Perspective

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Why the cellulosic biofuels mandate fell short: a markets and policy perspective

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Abstract: The revised Renewable Fuel Standard's cellulosic biofuels mandate requires the USA to consume 16 000 million gallons of cellulosic biofuel per year by 2022. The cellulosic biofuels industry has fallen far short of reaching the production targets needed to achieve this volume, and it has even struggled to achieve the greatly reduced revised volumes that were created by the US Environmental Protection Agency despite the subsequent inclusion of landfill gas within the mandate. This article examines the underlying causes of this shortfall from the perspectives of markets and policy. It examines how the cellulosic biofuels production environment has not been conducive to the cost-competitiveness of pioneer, first-of-their-kind facilities and pathway buildout, and how recent techno-economic analyses have used uncertainty to quantify the impacts of this environment. It further examines how the cellulosic biofuels mandate has actually hindered commercialization despite being intended to support it. © 2019 Society of Chemical Industry and John Wiley & Sons, Ltd

Keywords: cellulosic biofuels; commercialization; renewable fuel standard; techno-economic analysis; uncertainty

Introduction

The revised Renewable Fuel Standard (RFS2), created by Congress in response to the Energy Independence and Security Act (EISA) of 2007, requires that US-obligated parties, primarily petroleum refiners, blend 8500 million gallons of cellulosic biofuels in 2019 to achieve 16 000 million gallons in 2022.[1] The legislation defines cellulosic biofuels as renewable fuels produced from qualifying lignocellulosic feedstocks that also achieve lifecycle greenhouse gas emission reductions of at least 60% compared to similar refined fuels such as gasoline.[2] Congress intended cellulosic biofuels to surpass ethanol made from corn starch as the country's most blended biofuel to mitigate concerns about the latter's limited greenhouse gas emissions reductions and alleged competition with food supplies.

The overarching cellulosic biofuel blending goal was ambitious given that the legislation imposed a volume of only 100 million gallons for 2010, the cellulosic biofuel blending mandate's first year. Even within that context, however, the original annual blending targets greatly overestimated the volume of cellulosic biofuel that the global biofuels industry was capable of producing for blending with refined fuels. The US Environmental Protection Agency (EPA), which is tasked with implementing and administering the RFS2, recognized early in the mandate's life that insufficient cellulosic biofuel production capacity

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existed to meet the mandate's blending volumes, and it has used its powers under the EISA to revise the statutory volumes lower to reflect existing cellulosic biofuel production capacity every year since 2010.[2,3] Between 2010 and 2019 the EPA has revised the statutory volumes down by an average of 96.2%, with annual reductions being as high as 98.6% (in 2013).[2,3] As Fig. 1 shows, however, the actual annual blending volume has come in below even the smaller revised mandated volumes in 7 of the last 9 years, missing by an average of 46.5% over the period.

The low blending volumes have occurred even as the EPA has expanded the definition of cellulosic biofuels in ways not originally envisioned by Congress. In 2014 the EPA began allowing so-called 'renewable natural gas' (RNG) in both compressed and liquefied forms to contribute to the cellulosic biofuel mandate.[4] Renewable natural gas quickly became the predominant source of cellulosic biofuel under the mandate (see Fig. 2), achieving at least 95%

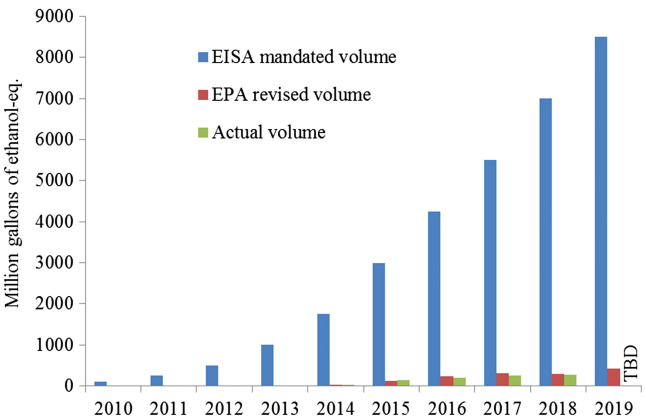

Figure 1. Cellulosic biofuel blending volumes as set by the Energy Independence and Security Act of 2007, subsequent EPA revisions, and actual blending volumes. The 2018 actual volume is extrapolated based on blending data for the year through the end of November.[1,3,4]

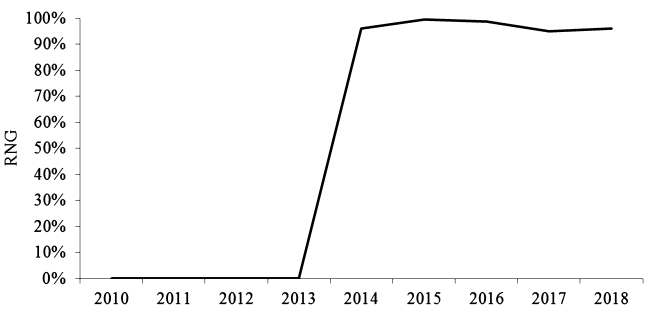

Figure 2. Percentage of annual cellulosic biofuel actual volume (gallons of ethanol-eq.) met by RNG in compressed or liquefied form.[2–4]

of total blending on an ethanol-equivalent basis in every year since its introduction.[4] The contribution of RNG has been particularly notable given that it is a gas rather than a liquid and, as such, is not blended with refined fuels such as gasoline and diesel fuel. Instead RNG can qualify as a cellulosic biofuel if it is injected into a common carrier pipeline that is connected to compressed natural gas (CNG) / liquefied natural gas (LNG) vehicle refueling stations. Unlike liquid biofuels that are sent directly to refueling stations, often being blended at the fueling station itself, RNG is assumed to displace fossil natural gas even though its ultimate destination might instead be a residential heating unit or electric power plant, so long as an equal amount of natural gas is pulled from the pipeline by a CNG/LNG refueling station.[5]

Only very small quantities of liquid cellulosic biofuels have been blended under the mandate: 11.8 million gallons of ethanol equivalent (EE) in 2017 and 11.2 million gallons of EE on an annualized basis in 2018.[4] At no point since the mandate was implemented has it appeared that sufficient investments in production capacity had occurred for the statutory volumes of 5500 million gallons and 7000 million gallons of EE in 2017 and 2018, respectively, to be achieved. As recently as 2012, however, planning and, in some cases, construction was underway that would have resulted in 323 million gallons of 'first-of-their-kind' commercial-scale (defined here as facilities with annual production capacities of 20 million gallons or more) liquid cellulosic biofuel production capacity in the USA by 2014.[6] This initial production would have been spread across six different pathways producing a total of two different fuels: cellulosic ethanol and cellulosic hydrocarbons. All of the projects were characterized by capital costs of as much as $10/gallon of EE installed capacity. Although this was expensive, it was anticipated that these first pioneer facilities would lead to lower capital and production costs via learning, efficiency improvements, and economies of scale, resulting in a rapid (if late) buildout of production capacity in subsequent years.

Three of the planned nine commercial-scale facilities identified in 2012 were built, resulting in 65 million gallons of nameplate capacity: a 25 million gallon cellulosic ethanol facility built by DuPont Biofuel Solutions in Nevada, IA; a 20 million gallon cellulosic ethanol facility ('Project Liberty') built by POET and DSM in Emmetsburg, IA; and a 25 million gallon cellulosic ethanol facility built by Abengoa Bioenergy in Hugoton, KS. Two of the three facilities have been shut down and / or sold by their original owners as of December 2018: the Nevada, IA facility is being converted to methane production[7] and the Hugoton, KS facility was auctioned for

  | *Biofuels, Bioprod. Bioref.* **13**:889–898 (2019); DOI: 10.1002/bbb

approximately 14% of its original capital cost following the bankruptcy of Abengoa Bioenergy's parent company.[8] Project Liberty, meanwhile, has struggled to scale up its production in the four years since its construction due to the failure of its original pretreatment process.[9] The remaining six planned commercial-scale facilities identified in 2012 have all been either cancelled or indefinitely postponed as of December 2018 (see Table 1).[10-15]

A notable consequence of the liquid cellulosic biofuel sector's underperformance to date relative to the RFS2's blending targets is growing political opposition to the cellulosic biofuels mandate. Several bills to reduce the volumes under the cellulosic biofuels mandate have been introduced by members of Congress in recent years, including proposals to cap the mandated blending volume at the previous year's production,[16] impose a sunset provision on the cellulosic biofuels mandate,[17] and limit the volume of ethanol that can be blended with gasoline in a way that would force cellulosic ethanol to compete with corn ethanol for US market share.[18] The cellulosic biofuels mandate has also been opposed by multiple members of the Trump administration, including former EPA Administrator Scott Pruitt.[19]

The objective of this paper is to examine why liquid cellulosic biofuels have produced only a tiny fraction of the total amount of cellulosic biofuel production to date, let alone the revised volumes established by the EPA (and let alone the EISA's original volumes). Even if it is assumed that the cellulosic biofuels mandate will not be successful but instead replaced by growing vehicle electrification,[20] it is important to understand why this national mandate has not been successful given its relevance to the introduction and intended rapid commercialization of next generation renewable technologies as the world's leading economies attempt to undergo deep decarbonization.

The immediate cause of the cellulosic biofuels mandate's limited success to date is a lack of cellulosic biofuel production capacity. Multiple factors explain why the necessary investment in commercial-scale capacity has failed to occur despite short-term plans by companies in late 2012 to spend $2.7 billion on capacity investments, with several billion dollars of additional investment planned in the longer term.[6] These factors fall into two broad categories: market dynamics and policy uncertainty. The rest of this paper examines these factors in further detail.

Market dynamics

The RFS2 was created at a time when the price of US gasoline had tripled over the course of 5 years (see Fig. 3), leading to industry expectations that cellulosic biofuels would be cost-competitive with refined fuels when produced at commercial-scale volumes. While the 2008 financial crisis and subsequent gasoline price collapse caused investment in cellulosic biofuel capacity to fall sharply, by 2011 the price of gasoline was approaching its 2008 highs, prompting renewed interest in cellulosic biofuels investments.[6] Several would-be producers of cellulosic biofuels including Abengoa Bioenergy, Beta Renewables, and ZeaChem received USDA loan guarantees during this time to support the construction of their first commercial-scale facilities, whereas others, such as Sundrop Fuels, POET-DSM, Mascoma, and KiOR, received individualized forms of state financial support in addition to limited state-level subsidies for all cellulosic biofuel producers (KiOR also staged a successful initial public offering).[6,22] While the price of gasoline never surpassed its 2008 high, it remained higher in 2011 and 2012 than the US National Renewable Energy Laboratory's projected cellulosic ethanol production costs on an unsubsidized basis for the same years.[23]

Table 1. Planned commercial-scale liquid cellulosic biofuel production facilities in 2013 with status as of 2018.

Company	Pathway	Product	Capacity (MGY)	Status
KiOR	Catalytic pyrolysis and hydrotreating	Hydrocarbons	41	Cancelled
ClearFuels	Gasification	Hydrocarbons	20	Cancelled
Sundrop Fuels	Gasification	Hydrocarbons	50	Cancelled
ZeaChem	Dilute acid hydrolysis	Ethanol	25	Indefinitely postponed
Abengoa Bioenergy	Enzymatic hydrolysis	Ethanol	25	Shutdown and sold
Beta Renewables	Enzymatic hydrolysis	Ethanol	20	Cancelled
DuPont Biofuel Solutions	Enzymatic hydrolysis	Ethanol	25	Converted to methane production
POET	Enzymatic hydrolysis	Ethanol	20	Operating at fraction of nameplate capacity
Mascoma	Consolidated bioprocessing	Ethanol	40	Cancelled

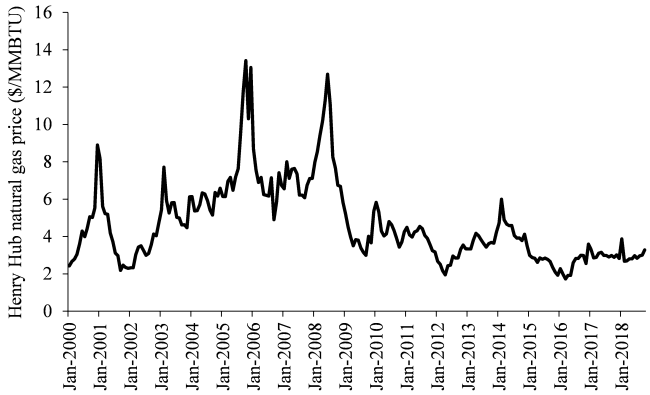

Figure 3. U.S. Henry Hub natural gas nominal price, January 2000 to October 2018.[24]

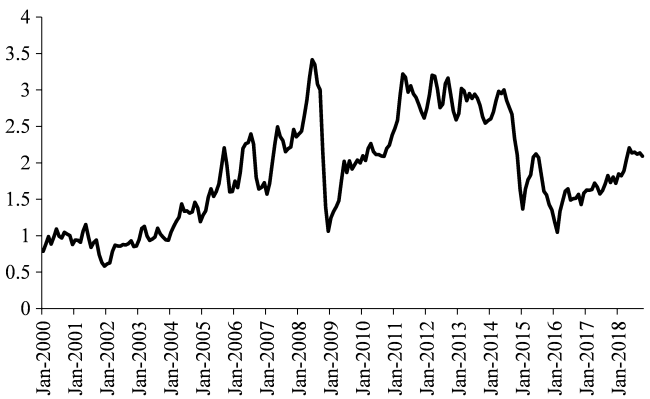

Figure 4. U.S. wholesale gasoline nominal price, dollars per gallon, January 2000 to October 2018.[21]

Market dynamics began to turn against cellulosic biofuel production capacity investments again as early as 2012, despite gasoline's price rebound. The advent of widespread hydraulic fracturing as a means of extracting natural gas from unconventional reserves caused the price of natural gas to disconnect from that of petroleum beginning in 2010. By 2012 the price of natural gas at the Henry Hub had fallen to its lowest level in the 21st century (see Fig. 4). While this was a boon for US corn ethanol producers, it caused producers of cellulosic biofuels via biomass gasification pathways to reevaluate their choice of feedstock. Four different cellulosic biofuel producers cancelled planned commercial-scale gasification facilities in 2012 and 2013. Coskata[25] and Sundrop Fuels[26] announced that their first planned facilities would utilize natural gas as feedstock rather than biomass due to the low cost of the former, while Rentech cancelled both its own planned facility and that of ClearFuels after acquiring the latter company.[14]

In the second half of 2014 the prices of natural gas and petroleum fell sharply and unexpectedly. The downturns were sustained and by early 2016 gasoline and natural gas prices were both trading at lows not experienced since the depths of the 2008 financial crisis (see Figs 3 and 4). Meanwhile, difficulties in making cellulosic biofuel technologies work at first-of-their-kind commercial-scale facilities prevented industry output from equaling more than a small fraction of the capacity that had been built. KiOR filed for bankruptcy in November 2014 after failing to achieve sustained production at its 11 million gallon 'small commercial' facility and cancelled plans to construct multiple commercial-scale facilities.[13] Only one of the nine planned pioneer commercial-scale facilities identified in 2012, POET-DSM's Project Liberty, was operational as of December 2018, and its current output is equal to only a small fraction of its nameplate capacity.[9]

The low gasoline prices that have largely characterized the US fuels market since late 2014 have had a major impact on the cellulosic biofuels industry. The projected production costs released by NREL in 2008 and 2009 were predicated on commercial-scale production being achieved. A large body of techno-economic literature in subsequent years identified similar production costs across a variety of biochemical[27] and thermochemical[28] pathways for the production of cellulosic biofuels. In most of these cases, however, the analyses assumed that the production costs were for *n*th-plant facilities at which past learning and scale-up allowed for maximum efficiencies and productivities to be achieved. Techno-economic analyses of first-of-their-kind, or pioneer, facilities are rare, but they calculate production costs for pioneer facilities that are approximately 100% higher than those for *n*th plants employing the same cellulosic biofuel pathways.[29] With many *n*th-plant facilities being calculated to have production costs of $1–$2/gallon of gasoline equivalent (GE),[27,28] pioneer facilities faced a very disadvantageous operating environment when the wholesale gasoline price averaged $1.62/gallon between January 2015 and December 2017.[21]

In theory the lack of a cost-competitive fuels market since late 2014 should not have been enough on its own to explain the lack of liquid cellulosic biofuel production to date. The RFS2's blending mandate is supported by tradable compliance commodities known as renewable identification numbers (RIN). Each RIN is created when a corresponding gallon of qualifying biofuel is produced (one RIN is equal to one gallon of ethanol on an energy basis, with cellulosic gasoline and cellulosic diesel receiving 1.5 RIN/gallon and 1.7 RIN/gallon, respectively). The RIN is separated from its gallon when the fuel is blended with a

  | *Biofuels, Bioprod. Bioref.* **13**:889–898 (2019); DOI: 10.1002/bbb

refined fuel for final consumption. The separated RIN can then either be submitted to the EPA to demonstrate partial compliance with the mandate, if held by an obligated blender, or sold to a third party. Each category of biofuel qualifies for a different type of RIN, with cellulosic biofuels qualifying for the highest value D3 (cellulosic ethanol and RNG) and D7 (cellulosic heating oil and cellulosic diesel) RINs.[4] The market value of each RIN category is expected to operate as a function of that biofuel category's supply relative to the demand set by the mandate, thereby ensuring that biofuel producers have a sufficient financial incentive to achieve the production volume necessary for the blending mandate to be achieved.

In practice RIN prices have been stated, at various times, to operate, instead, as a function of market manipulation,[30,31] headline volatility,[32] petroleum industry opposition,[33] and political and regulatory uncertainty.[34] The last 6 years have seen RIN prices exhibit a very large amount of volatility, which has exacerbated the challenging operating outlook that cellulosic biofuel producers have faced over that period. The next section considers how this policy uncertainty has factored into a lack of liquid cellulosic biofuel production to date.

Policy uncertainty

An initial shortcoming of the RIN system was that RIN trading was a prerequisite to determining RIN value. This was not an issue for most of the RIN categories (D4 – biomass-based diesel, D5 – advanced biofuel, and D6 – renewable fuel) due to the large volumes of corresponding biofuels that were already being produced when the mandate went into effect. A complete lack of cellulosic biofuel production under the mandate in 2010 and 2011, on the other hand, meant that would-be producers had no way of knowing the value of D3 (cellulosic biofuel) and D7 (cellulosic diesel) RINs, complicating their efforts to demonstrate the financial feasibility of their chosen pathway when attempting to finance their pioneer facilities. Cellulosic biofuel producers instead frequently used the combination of D5 (mostly in the form of cane ethanol) RIN prices and cellulosic waiver credit (CWC) values as a surrogate for the then-unknown D3 RIN values.

The CWCs resulted from the inability of cellulosic biofuel producers to provide obligated blenders with the volumes needed to meet even the EPA's revised cellulosic biofuel blending requirements, which prompted the EPA to sell them to the obligated blenders so as to cap their expenditures. Under the scheme, obligated blenders were allowed to submit one D5 RIN and one CWC in place of each required D3 or D7 RIN.[35] The value of a CWC was set to be the greater of either $0.25 or $3 minus the wholesale price of a gallon of gasoline. For example, if the wholesale gasoline price is $2/gallon then the CWC value is $1 ($3 minus the $2/gallon gasoline price) but if the wholesale gasoline price is $3/gallon then the CWC value is $0.25 ($0.25 being greater than $3 minus the $3/gallon gasoline price). In this way the CWC value moves inversely to the price of gasoline so that the D3 surrogate value increases when the cellulosic biofuel becomes less valuable, and vice versa. This methodology effectively caps the cellulosic biofuel premium and resulted in CWC values of $0.42 and $0.49 for 2013 and 2014,[36] respectively, despite the fact that the majority of the D5 RINs generated in those years were derived from imported cane ethanol,[4] which is a widely commercialized and comparatively inexpensive fuel. Furthermore, until 2015 the EPA would sometimes publish the official CWC values well after the period that they covered had ended; the 2014 value was not published until March 2015, for example.[36]

In 2013 a new form of policy uncertainty was introduced into the cellulosic biofuel market due to the arrival of the ethanol 'blend wall' and subsequent period of RIN price volatility, which became known as 'RINsanity' in the press. In 2013, for the first time, the RFS2 required a volume of biofuel, primarily in the form of ethanol, to be blended that exceeded 10 vol% of US gasoline consumption.[37] RIN prices responded by moving sharply higher in response, resulting in a 2800% increase in the daily D6 RIN price between January and July 2013.[38] D5 and D6 RIN prices converged in March 2013 and remained closely correlated until late 2016 (see Fig. 5). D5 and D6 RINs together comprised 84% of the total RINs generated in 2013[4] and the rapid price increase caused the expenditures of RIN purchasers to exceed expectations quickly as a result.

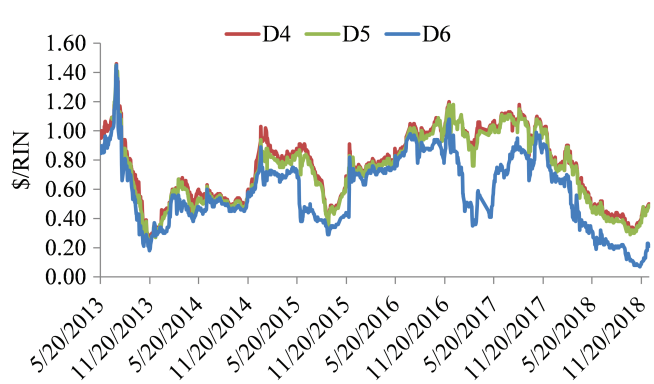

Figure 5. Historical D4, D5, and D6 RIN prices since May 2013.[38]

Infrastructure constraints mean that most of the ethanol that is consumed under the RFS2 is blended at either the wholesale rack or the retail station, as US-refined product pipelines do not allow access to ethanol due to that biofuel's hydrophilic nature. The mandate itself, however, imposes the obligation to blend biofuels with refined products in fulfillment of the mandate on refiners (the so-called 'obligated parties'). While integrated petroleum companies often own sufficient wholesale and retail capacity to generate enough RINs to meet their shares of the mandate internally, 2011 and 2012 saw many smaller independent, or 'merchant' refiners spin their wholesale and retail operations off as 'logistics' master limited partnerships (MLP) in which they retained only partial ownership stakes.[39] Lacking direct ownership of sufficient blending capacity to meet their blending obligations under the mandate, these merchant refiners made up their RIN deficits by acquiring RINs from other entities. While their RIN expenditures were limited prior to 2013 when D6 RINs, which made up the vast majority of the blending obligations, traded for as little as $0.02, the merchant refiners' RIN costs quickly began to rise as D6 RIN prices increased in early 2013.

The result was a widespread lobbying campaign directed at the EPA by merchant refiners in particular.[32,40] In August 2013 the EPA responded by announcing that it would take steps to ensure that the mandated blending volume did not exceed 10 vol% of domestic gasoline demand.[32] By November 2013, when the EPA released a formal proposal to implement its August announcement, the daily D5 RIN price had fallen from its July high of $1.45 to $0.21, a decline of 86% in less than 5 months.[38] It remained well below its 2013 levels throughout 2014 even as the EPA refrained from adopting its November proposal. Prices began to rebound at the end of 2014 as fuel prices collapsed, however. D5 RIN prices continued to climb in 2016 as the RFS2 became a topic in that year's US presidential election, eventually peaking at $1.18 on a daily basis in early December 2016.[38]

The Trump administration introduced a new form of policy uncertainty when it named activist investor and refiner owner Carl Icahn as a special adviser to the White House on regulatory reform.[41] Mr Icahn had been a vocal critic of high RIN prices during the presidential election campaign,[42,43] and as a White House adviser he advocated for a proposal to have the RFS2's 'point of obligation' changed from refineries to the point of biofuel blending to reduce merchant refiners' blending obligations and RIN expenditures.[31] While the proposal was never actually adopted by the EPA, D5 RIN prices fell by 36% in the months following Mr Icahn's appointment amid frequent reports in the financial media about his efforts to change the point of obligation.[44]

The daily D5 RIN price returned to a high of $1.15 in August 2017 following Mr Icahn's resignation as White House adviser in the aftermath of a critical profile in *The New Yorker*[31] and allegations of ethics violations by members of Congress,[45] which prompted an investigation by federal prosecutors later that year.[46] A final source of D5 RIN price volatility commenced in early 2018 after then-EPA administrator Scott Pruitt, who had been vetted by Mr Icahn when interviewing for the EPA position,[47] announced the widespread allocation of small refinery exemptions (SREs), better known as 'hardship waivers' in the financial media, to refiners. The SREs release the recipient refiners from submitting the full volume of RINs that they were normally obligated to submit under the mandate. The number of RINs covered by the SREs awarded per year increased by 84% between 2016 and 2017 (see Fig. 6) even as US refining margins increased by 41% (West Texas Intermediate, or crude produced in the Permian basin) and 31% (Bakken, or crude produced in the Dakotan Bakken shale formation) over the same period.[49] The EPA took the additional step of not reallocating the exempted RINs, effectively reducing RIN demand under the conventional mandate even as supply remained unchanged.[50] This put renewed pressure on D5 RIN prices, causing them to decline by 68% in the 12 months following Mr Icahn's resignation.[38] D3 RIN prices, which became publicly available on a daily basis only in May 2017, fell by 26% over the same period, and by December 2018 this decline had increased to 37%.[38]

The increased policy uncertainty and consequent RIN price volatility that has characterized the last 5 years has

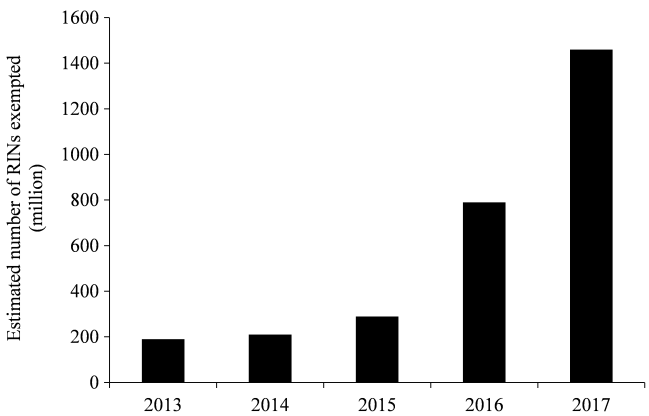

Figure 6. Number of SREs (RIN basis) allocated by the EPA per year.[48]

  | *Biofuels, Bioprod. Bioref.* **13**:889–898 (2019); DOI: 10.1002/bbb

been an important contributing factor to the underwhelming investment in liquid cellulosic biofuel production capacity to date. The pathways that were undergoing commercialization earlier in the decade were not going to be competitive with gasoline without the additional financial support that was supposed to have been provided by the blending mandate. A recent stochastic techno-economic analysis of four different *n*th-plant cellulosic biofuel pathways found that all had low probabilities of achieving positive net present values (NPVs) under most policy scenarios (see Table 2).[51] The sole exception was a policy scenario in which the pathways generated RINs, in which case all four had greater-than-even probabilities of achieving positive NPVs. Notably, however, the analysis further found that pioneer facilities employing the cellulosic biofuel pathways had low probabilities of achieving positive NPVs even with RINs valued according to historical RIN prices (D5 RINs plus CWCs).

Even RIN price volatility on its own, as distinct from lower average RIN prices, has likely harmed the commercialization prospects of liquid cellulosic biofuel pathways.[52] Statistical analyses of corporate datasets have determined that cash-flow volatility is positively correlated with a firm's financing costs.[53,54] Furthermore, firms with high levels of cash-flow volatility have lower levels of capital expenditure and R&D spending.[54] An important consequence of high levels of cash-flow volatility (actual or expected) is a reduced ability to expand production and, in the case of the pioneer liquid cellulosic biofuel facilities that were being planned in 2013, to achieve lower production costs and increased competitiveness with fossil fuels via learning and improved economies of scale. The RIN price volatility of recent years has been especially impactful because RINs were intended to act as a hedge against fuel price volatility for cellulosic biofuel producers by providing financial support when production margins were low but without resulting in the windfall profits that corn ethanol producers gained from the now-defunct volumetric ethanol excise tax credit (VEETC), when production margins were high. (The VEETC was a fixed refundable income tax credit of up to $0.54 – the specific amount varied over time in response to Congressional actions – per gallon of qualifying ethanol that was awarded even when corn ethanol margins were high.)[55] Instead RIN prices have compounded cellulosic biofuel producers' uncertainty by adding policy uncertainty to an operating environment that is already characterized by substantial fuel-price uncertainty.

Discussion

An important lesson from the experience with renewable energy commercialization of the last decade is that 'market-stimulating' government policy provides a critical role in determining whether a pioneer technology that has been successfully demonstrated at smaller volumes is successful at the commercial scale.[56] Such policies are needed to make first-of-their-kind technologies initially cost-competitive so as to permit the capacity buildouts that ultimately result in economies of scale and learning. Unlike solar photovoltaic, wind, and even corn ethanol, all three of which have experienced rapid buildouts of commercial-scale production capacity in the current century with the support of mandates and financial subsidies, liquid cellulosic biofuel pathways have not been the beneficiaries of policies creating cost-competitive production environments for pioneer facilities.[51]

This result is in part a consequence of adverse market dynamics in the form of fuel price volatility, which caused the wholesale price of gasoline to fall to a decade low in real terms, prompting cellulosic biofuel companies to turn to inexpensive fossil feedstock or cancel commercialization plans altogether. It is unsurprising that the cellulosic biofuels industry has been unable to achieve commercial-scale production volumes, let alone meet the RFS2's original blending targets, given the operating conditions that have prevailed. Adverse market conditions alone should not have been sufficient to prevent cellulosic biofuel commercialization given that the primary policy in support of liquid cellulosic biofuel production, the RFS2, was

Table 2. Median NPVs of *n*th and pioneer cellulosic biofuel facilities under different policy scenarios.

Pathway	*N*th-plant median NPV ($MM) with no policies	*N*th-plant median NPV ($MM) with current policies	Pioneer plant median NPV ($MM) with current policies
High-temp gasification and F-T synthesis	–1011	95	–492
Isobutanol via enzymatic hydrolysis	–930	8	—
Fast pyrolysis and hydroprocessing	–531	861	9
Ethanol via enzymatic hydrolysis	–871	35	–422

Source: Data from Brown (2018).[51]

designed by Congress to insulate producers from the negative impacts of price volatility. Instead, however, because of policymakers' attempt to eliminate the windfall profits that biofuel producers had earned under earlier policies such as the VEETC by utilizing an incentive with a flexible value mechanism that has proven to be susceptible to political intervention, the mandate has increased rather than mitigated market price uncertainty for would-be producers. Replacing that flexibility by using a long-term fixed subsidy mechanism such as the VEETC provided to corn ethanol producers would minimize this susceptibility. Concerns about the potential for windfall profit generation as production costs declined could be mitigated by implementing a gradual sunset provision such as that used with the latest iteration of the solar investment tax credit.

Conclusion

The buildout of cellulosic biofuel capacity has fallen well short of the volumes that were expected as recently as 2013, let alone those needed to achieve the RFS2's statutory blending volumes. This article argues that this lack of capacity was the result of a disadvantageous financial operating environment that was exacerbated by a policy environment that increased rather than decreased uncertainty for liquid cellulosic biofuel producers. RINs were implemented as part of the mandate to insulate cellulosic biofuel producers from the types of fuel price volatility that occurred in 2009–2010 and again in 2014–2017. An uneven implementation and strong opposition to the mandate from obligated blenders resulted in policy uncertainty that, in turn, created RIN price volatility. The combination of high levels of fuel and RIN price uncertainty created a production environment in which pioneer facilities were unlikely to be profitable and therefore also unlikely to obtain the financing needed to progress to increasingly cost-competitive *n*th-plant facilities. Techno-economic analyses of liquid cellulosic biofuel pathways broadly find that the resulting biofuels that qualify for RINs are cost-competitive with refined fuels when produced by *n*th-plant facilities. The same biofuel pathways are not competitive even with RINs when produced by pioneer facilities, however, illustrating the negative impacts that RIN price volatility and attempts to minimize RIN prices have had on the ability of cellulosic biofuel producers to supply the volumes required by the RFS2.

An important lesson from the cellulosic biofuels commercialization experience is that government policy can inadvertently hinder rather than support its desired outcome when it has been designed in a way that does not mitigate the price uncertainty that is inherent in the transportation fuels market. This is not the only lesson, however, given that cellulosic biofuels were required by the RFS2 to scale up rapidly despite its level of technological readiness when the cellulosic biofuels mandate was implemented in 2010. Further research is needed to understand how technological readiness affects and is affected by the market and policy conditions described in this article.

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