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 compliance costs exceeded $174 billion over 2011-2023, with full pass-through to consumers 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

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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. Established in the Energy Policy Act of 2005 and significantly expanded in the Energy Independence and Security Act of 2007, 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 (e.g., 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 2007 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 has become increasingly critical for economists, market participants, and policymakers as the program does not sunset and will continue indefinitely. 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, like 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 mid-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 with recent developments including the program's post-2022 reset authority and emerging market dynamics (e.g., Stock 2015, 2018). 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, 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 pass-through of RIN compliance costs through competitive fuel markets at the bulk wholesale level, confirming that the ultimate incidence of RFS mandates tends to fall on consumers rather than obligated parties. Finally, we identify emerging structural changes in biofuel markets, particularly the growing importance of renewable diesel relative to traditional biodiesel, that 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 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. 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). 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 also required by the RFS statutes to issue annual rulemakings to set the RVOs.

An important feature of the 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 the 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 mandate, the overall advanced mandate, and the conventional mandate, but not the biomass-based diesel mandate. Similarly, biomass-based diesel is eligible to meet its own mandate, the overall advanced mandate, and the (implied) conventional mandate, but not the cellulosic mandate. Other advanced biofuels must reduce GHG by at least 50 percent and can meet the overall advanced mandate as well as the conventional mandate. Conventional biofuels must reduce GHG by at least 20 percent and can only meet the conventional mandate and none of the other mandate categories. In practice, the conventional mandate is often referred to as the corn ethanol mandate because ethanol is the most commonly used biofuel fuel to fill this implied mandate.

The 2007 RFS statute specified the level of volumetric standards through 2022. These standards 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 at 36 billion gallons. Note that the biomass-based diesel mandate was established as a minimum of one billion (physical) gallons per year from 2012 through 2022, with larger amounts subject to EPA approval.

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 in order 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 also 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."

Figure 3 presents the final RFS RVOs for 2010 through 2022, along with total statutory RVOs (from Figure 2). The final 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 very aggressive from the outset, given that industrial-scale production was virtually non-existent when the RFS was passed in 2007. While several plants were built since then, cellulosic production struggled to reach even a few million gallons. The bulk of what has been produced in this category is captured landfill gas in the form of renewable natural gas ("biogas"), which qualifies as a cellulosic biofuel due to the breakdown of paper lignin in landfills. The low cellulosic production totals from all sources caused the EPA to use its RFS waiver authority to write down the cellulosic mandate to very low levels relative to statutory levels every year over 2007 through 2022. The total renewable and advanced RVOs have also been written down in conjunction with the write-down in the cellulosic mandate.

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 traditionally 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 2007, it was commonly projected that U.S. gasoline consumption by 2015 would be 150 billion gallons. So, it is no surprise that the cap on the conventional mandate 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 mandate as specified in the RFS statute began to surpass the E10 blend wall in 2012. 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 conventional RVOs.

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 "resetting" RVOs after 2022, using a process that follows the following 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 mandates and minimum biomass-based diesel requirements.

In June 2023, the EPA announced final RVOs for 2023, 2024, and 2025 based on these criteria for the first time.[2] 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 mandate shows steady growth from 2.82 to 3.35 billion gallons, while the cellulosic mandate increases from 0.84 to 1.38 billion, representing EPA's cautious but optimistic assessment of emerging cellulosic production in recent years.

It is important to understand that compliance with annual RVOs is enforced via fractional 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

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

consumption in the lower-48 states plus Hawaii (Alaska opted out). 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 follows:

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

where $FRVO_i$ is the fractional percentage RVO for the i^{th} renewable fuel (i = total, advanced, biomass-based diesel, and cellulosic), RVO_i is the volume RVO for the i^{th} renewable fuel, 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 renewables 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 renewables, 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, primarily domestic petroleum refiners and importers as well as foreign producers, use the fractional mandates to calculate their 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 mandates 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 different biofuel category.[3] 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 mandate 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 EPA 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 and separated (detached) from that fuel when blended or sold into the transportation fuel supply. 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 RIN market. Once obtained via blending or purchase, obligated parties can turn RINs in to the EPA to demonstrate compliance ("retire" the RIN).

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.

[3] 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.

- 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 life cycle GHG emissions. Based on the feedstock, fuel type, and life cycle GHG reduction relative to petroleum, the EPA evaluates the petition. If the petition is approved, a RIN D 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" (actual physical) gallons of a biofuel and RIN-equivalent gallons. For example, one wet gallon of biodiesel generates 1.5 RIN gallons.[4]

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, obligated parties 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.[5]

Figure 4 presents annual RIN generation by category over 2010 through 2024.[6] While RIN generation is obviously related to the RVOs presented in Figure 2 and Table 1, it is

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[4] 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.

[5] 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.

[6] 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.

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 near 15 billion gallons since 2014, except for the COVID year of 2020. This is no accident given that conventional mandate has been set at or near 15 billion gallons this entire period. 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.

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. Ethanol RIN generation has been near 15 billion gallons in most years, which reflects the fact that the vast majority of D6 RINs are associated with ethanol production. FAME biodiesel RIN generation has been about 3 billion gallons every year since 2016, whereas renewable diesel RIN generation has exploded.[7] Over the last decade, renewable diesel RIN generation increased 600 percent, reaching 6 billion gallons in 2024. This represented nearly a quarter of 2024 RIN generation. The factors driving the boom in renewable diesel production include increases in RVOs, especially biomass-based diesel, federal tax credits, and state-level low-carbon fuel program credits (Gerveni, Irwin, and

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

Hubbs 2023b; Gerveni and Irwin 2025; Lade and Smith 2025).[8] Renewable natural gas production has also increased substantially in recent years, increasing to nearly a billion gallons in 2024. This is primarily associated with growth in natural gas production from landfills and dairy manure anaerobic digesters.

Historical RIN Prices and Compliance Costs

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 mandate 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 can 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 plus waiver credit over January 2011 through June 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 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 very low values, only a few cents, for the first five years of the available market history. The extremely low prices, more than likely, simply reflected the cost of transacting in the RIN market by obligated parties. The implication is that blending ethanol into gasoline through 2012 required little if any incentives through the RIN mechanism. In other words, ethanol was a competitive blend component in gasoline without the RFS mandate. This is directly related to the transition from MTBE (methyl tert-butyl ether) as the primary source of octane and oxygenate in gasoline blends to

[8] An extensive list of articles on the renewable diesel boom can be found on the *farmdoc daily* website at this link: https://farmdocdaily.illinois.edu/category/areas/other/renewable-diesel-boom.

ethanol providing these additives (Anderson and Elzinga 2014). After MTBE was effectively banned in the early 2000s, ethanol became the lowest cost source of octane and oxygenate in gasoline blends (Babcock and Fabiosa 2011, Irwin and Good 2012, Tyner, Taheripour, and Hurt 2012, Babcock 2013). Crucially, the average octane benefit of ethanol in E10 gasoline blends fully offsets the average penalty for the lower energy value of ethanol (Irwin and Good 2017a, Irwin 2019).

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 the lowest cost source of octane and oxygenate in gasoline blends. Instead, 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 exceeding the E10 blend wall in 2012. The rise in RIN prices in the first half of 2013 was associated with the recognition by market participants that the gap between the conventional mandate and the E10 blend wall would have to be filled by D4 RINs, the most widely available alternative for filling the conventional mandate. 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 mandate, 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 biodiesel, which tends to be much more expensive to produce than ethanol.

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 50, 48, and 89 percent for D4, D5, and D6 prices, respectively. Since RINs can banked from year-to-year (up to 20 percent of RVOs), the current RIN price depends not only on market conditions today but also 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 2014a 2014b 2015; Lade, Lin Lawell, and Smith 2018b).

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 were the marginal gallon for filling both the advanced and conventional mandates (Irwin and Good 2017b). In other words, D4 RINs were produced in excess of the amount needed to fulfill the biomass-based diesel mandate and these excess RINs were used to "top off" the advanced and conventional mandates. For a D4 RIN to be substituted for a D5 or D6 RIN, the price of the D4, D5, and D6 RINs must in theory be the same.

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.[9] 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 (Irwin 2018). Assume that: i) annual gasoline consumption is 150 billion gallons, ii) 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. The ethanol mandate represents 7.5 percent of total gasoline and diesel consumption, whereas the biodiesel mandate represents 1 percent. 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

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

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,

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

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 because RINs used for compliance do not necessarily track precisely with fractional RVOs due to the nesting provisions of the RIN system. In the previous example these were assumed to be one and 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 mandate and the sum of the cellulosic and biodiesel mandates, and ii) only D6 RINs are used to meet the conventional mandate.[10] 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 from higher nested categories (e.g., D4 for D6 compliance).

Our estimates of the weighted-average price of a RIN bundle from January 2011 through June 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 right 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

[10] By definition, only D3 RINs can be used to meet the cellulosic RVO and only D4 RINs can be used to meet the biomass-based diesel RVO.

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 experienced in the first Trump Administration. Since that initial spike, the price of a RIN bundle has been trading mainly between 10 and 20 cents per gallon.

We can use the RIN bundle prices to estimate compliance costs associated with the RFS. This requires three steps. First, we collect data on obligated gasoline and diesel volumes under the RFS reported to the EPA for 2011 through 2023.[11] The last available year is 2023 since compliance for 2024 has been extended and does 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 obligated volumes from the EPA. Third, we multiply the obligated volumes by the average annual RIN bundle prices.

Figure 9 shows that compliance costs estimated in this manner are large in economic terms, averaging $13.4 billion over 2011 through 2023.[12] The range in RIN compliance costs is also very large, ranging from $1.9 billion in 2011 to $32.8 billion in 2022. Since obligated volumes 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 $25 billion in each year over 2021 through 2023. Finally, RIN compliance costs over 2011 through 2023 total $174.4 billion. By 2025, total compliance costs will easily surpass $200 billion. It is important to emphasize that actual

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

[12] 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."

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.

Economic Fundamentals and RIN Pricing

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.

In economic terms, the RIN price is meant to equate supply and demand so that the fraction of biofuel blended and consumed equals the fraction specified in the EPA's annual RVO. If an RVO binds in economic terms, then biofuel producers must be incentivized to produce at a higher level than under a competitive equilibrium. This requires a supply price that is high enough to elicit biofuel 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. The price of the RIN represents the incentive needed to enforce production and consumption at the mandated RVO quantity.

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 also been used to fill the advanced and conventional mandates (Irwin and Good 2017b). 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 2017c; Gerveni, Hubbs and

Irwin 2023b). The model shown in 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 Figure 10 also assumes that biodiesel demand is perfectly elastic (horizontal) at the level of ultra-low sulfur diesel (ULSD) prices. 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, including any "rebound" effects (Lewis, 2016). 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.

The policy scenario we consider in Figure 10 includes both a binding volume mandate and a blenders tax credit. This scenario reflects the situation for most of the last 15 years when both the RFS mandate and the $1 per gallon blenders tax credit have been in place in the U.S. The mandate is assumed to be binding because it requires a higher level of biomass-based diesel production than under a tax credit alone ($Q^M > Q^*$).[13] To incentivize higher production, biomass-based diesel producers must be paid a higher price than the energy-adjusted ULSD price. This means that the demand for biomass-based diesel effectively becomes perfectly inelastic at the mandated quantity. The entire demand curve becomes

[13] 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.

L-shaped, with the vertical and perfectly inelastic portion equal to the volume mandate and the horizontal perfectly elastic portion above the mandate quantity equal to the energy-adjusted ULSD price. The effect of the tax credit under this scenario is purely distributive because the biomass-based diesel price and quantity are unaffected by the blenders tax credit.

The wet D4 RIN price in the policy scenario considered in Figure 10 is easily computed. It is simply the difference between the biomass-based diesel supply price at the mandated quantity, P_{BBD}, and the ULSD demand price after accounting for the tax credit. This can be expressed in mathematical terms as follows,

$$\text{Wet D4 RIN Price} = P_{BBD} - (0.927{*}P_{ULSD} + 1), \tag{3}$$

which can be converted into ethanol equivalent terms,

$$\text{D4 RIN Price} = [P_{BBD} - (0.927{*}P_{ULSD} + 1)]/1.6. \tag{4}$$

Irwin, McCormick, and Stock (2020) consider this last relationship to be the "fundamental" in the D4 RIN market.[14]

We predict D4 RIN prices using this model and bulk wholesale FAME biodiesel prices in Chicago. We use FAME biodiesel prices because 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. 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 comparison of predicted and actual D4 prices over January 2011 through June 2025 is presented in Figure 11. The red line in the figure is the actual D4 price and

[14] The factor for converting from wet to ethanol equivalent RIN gallons for biomass-based diesel has varied through time. Irwin, McCormick, and Stock (2020) assume it is 1.5 because this is the conversion factor for FAME biodiesel, which was the dominant biofuel used to fill the biomass-based diesel RVO during their sample period. In the last few years, 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.

the blue line is the predicted price. The predictions from this simple model track actual D4 market prices reasonably well. The R-squared from a regression of the predictions on actual D4 prices is 70 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 and D5 RIN prices follow the same pricing process as long as biomass-based diesel is the marginal gallon for complying with the advanced and conventional mandates.

There are several periods where the predicted D4 price in Figure 11 is above the actual price. 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 assumes that the tax credit is zero during these periods, which results in a prediction higher than the market price. Irwin, McCormick, 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 reveals that predicted D4 prices have been unusually low relative to actual prices so far in 2025. FAME biodiesel prices dropped by about $1 per gallon shortly after January 1st but D4 RIN prices did not change appreciably. The most likely explanation is uncertainty over implementation of the new 45Z tax credit, which had been passed as part of the Inflation Reduction Act (IRA) of 2022 under the Biden Administration. The 45Z credit is variable based on carbon intensity scores (Buffie 2023), whereas the old the blenders tax credit 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.

The same principles can be applied to D6 RIN prices. Since the majority 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,

$$\text{D6 RIN Price} = P_E - (0.667 * P_{CBOB} + \text{VEETC}), \quad (6)$$

where P_E is the bulk wholesale price of ethanol in Chicago, P_{CBOB} is the bulk wholesale price of CBOB gasoline blendstock in Chicago, and VEETC (volumetric ethanol excise tax credit) is a blenders tax credit for ethanol when it was in effect. VEETC expired permanently at the end of 2011.[15] Ethanol has approximately two-thirds of the energy as CBOB, and this is reflected in the adjustment to the price of CBOB.

Figure 12 compares the predicted D6 RIN price based on the ethanol fundamental and actual D6 RIN prices over April 2008 and June 2015. While there are some periods where the predictions and actual D6 prices track one another, the overall impression is that the two are not very closely related. There are long stretches of time where the predicted and actual prices move in opposite directions. This is confirmed by the regression of predicted on actual D6 prices, which only has an R-squared of 0.16. This could be seen as an indictment of pricing efficiency in the D6 RIN market. However, such a conclusion would be misleading because the wrong fundamental is used most of the time in Figure 12. Recall that biomass-based diesel has functioned as the marginal gallon for filling the conventional RVO for much of the history of the RFS. In this circumstance, the D6 price should track the D4 RIN price, and consequently, the same fundamental should determine D4 and D6 RIN prices. In view of this fact, we predict D6 RIN prices in Figure 13 with the same biodiesel fundamental that we used earlier to predict D4 RIN prices. One can easily see that the predicted and actual D6 series track one another reasonably closely starting in 2013, the first time that biomass-based diesel became the marginal

[15] Between 2007 and 2011, VEETC was either $0.45 or $0.51 per gallon of ethanol.

gallon for filling the conventional RVO. The R-squared for this period jumps to 0.67 using the biodiesel fundamental, only slightly lower than when using this same fundamental to predict D4 prices.

The results presented in this section indicate RIN price volatility has a rational foundation, consistent with the findings reported by Irwin, McCormick, 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 for 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. Competitive economic theory predicts that RIN prices are ultimately passed through to the consumer. More specifically, complete passthrough requires RIN prices to be fully passed through at all points in the supply chain. This passthrough begins with obligated refiners and blenders who pass on their RIN cost per gallon of petroleum gasoline and diesel to blenders and distributors at the next point in the supply chain. Blenders and distributors then pass on the RIN cost to retail gasoline stations, who in turn pass this cost on to drivers at the pump. At the end of the chain, consumers absorb the full RIN cost in the form of higher gasoline and diesel prices than otherwise would be the case. The conceptual model used in the previous section assumed exactly this type of full passthrough of RIN prices from obligated parties to the consumer.

The passthrough of RIN prices is one of the most controversial aspects of the operation of the RFS. Smaller merchant refiners have repeatedly voiced concerns about their ability to fully pass through RIN costs, 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. Thus, the extent to which RIN prices are passed through the fuel supply chain ultimately is an empirical question.

The basic strategy we adopt for examining RIN price passthrough at the bulk wholesale stage is to compare 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 price of a RIN bundle.

Here, we compare daily spot prices of ULSD and ultra-low sulfur heating oil (ULSHO) at the U.S. Gulf. These two fuels have very similar 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 price, 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 refiners can fully passthrough RIN costs to sellers in this bulk wholesale market, the spread between the two fuel prices should equal the price of a RIN bundle.

Figure 14 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 R2 for a regression of the RIN bundle on the spread is 0.99 and the estimated intercept and slope are very close to zero and one, respectively. 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, that occurred in 2013.

The results in Figure 14 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).[16] 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. It is also important not to over-generalize the results presented here. This competitive outcome may not hold for smaller market participants at the bulk wholesale level or for geographically isolated markets.[17] While the U.S. Gulf is one of the most important fuel markets, we only analyze one pair of fuels for one location in the U.S. This is another area where further academic research is needed.

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

[16] A related but different issue is the extent to which the RIN value created by detaching a D6 RIN from ethanol blended with gasoline blendstock at the rack level is passed through to consumers in the form of a reduced price for the blended fuel based on its ethanol content. Several studies in literature examine this type of passthrough issue (Pouliot, Smith, and Stock 2017; Lade and Bushnell 2019; Li and Stock 2019; Luo and Moschini 2019) and find mixed results.

[17] 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.

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 original 2007 legislation 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 mandates reached only 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 mandates below statutory levels, particularly for cellulosic biofuels

Two critical constraints have shaped RFS implementation. The “E10 blend wall”—the practical limit of 10% ethanol content in gasoline—became binding when conventional mandates exceeded this threshold around 2012, triggering the dramatic 2013 RIN price spike. The COVID-19 pandemic provided another major disruption, causing the EPA to reduce 2020-2021 mandates due to collapsed fuel demand.

Compliance with RFS mandates is enforced through Renewable Identification Numbers (RINs), tradeable credits generated when qualifying biofuels are produced or imported. Five RIN categories correspond to different biofuel types (D3-D7), with RIN generation based on energy equivalence to ethanol. RINs can be banked for one year and obligated parties may incur deficits up to 20 percent of their annual obligation. We document substantial RIN generation growth, particularly for D4 biomass-based diesel RINs, which increased from 4.1 billion gallons in 2019 to 9.2 billion by 2024. This growth reflects the rapid expansion of renewable diesel production driven by RFS mandates, federal tax credits, and state low-carbon fuel programs.

RIN prices have exhibited extraordinary volatility, with prices for D6 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 speculative excess or market manipulation. We demonstrate strong correspondence between predicted and actual D4 RIN prices, with RIN prices reflecting the difference between biofuel supply costs and petroleum-equivalent demand prices. The analysis reveals that D4 RINs often serve as the "marginal gallon" for filling multiple mandate categories due to the nested structure of the RFS, which causes D4, D5, and D6 RIN prices to converge for extended periods. RIN bundle costs—the weighted average cost of compliance across all categories—have also fluctuated substantially, reaching a peak of 23 cents per gallon in 2021.

Total RIN compliance costs are estimated at $174.4 billion over 2011 through 2023, averaging $13.4 billion annually but ranging from $1.9 billion to $32.8 billion depending on RIN price levels. The analysis finds complete pass-through of RIN costs 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. This indicates that the ultimate incidence of RFS mandates tends to fall on consumers rather than obligated parties.

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).

In sum, the RFS represents a natural experiment in large-scale biofuel policy implementation, offering valuable lessons for economists and policymakers considering similar interventions. As energy systems transition toward further decarbonization, the lessons learned from RFS implementation provide valuable guidance for designing more effective, efficient, and equitable renewable energy policies. The challenge for energy economists and policymakers is to internalize these lessons while remaining adaptive to the rapidly evolving landscape of energy technologies and climate imperatives.

Several areas merit further research. The evolving role of renewable diesel in compliance strategies requires updated analysis of RIN pricing fundamentals and market dynamics.

The interaction between the RFS and broader climate policies, including state low-carbon fuel standards and federal clean fuel production credits, creates complex policy interactions that warrant systematic investigation. Additionally, the distributional impacts of RIN costs across different regions and income groups remain understudied, despite their importance for policy evaluation.

The international dimensions of RFS implementation also deserve greater attention. The program's treatment of imported biofuels and feedstocks has significant trade implications, while its influence on global biofuel markets and land use patterns extends beyond U.S. borders. As other countries implement similar renewable fuel policies, comparative analysis of different policy designs and their interactions will become increasingly important.

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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.

Figure 1. The RFS Biofuel Nesting Scheme

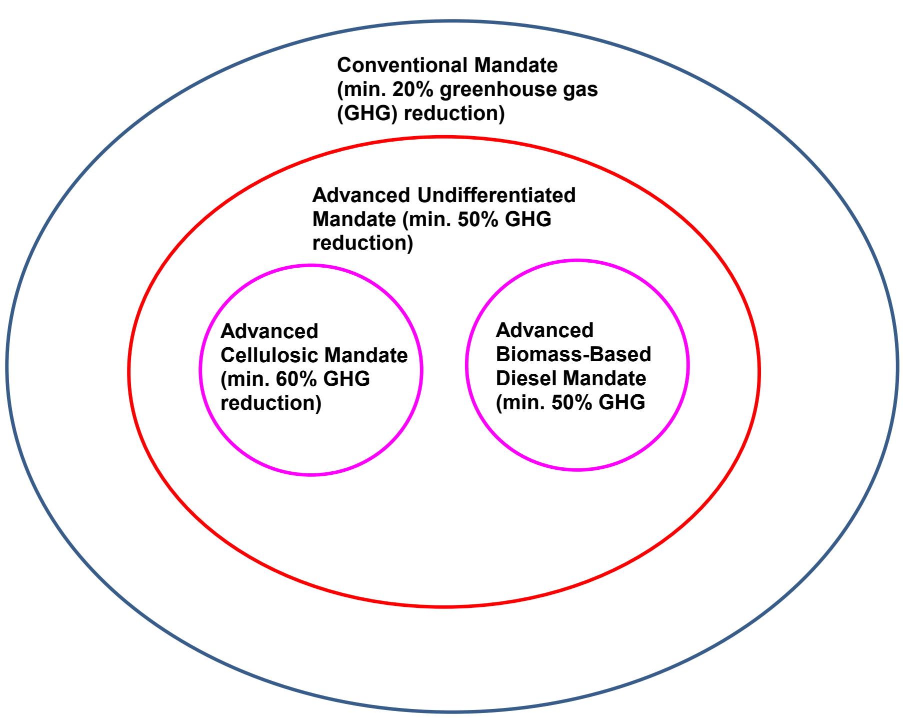
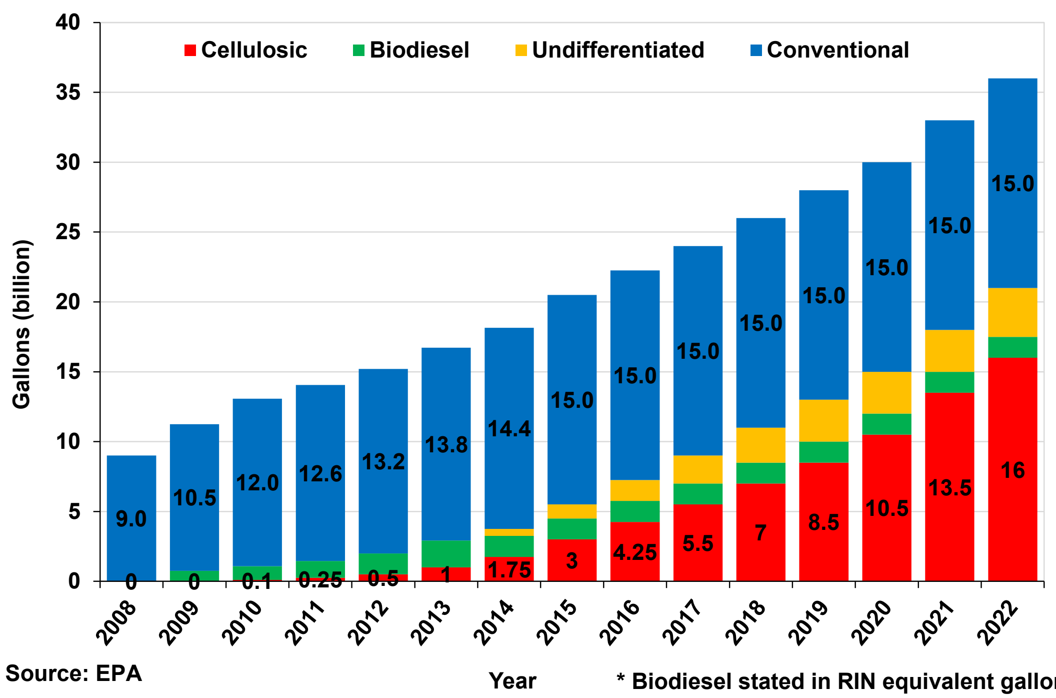


Figure 2. Statutory U.S. Renewable Fuel Standard Volume Obligations (RVOs), 2008 - 2022*



Source: EPA

* Biodiesel stated in RIN equivalent gallons

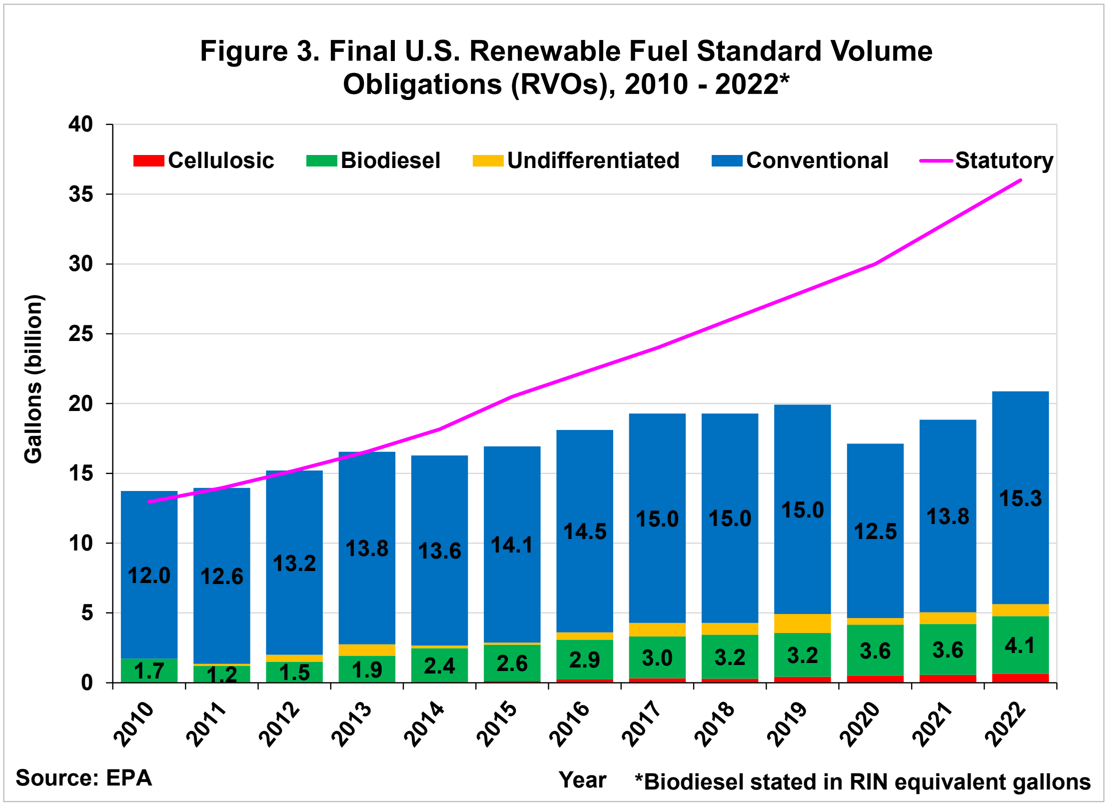


Figure 3. Final U.S. Renewable Fuel Standard Volume Obligations (RVOs), 2010 - 2022*
Cellulosic
Biodiesel
Undifferentiated
Conventional
Statutory
Gallons (billion)
40
35
30
25
20
15
10
5
0
12.0
12.6
13.2
13.8
13.6
14.1
14.5
15.0
15.0
15.0
12.5
13.8
15.3
1.7
1.2
1.5
1.9
2.4
2.6
2.9
3.0
3.2
3.2
3.6
3.6
4.1
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
Source: EPA
Year
*Biodiesel stated in RIN equivalent gallons

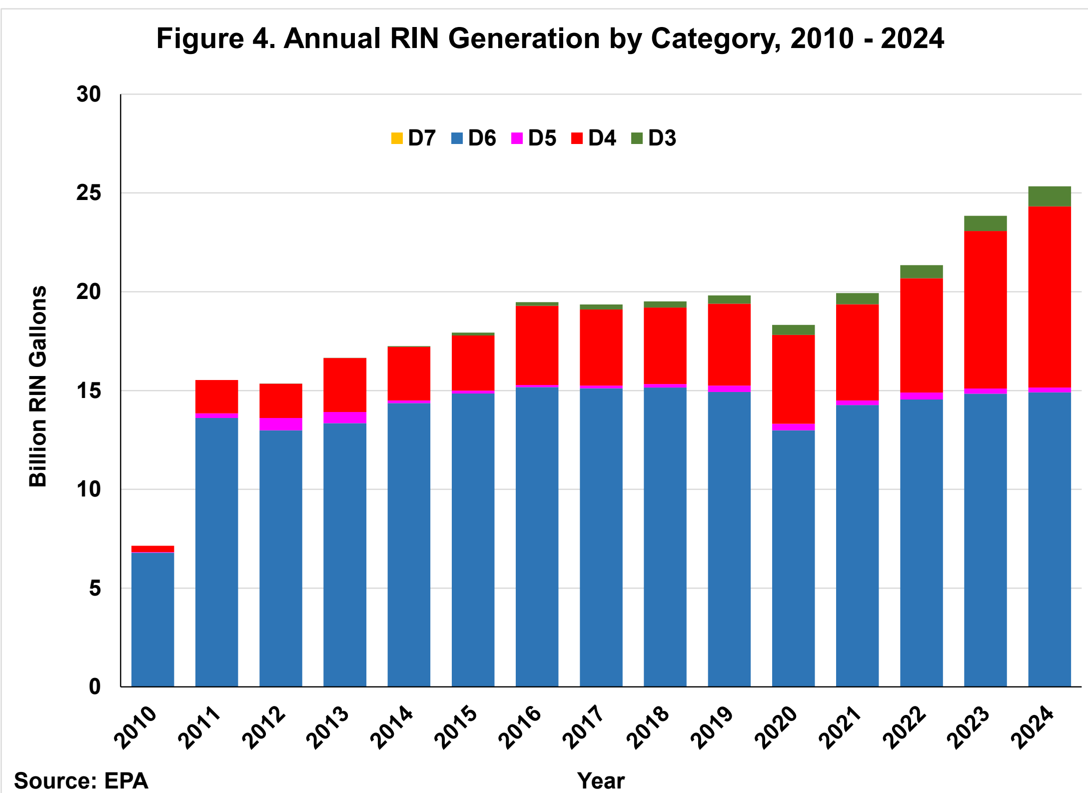


Figure 4. Annual RIN Generation by Category, 2010 - 2024
D7
D6
D5
D4
D3
Billion RIN Gallons
30
25
20
15
10
5
0
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
Source: EPA
Year

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

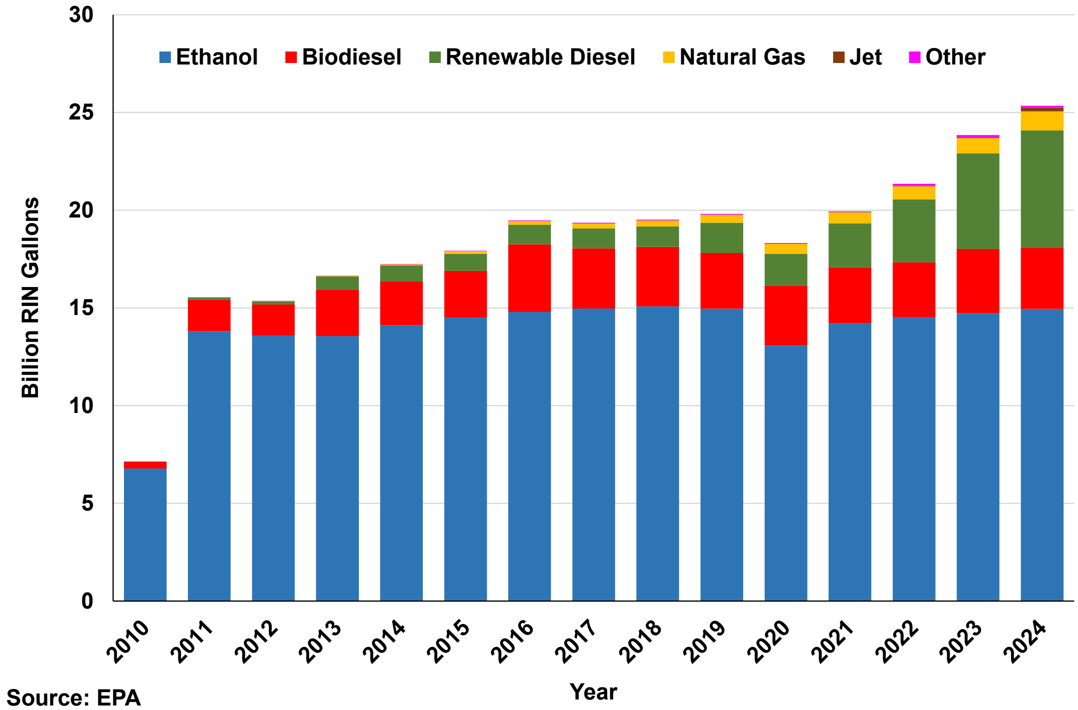


Figure 6. Weekly (Thursday) Sum of D5 Advanced RIN Price and Cellulosic Waiver Credit and D3 Cellulosic RIN Price, January 27, 2011 - June 19, 2025

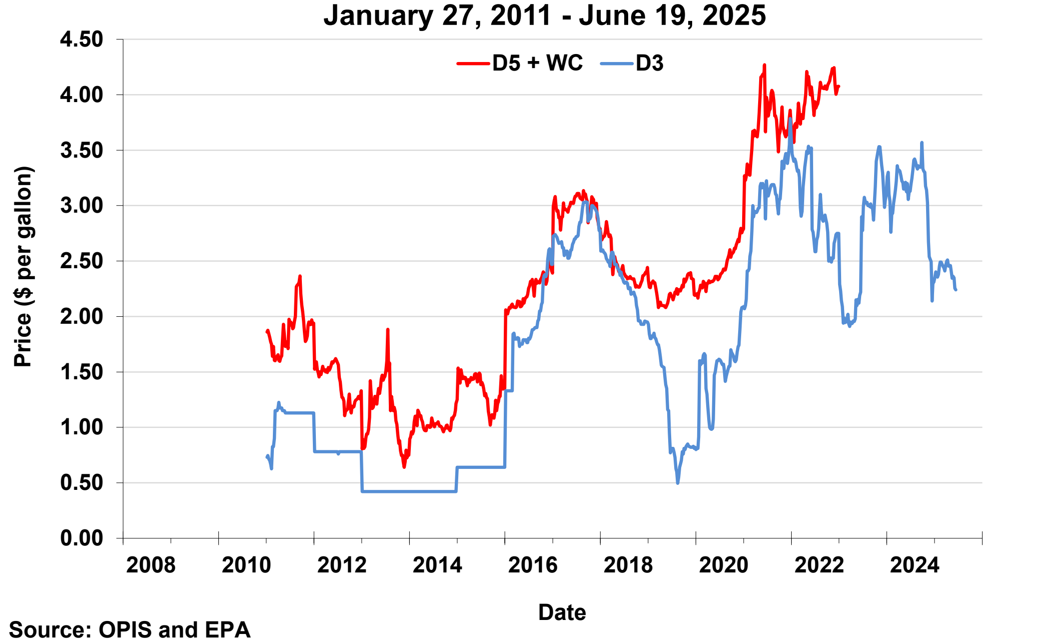
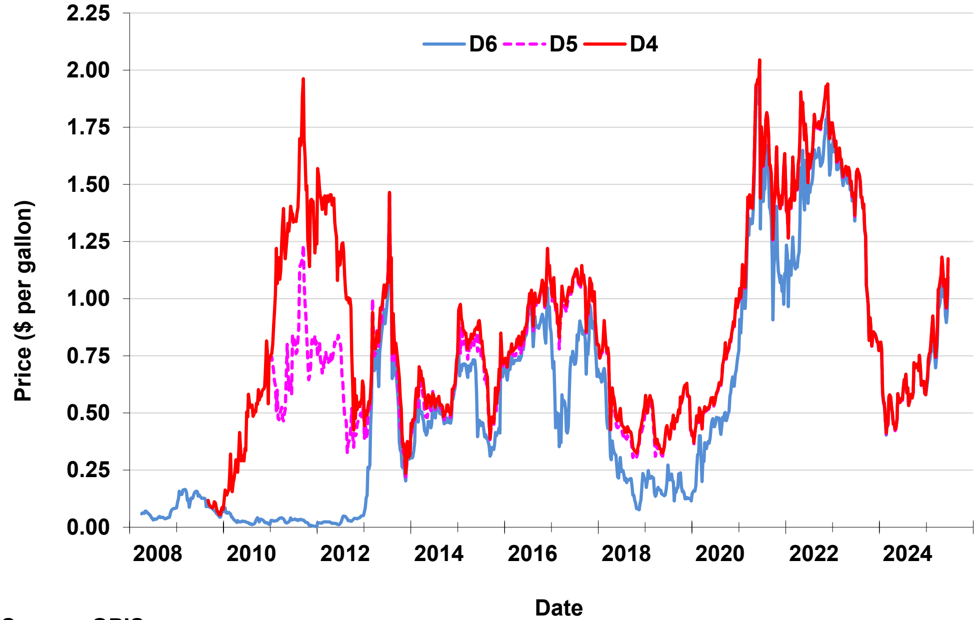


Figure 7. Weekly (Thursday) D4 Biodiesel, D6 Advanced, and D6 Ethanol RIN Prices, April 3, 2008 - June 19, 2025



Source: OPIS

Figure 8. Weekly (Thursday) Price of RIN Bundle, January 27, 2011 - June 19, 2025

Source: OPIS and EPA

Figure 9. Estimated Annual RIN Compliance Costs for the U.S. Renewable Fuel Standard, 2011 - 2023

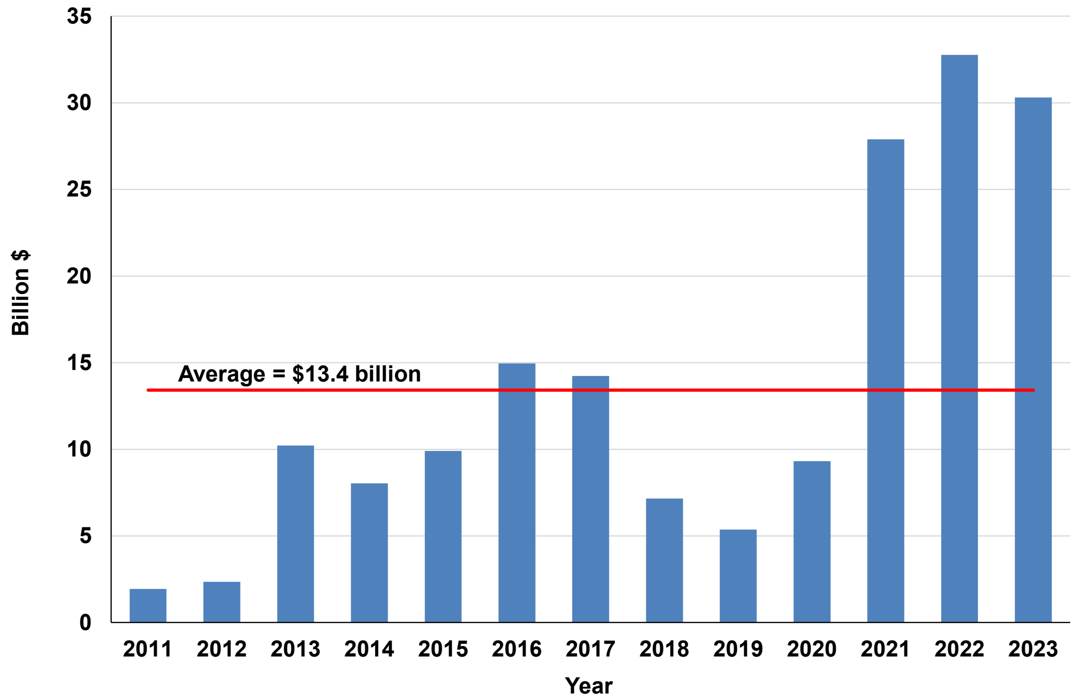


Figure 10. The Biomass-Based Diesel Market with a Binding RFS Volume Mandate and Blenders Tax Credit

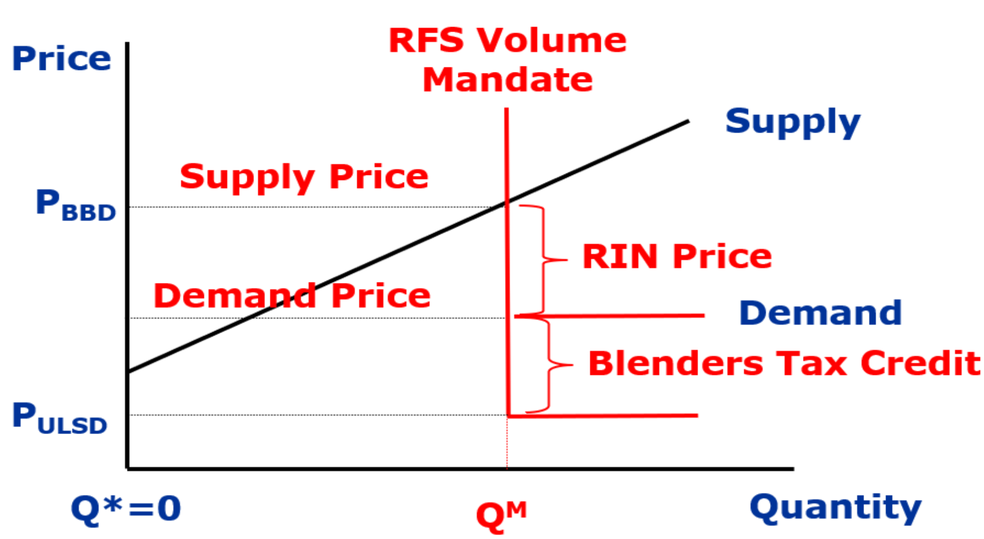


Figure 11. Weekly (Thursday) Predicted D4 RIN Price Based on Biodiesel Fundamental and Actual D4 RIN Price, September 3, 2009 - June 19, 2025

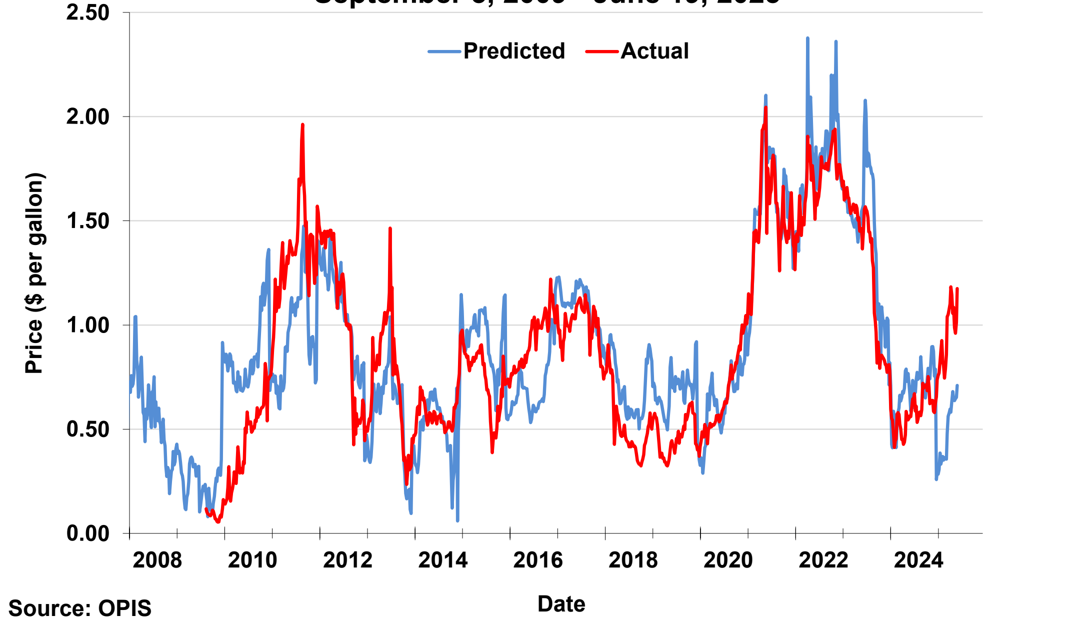
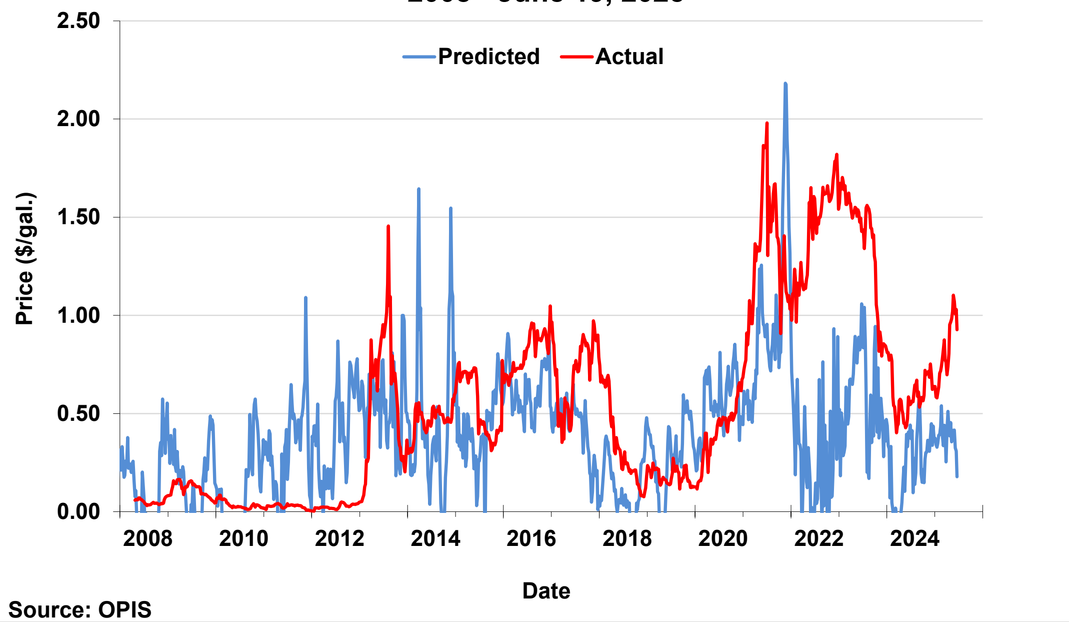


Figure 12. Weekly (Thursday) Predicted D6 RIN Price Based on Ethanol Fundamental and Actual D6 RIN Price, April 3, 2008 - June 19, 2025



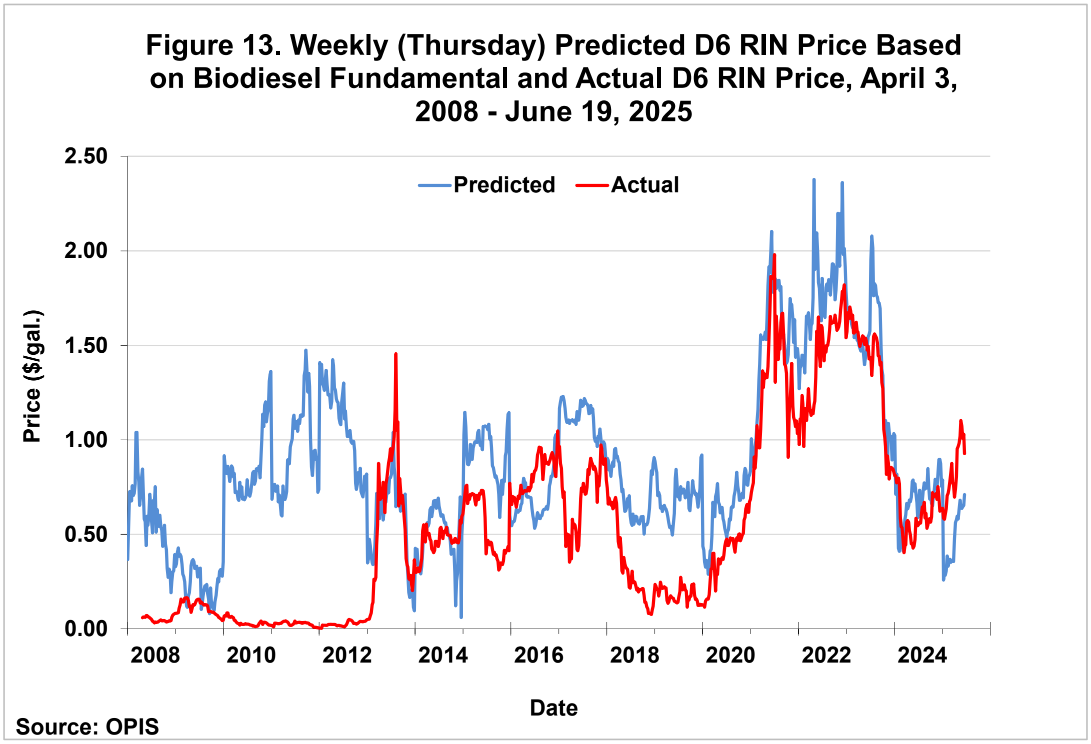


Figure 13. Weekly (Thursday) Predicted D6 RIN Price Based on Biodiesel Fundamental and Actual D6 RIN Price, April 3, 2008 - June 19, 2025
Predicted
Actual
Price ($/gal.)
2.50
2.00
1.50
1.00
0.50
0.00
2008
2010
2012
2014
2016
2018
2020
2022
2024
Date
Source: OPIS

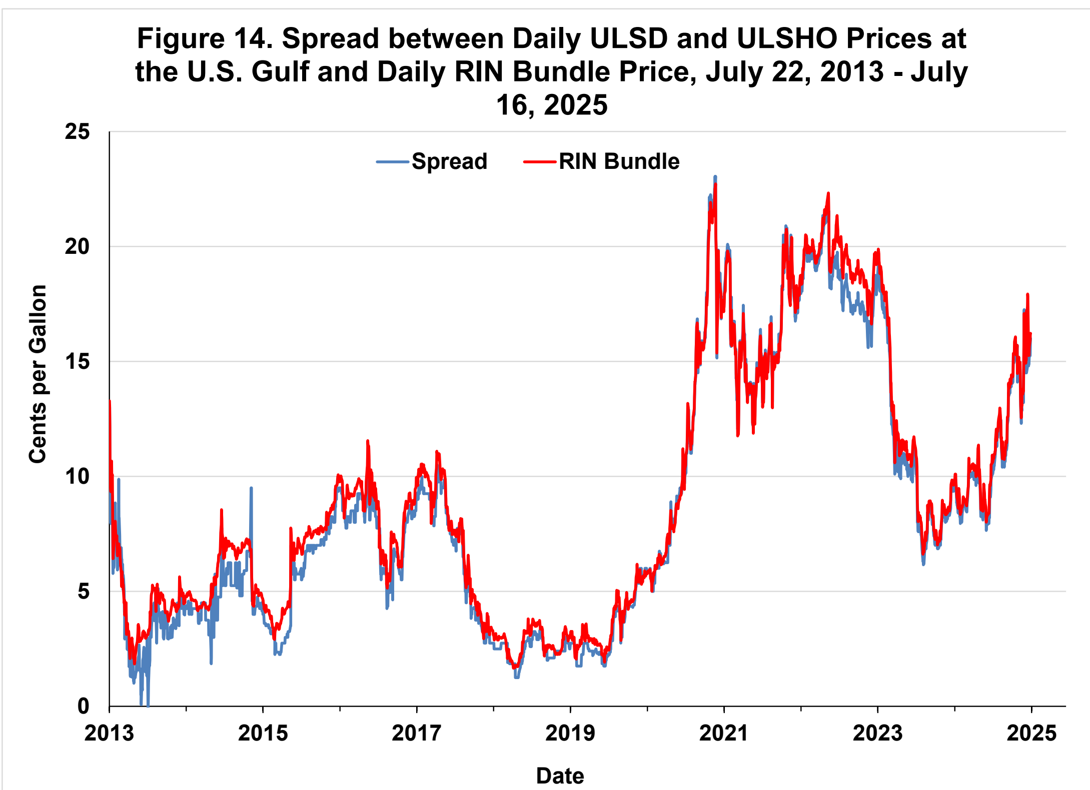


Figure 14. Spread between Daily ULSD and ULSHO Prices at the U.S. Gulf and Daily RIN Bundle Price, July 22, 2013 - July 16, 2025
Spread
RIN Bundle
Cents per Gallon
25
20
15
10
5
0
2013
2015
2017
2019
2021
2023
2025
Date