices—working through the price of ethanol— would have a similar effect on predicted D6 RIN prices as low crude oil prices. However, a plot of the two series shows little relationship between high observed corn prices and predicted D6 prices.

[28] Detailed examples and discussion of the theory of RIN price passthrough can be found in Burkholder (2015) and Stock (2015).

[29] Since the RFS program is designed to be revenue neutral, the aggregate value of the tax and subsidy terms must sum to zero. We earlier estimated the total compliance cost for the RFS over 2011 through 2023 to be $174.8 billion. This is an estimate of the aggregate RIN tax for those years. It is also an estimate of the aggregate value of the RIN subsidy needed to incentivize biofuel consumption at mandated levels.

[30] It should be noted that the net retail passthrough estimates for E10 presented in Figure 14 do not incorporate cost reductions associated with the octane value of ethanol. As discussed earlier, ethanol provides a lower cost alternative to the most widely available petroleum octane additives. Based on the estimates in Irwin and Good (2017a) and Irwin (2019), using ethanol instead of a petroleum octane additive reduces the retail pump price of E10 by 4 to 7 cents per gallon after accounting for the lower energy value of ethanol. This estimated cost saving is larger than the passthrough RIN price effect on E10, which is around one cent per gallon. Consequently, the phase-out of MTBE and adoption of ethanol as the main source of octane in gasoline blends over the last 20 years may have reduced the retail price of E10 by 3 to 6 cents per gallon. This is consistent with other estimates of the impact of ethanol on the price of gasoline in the U.S. Khanna, Rajagopal, and Zilberman (2021) review literature and report a range of price declines from 4 to 10 cents per gallon.

[31] Irwin and Stock (2018) conducted listening sessions with crude oil refiners regarding concerns about the operation of the RFS and RIN system. The sessions revealed three channels by which merchant refiners perceived they could be at a competitive disadvantage because of RIN compliance obligations: i) timing risks arising from RIN price fluctuations, ii) RIN price-sharing contracts, and iii) disproportionately large administrative costs of RIN purchases.