A stochastic techno-economic analysis of aviation biofuel production from pennycress seed oil

By

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Abstract

We conduct a stochastic techno-economic analysis of a plant that uses catalytic hydrothermolysis (CH) technology to produce drop-in aviation biofuels from pennycress seed oil. Since pennycress seed oil can be grown over winter in the US Midwest on land that would normally lie fallow, these fuels would avoid induced land use change (ILUC) CO_2 emissions. We incorporate a theory of Renewable Identification Number (RIN) pricing that allows for D4 and D5 RINs to be forecasted endogenously, based on the forecasted prices of soybean oil and low-sulfur fossil diesel fuel. Our output metrics include measures of net present value (NPV) and probability of loss (POL), along with breakeven prices (BEPs) for crude oil (used as an index for the prices of liquid fuel products) and pennycress oil. We find our pennycress oil BEPs from two perspectives. First, we conduct a TEA of a pennycress seed processing facility to estimate how low a pennycress oil price they could accept. Second, we use our core biofuels plant TEA model to determine the highest price that they could offer for pennycress oil as an input. By comparing these two BEPs, we are able to examine how much room for profitable negotiation of the pennycress oil price might exist in a full pennycress-to-biofuels value chain, were such a thing to exist. Our results indicate that aviation biofuels production at a greenfield CH plant fed by pennycress seed oil is not economic under current market and policy conditions, but that this could change if one of the following were to occur:

- A crude oil price increase of at least 31-52%
- A jet fuel price increase of at least 11-26%
- A pennycress oil price discount of 2-6% from soybean oil prices
- Some combination of the above

These findings are heavily influenced by current policy design.

Keywords: Sustainable Aviation Fuels, stochastic techno-economic analysis, catalytic hydrothermolysis, pennycress

Introduction

The air transport sector currently accounts for around 2% of global emissions of greenhouse gases (GHGs), and that figure could grow to up to 3% by 2050 in the absence of an effective mitigation effort (Boeing, 2017; and EPA, 2016). Due to the technical requirements of commercial flight, the use of alternative liquid fuels that conform to aviation's stringent fuel quality standards will be a necessary element of any such effort (Lüdeke-Freund et al., 2012; and Sgouridis, Bonnefoy, and Hansman, 2011). These quality standards restrict the use of "run-of-the-mill" biofuels, such as widely available fatty acid methyl ester products, and increases the pressure to find high-quality alternatives, especially so-called "drop-in" fuels, which are one-to-one functional substitutes for existing fossil fuels approved for blending at up to 100% of final product volume (Mawhood et al., 2016). Government and industry organizations such as the United States Federal Aviation Administration and the International Civil Aviation Organization are actively encouraging the development of such alternatives (FAA, 2012; ICAO, 2017a; ICAO, 2017b; ICAO, 2017c; ICAO, 2017d; and ICAO, 2017e).

The problem is that the alternative aviation fuels which have been developed so far are not economically viable without policy supports and are underwhelming in regards to their environmental sustainability. The objective of this research is to investigate a biofuels pathway that may perform better economically and environmentally than those which have thus far been developed. This paper will pursue this objective by conducting a TEA of a CH pathway fed by field pennycress under a number of possible scenarios.

Though life cycle emissions reductions from hydrotreated fuels made from vegetable oils are often estimated at around 50% compared to traditional petroleum-based fuels (Han et al., 2013), there are still important concerns about their overall sustainability. Two important such concerns are competition with food production and the environmental impacts of induced land use change (ILUC) (Lüdeke-Freund et al., 2012; Stratton, Wong, and Hileman, 2011; and Hileman and Stratton, 2014). Field pennycress (*Thlaspi arvense*) is a not-yet-commercialized oilseed crop that has been the subject of recent interest for use as a biofuel feedstock. This is due to its high yields with low inputs and the possibility of growing it on land that would ordinarily be left fallow as a "cash cover crop". These qualities would likely reduce its land use change impacts and competition with food production to a minimum (Lüdeke-Freund et al., 2012; Stratton, Wong, and Hileman, 2011; Fan et al., 2013; Phippen and Phippen, 2012; Sindelar et al., 2017; and Carvalho Carli and Phippen, 2015).

The economic environment surrounding biofuels is incredibly complex, and is decisively shaped by the design of numerous government policies designed to promote their production and use. In the United States alone, these include the United States Renewable Fuel Standard (RFS), California Low-Carbon Fuel Standard (LCFS), and Biodiesel Blender Tax Credit (BTC). The complexities of these policies, their interactions, and their links to other markets place difficult demands upon techno-economic analyses (TEAs) of biofuels production, such as this one. Our guiding principle in analyzing this complex economic environment is to seek to model each of these policies' impacts in ways that are realistic and in harmony with our other assumptions and modeling choices.

Commercial production of biofuels from triglyceride feedstocks such as vegetable oils is currently dominated by the hydroprocessed esters and fatty acids (HEFA) conversion technology

(Mawhood et al., 2016). Catalytic hydrothermolysis (CH) is a relatively new triglyceride-to-biofuel process that was jointly developed by Applied Research Associates, Incorporated (ARA) and Chevron Lummus Global (Mawhood et al., 2016; and ARA, 2015). A simplified diagram of the process can be found in figure 1 below. Though the literature strongly suggests that neither process is financially viable without policy supports (McGarvey and Tyner, 2018; Pearlson, Wollersheim, and Hileman, 2013; Chu et al., 2017; Wang, 2016; Bann et al., 2017; de Jong et al., 2015; and Liu, Yan, and Chen, 2013), CH boasts of technical advantages that may make it more economic than HEFA (Li et al., 2010; and Li, 2010). There are currently no stochastic TEAs examining CH's application in a pennycress-to-renewable jet fuel pathway, but one recent paper by Elspeth McGarvey and Dr. Wallace Tyner (2018) does examine the closely-related case of CH conversion of *Brassica carinata* oil into aviation biofuel (McGarvey and Tyner, 2018). Our work differs from theirs by making explicit connections to a modeled supply chain for our novel oilseed feedstock and taking a more sophisticated approach to modeling the values of credits generated under policies such as the RFS.

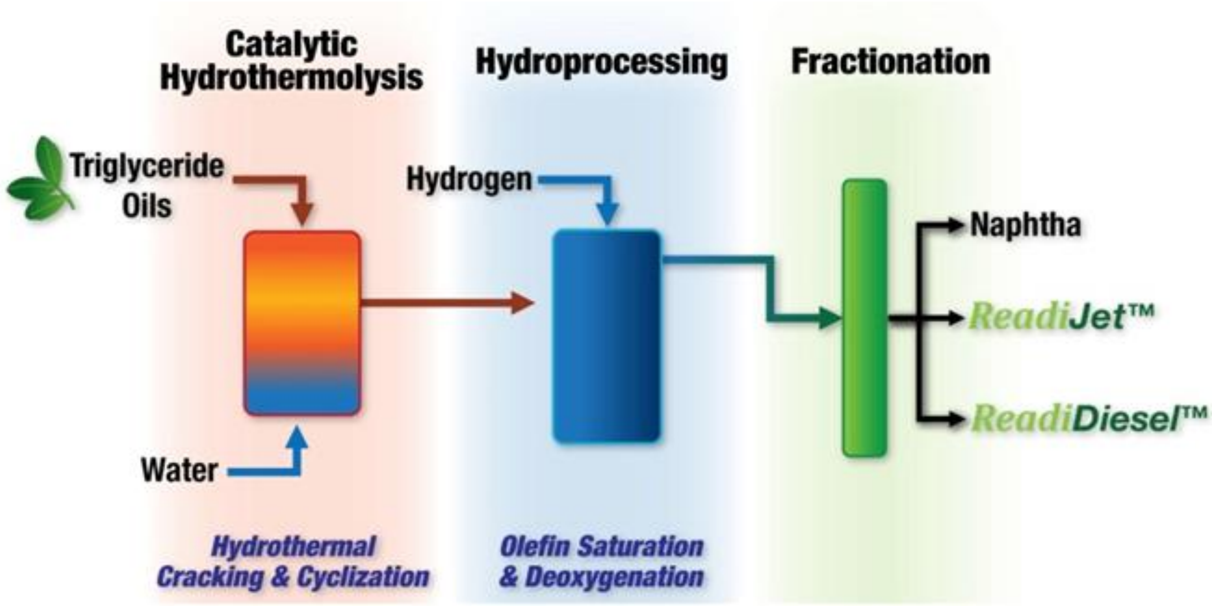

Figure 1: A diagram of the CH process as presented in an ASTM research report, from Coppola, 2019

Data and Methods

Most data for this paper were obtained from the United States Department of Agriculture (USDA), the United Stated Department of Energy's Energy Information Administration (EIA), or from Applied Research Associates, Inc. (ARA). USDA data were used for the prices of key agricultural commodities, namely soybean oil (used as a proxy for the potential market valuation of pennycress oil) and dried distiller's grains with solubles (DDGS), which served as a proxy for the potential market valuation of pennycress seed meal. Prices of energy commodities, including industrial electricity, natural gas, crude oil, and the liquid petroleum transport fuels, were obtained from publicly available EIA data. Estimates of the inputs, outputs, and equipment costs of the modeled CH-based biofuels plant were obtained from ARA engineers. For our analysis of pennycress seed processors' breakeven price of pennycress oil, we are indebted to the cooperation and published works of a research group at the University of Tennessee led by Dr. Burton English (Markel et al., 2018; and Trejo-Pech et al., 2019).

Financial Model

We conduct a stochastic discounted cash flow TEA of a plant designed to use CH technology to produce renewable diesel fuel, renewable jet fuel, and renewable naphtha from pennycress seed oil on a "greenfield" site. We combine process parameters such as conversion efficiencies, heat and water requirements, and capital costs for our model plant with stochastic projections of key input and output prices in order to model the distribution of possible financial outcomes for the plant. Our work follows McGarvey and Tyner (2018) in many respects, notably in borrowing their learning curve methodology for estimating cost reductions associated with the "nth" plant. This work goes beyond theirs by connecting with economic analyses of the potential pennycress oil supply chain and includes novel approaches to modeling key policies (RFS, LCFS, and BTC)

(McGarvey and Tyner, 2018). We assume that construction of the plant begins in 2017 and takes place over three years, and that production begins in the final year of construction (2019) at 50% of total annual capacity. The investment life then continues for twenty years of full output. We assume a 75:25 debt-to-equity ratio, and that the debt portion is financed over ten years at an 8% annual nominal interest rate. Depreciation of the initial capital investment takes place over ten years by 200% double declining balance depreciation with a switch to straight line. Working capital is calculated as 40% of the difference in operating costs between the current year and the next year. We assume 2% annual inflation over the course of the project, and a 10% real discount rate. All of these assumptions were also used for our analysis of a pennycress seed crusher's breakeven output price for pennycress oil, except that construction was assumed to take only three years, and thus the crushing facility investment was evaluated over twenty-one years of full output. Our output metrics include distributions of Net Present Values (NPVs), Probabilities of Loss (POLs), and distributions of Breakeven Prices (BEPs) for key inputs and outputs.

Technical Uncertainty

We modeled a facility with a 5000 barrel-per-day pennycress oil input capacity that produces three fuel products: renewable diesel, renewable jet fuel, and renewable naphtha. Following guidance from ARA engineers, total volumetric fuel yield was held constant at 92%, and renewable naphtha yield at 23%. The volumetric yield of renewable jet fuel was modeled by a Pert distribution with a minimum of 30%, a mode of 33%, and a maximum of 36%. The balance of the total fuel yield was assigned to renewable diesel, and the resulting product slate breakdown was held constant through the entire lifetime of the plant. Other technical parameters, such as the natural gas, electricity, and water requirements, were modeled deterministically based on ARA's input.

Key Price Series

The largest source of uncertainty in our model was not from the economic side, rather than the technical side. Realistically modeling the stochastic behavior of key price series proved to be a demanding task. The financial viability of the production system we modeled relies heavily on the relative prices paid and received for pennycress oil (the biofuels plant's primary input), pennycress meal (a key output for pennycress seed processors), and liquid transportation fuels, for which the biofuels plant's products are "drop-in" substitutes. We used the wholesale price of US low-sulfur diesel fuel as the basis for modeling the prices of fossil jet fuel and gasoline (which we took as being the best estimate of the price of naphtha, which is gasoline blendstock). Our predictions for the price of diesel fuel thus drive our predictions of jet and gasoline prices. We chose diesel fuel as our focus because of the role its price appears to play in determining D4 and D5 RINs prices, as we detail later in this paper.

Pennycress oil and meal are not yet commercialized commodities, and so there are no price data available for them. We therefore use the prices of other agricultural commodities as proxies. Since soybean oil is a functional substitute for pennycress oil in the biofuels input market, we use the price of soybean oil as a proxy for our pennycress oil price, following McGarvey and Tyner, 2018, in their treatment of carinata oil. Conducting breakeven analysis on the price of pennycress oil in both the upstream and downstream directions allowed us to assess the sensitivity of our results to this assumption in a meaningful, orderly manner, as we will detail later.

Relying on what is known of the nutritional value of pennycress meal as an animal feed (Alhotan et al., 2017; and Tretsven and Nelson, 1946), we used a feed ration cost minimization model to estimate the marginal value of pennycress meal to livestock farmers, given the prices of other important feed commodities such as corn, soybean meal, and DDGS, following a similar methodology as was used by Hubbs et al., 2009. Our results indicated DDGS as a reasonable proxy, which is unsurprising given their similar crude protein percentages (Alhotan et al., 2017; (Hojilla-Evangelista et al., 2013; and Heuzé et al., 2015). The full details of this work are beyond the scope of this paper, but are available from the authors upon request.

Price Series Projection

These three price series tend to be highly correlated to each other and highly serially correlated to themselves over time, which makes modeling their behavior accurately a tricky matter. The details of our approach to this issue are too involved to be presented in this paper, but are available upon request from the authors. The core of our method shares some similarities with autoregressive moving average models and relies on a hand-tuned correlation matrix in @Risk to enforce historically realistic degrees of inter-series correlation over time. The key innovation to our approach is that we apply upper and lower bounds on our price forecasts inside of the model's core stochastic structure, rather than over the top of it. This approach allows us to closely mimic the correlative behaviors of historical prices, avoid both "runaway" price projections and unrealistic "piles" of observations at the bounds, and tune our projected price levels to match experts' expectations of future prices, as embodied in the EIA's long-range fossil fuel price forecasts.

The Market for D4 RINs

This study relies on a theory of D4 RIN pricing used by several close observers of the US RIN market, perhaps most notably by Scott Irwin and Darryl Good of the University of Illinois at Urbana-Champaign in a series of *farmdoc daily* articles appearing from 2013 to 2017. To our knowledge, this theory has yet to be relied upon for RIN price modeling in a published biofuels TEA, but it appears fundamentally sound, and the results Irwin and Good have obtained using it are striking. We reproduce graphics from their articles again here for reference. The theory states that since transesterified soybean oil biodiesel is responsible for the majority of D4 RIN generation (EPA, 2017; Irwin, 2013a; and EIA, 2019a), that biodiesel represents the “marginal gallon” for that section of the RFS mandates. Therefore, the market value of the D4 RIN is determined by the difference between the cost of producing biodiesel and biodiesel’s value to fuel blenders in the absence of the RFS. Since relatively small volumes of biodiesel are blended with fossil diesel to be sold to the end user, the functional differences between the two products are insignificant. To blenders, biodiesel is just a substitute for fossil diesel fuel, and so the market price of fossil diesel fuel would determine its value in the absence of the RFS. The RFS aims to bridge the value gap created by the fact that a gallon of biodiesel is more expensive to produce than a gallon of fossil diesel, and the mechanism that closes that gap is the D4 RIN. The D4 RIN price is then followed closely by the D5 RIN, since both are used to fulfill the “advanced biofuels” section of the RFS volume mandates (EPA, 2017).

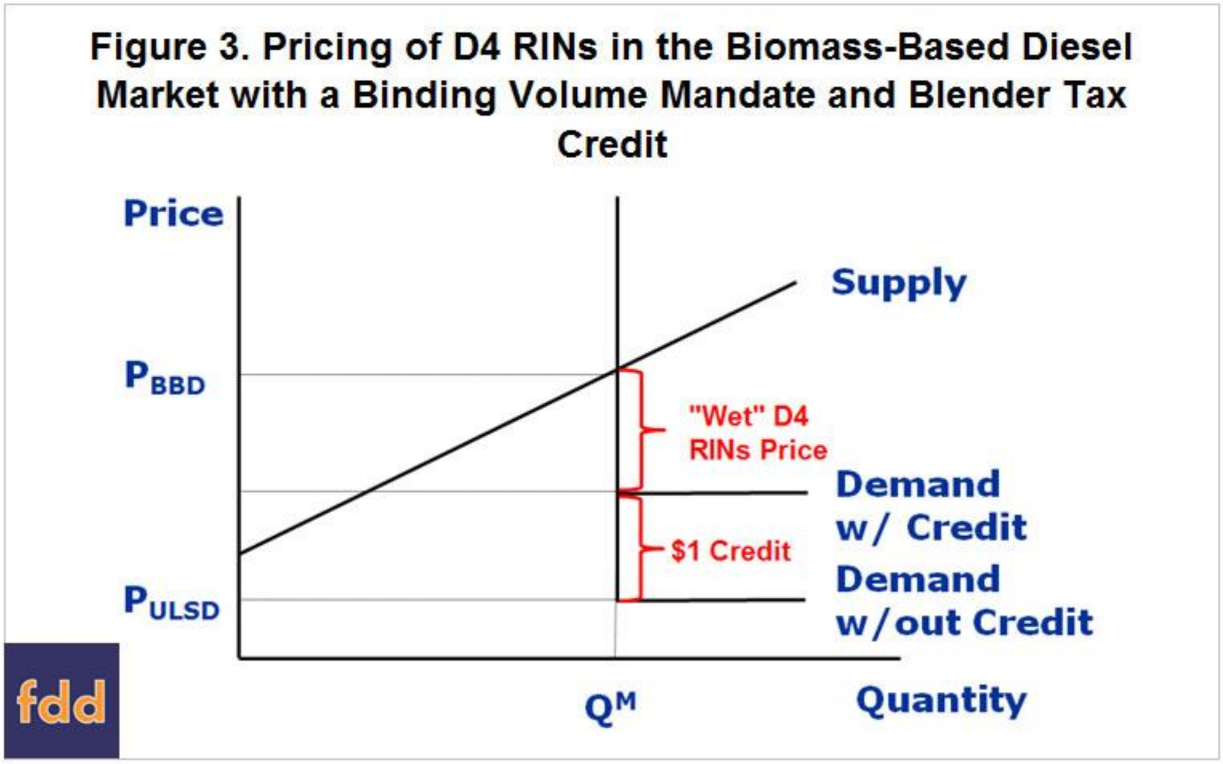

Figure 2: A theoretical model of wet D4 RINs pricing with a Blender Tax Credit, from Irwin, S. and Good, D., 2017

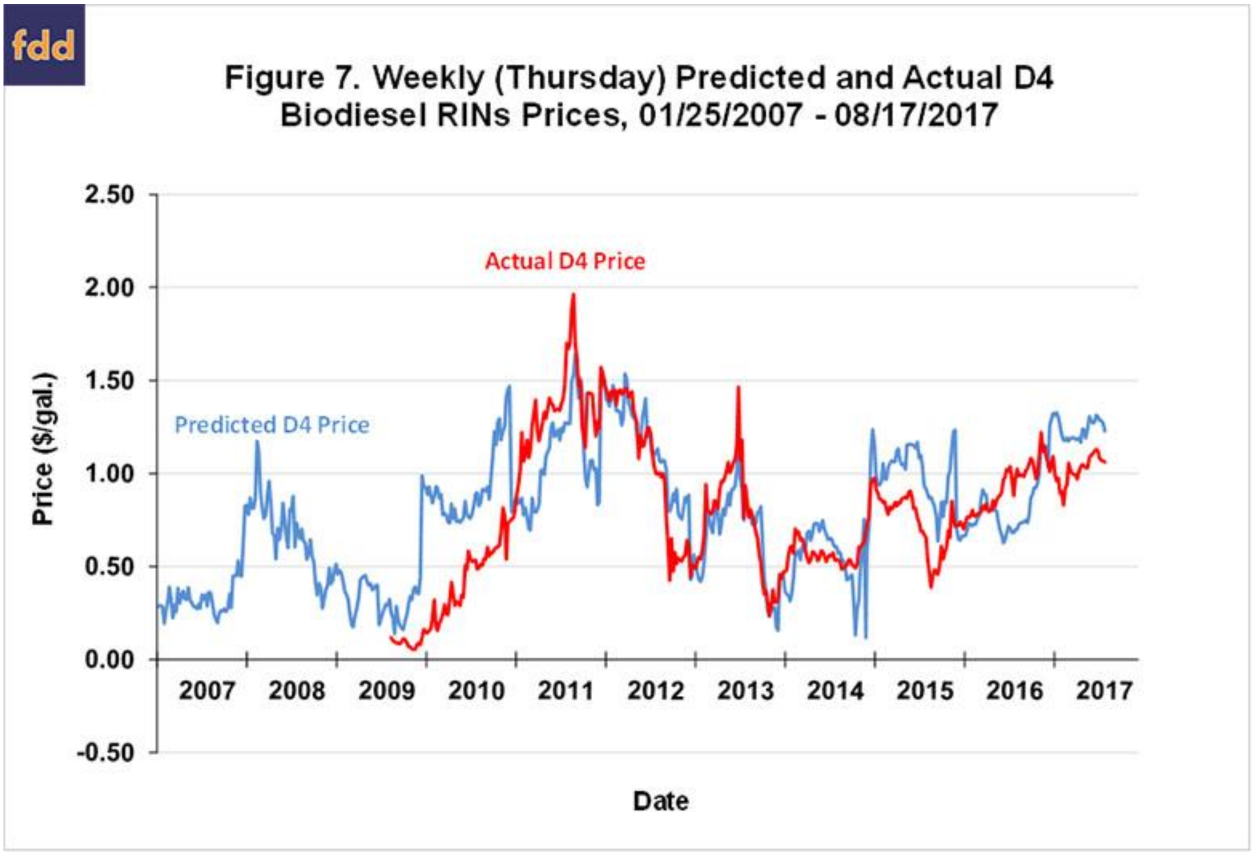

Figure 3: An example of the performance of the theoretical model, from Irwin, S. and Good, D., 2017

In relying on this theory, we assume that the RFS will continue in its current form for the next twenty to thirty years, that the market for D4 and D5 RINs is competitive, and that the demand in that market is perfectly inelastic at the level determined by the policy's mandate. Thus, we assume close-to-unit pass-through of D4 and D5 RINs values to producers at the time of sale, and that the values of those RINs credits are determined by the marginal production cost for RINs in that "bucket" of the RFS mandates. In order to model the marginal costs of US biodiesel production into the future, we assume that the level of the RFS mandates stay in roughly constant proportion to the US biodiesel production capacity, such that per-unit fixed costs stay constant. Thus, we rely on a Biodiesel Profitability Model developed by researchers at Iowa State University

(Hofstrand, 2018) to model the costs of production of US biodiesel based on the cost of its primary input (soybean oil). We then model the price of D4 RINs in each period based on the "blend gap" between the cost of producing biodiesel in that period and the wholesale price of diesel fuel in that period (Irwin, 2014; Irwin, 2013b; Irwin and Good, 2017a; and Irwin and Good, 2017b), and use linear regression to estimate the price of D5 RINs from the D4 RINs price.

Modeling the BTC

Our RINs price modeling is complicated slightly by the biodiesel BTC, which is thought to reduce the value of RINs relative to the biodiesel blend gap in years in which it is in effect ex-ante (Irwin, 2017; Irwin and Good, 2017a; and Irwing and Good, 2017b). The BTC is a US policy that grants a nominal $1.00 per gallon tax credit to blenders of transportation fuels for every gallon of biodiesel or renewable diesel that they blend into their final product. This policy is generally put into effect one year at a time, and must be either renewed or allowed to expire each calendar year. It has often been reinstated retroactively for years in which it was previously allowed to expire. In years in which it is reinstated retroactively, value from the BTC is thought to be shared roughly evenly between producers and blenders without affecting RINs prices (Irwin, 2017; Irwin and Good, 2017a; and Irwing and Good, 2017b). We model the BTC as an annual, random binary variable which takes value "1" if the BTC is in effect ex-ante, and value "0" if it is not. If the BTC is not in place ex-ante, a secondary binary random variable defining the probability of its being reinstated retroactively then takes effect. Both of these variables are set to zero in all years in the scenarios that assume that the BTC is discontinued.

The Endogenous RINs Pricing Model

Due to the short history of the Renewable Fuel Standard, and thus of RINs price data, we conduct our RIN prediction regressions twice: once in the monthly data, relying on larger sample size to give us a reliable indication of whether a statistically significant relationship exists, and once in the annual data for implementation in our TEA model, which is based on yearly discounted cash flows. Tables 1 through 7 below present these regression results, and figures 4 and 5 illustrate our model's performance in "predicting" past D4 and D5 RINs prices. The prices of LCFS credits are modeled using the same method used for soybean oil, DDGS, and diesel fuel prices, with a price cap set to $200 per MT (2016 USD), per the current LCFS statute (ARB, 2018).

Table 1: Robust OLS of monthly real biodiesel breakeven price on monthly real soybean oil price

	Biodiesel breakeven price, 2017 $/gal
Soybean oil price, 2017 $/gal	0.997*** (0.00421)
Constant	0.667*** (0.0151)
Observations	96
R-squared	0.997

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 2: Robust OLS of monthly nominal wet D4 RIN prices on monthly predicted nominal blend gaps if the BTC is NOT in place ex-ante

	Wet D4 RIN price, $/gal
Blend gap, $/gal	0.931*** (0.0901)
Constant	0.151* (0.0876)
Observations	60
R-squared	0.643

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 3: Robust OLS of monthly nominal wet D4 RIN prices on monthly predicted nominal blend gaps if the BTC IS in place ex-ante

	Wet D4 RIN price, $/gal
Blend gap, $/gal	0.660***
	(0.184)
Constant	0.486*
	(0.264)
Observations	36
R-squared	0.280

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 4: Robust OLS of monthly real wet D5 RIN price on monthly real wet D4 RIN price

	Wet D5 RIN, 2017 $/gal renewable naphtha
Wet D4 RIN, 2017 $/gal renewable biomass-based diesel	1.01***
	(0.0205)
Constant	-0.0888***
	(0.0213)
Observations	72
R-squared	0.965

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 5: OLS of annual nominal wet D4 RIN prices on annual predicted nominal blend gaps if the BTC is NOT in place ex-ante

	Wet D4 RIN price, $/gal
Blend gap, $/gal	0.939**
	(0.235)
Constant	0.142
	(0.273)
Observations	5
R-squared	0.842

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 6: OLS of annual nominal wet D4 RIN prices on annual predicted nominal blend gaps if the BTC IS in place ex-ante

	Wet D4 RIN price, $/gal
Blend gap, $/gal	0.885
	(0.723)
Constant	0.150
	(1.10)
Observations	3
R-squared	0.599

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 7: OLS of annual real wet D5 RIN price on annual real wet D4 RIN price

	Wet D5 RIN, 2017 $/gal renewable naphtha
Wet D4 RIN, 2017 $/gal renewable biomass-based diesel	1.06***
	(0.0920)
Constant	-0.146
	(0.108)
Observations	6
R-squared	0.971

Standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

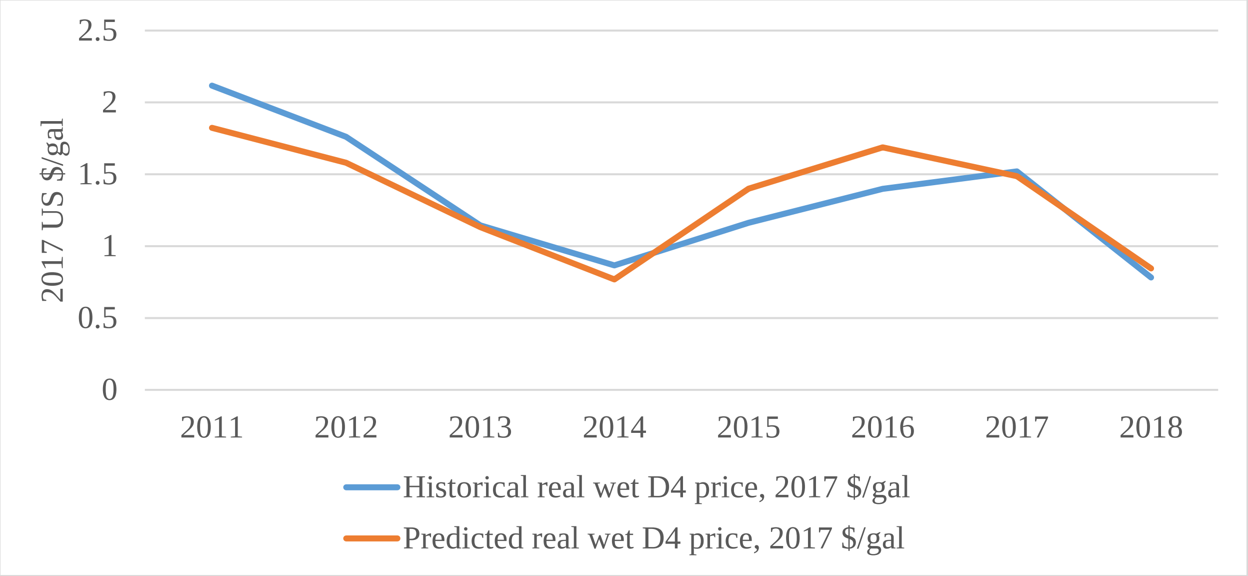

Figure 4: Historical vs predicted real wet D4 RIN prices

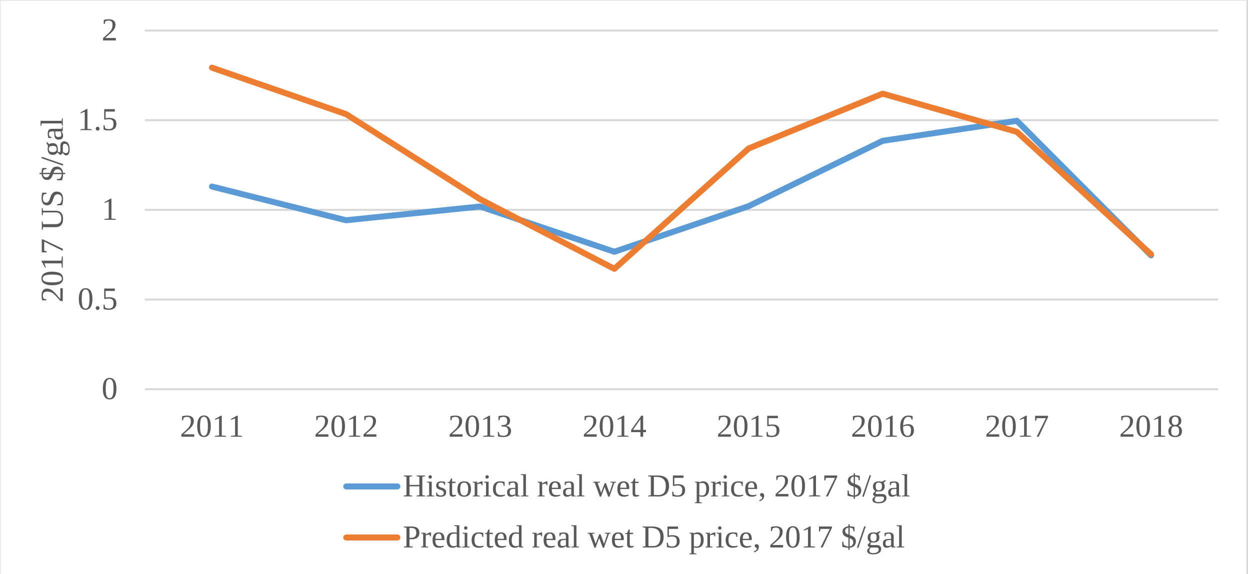

Figure 5: Historical vs predicted real wet D5 RIN prices

Output Metrics

The foundation of all of our metrics of financial performance is the NPV, which is found by discounting the total net cash flow for each year, and then summing these discounted net flows over the life of the investment. A positive NPV indicates that the investment earns returns at an annual rate that is at least as great as the discount rate, or "hurdle rate". We use 2017 as a base year for all our prices, and as the year in which plant construction is assumed to begin. A scenario's POL is the probability that the project fails to earn returns at least as great as the specified hurdle rate. This is equal to the percent of that scenario's NPV distribution that is less than zero.

From the NPV, we calculate BEPs. A BEP is the price of an input or output that drives the NPV to zero. A project with an output BEP lower than the actual price of that output would earn annual returns at least as great as the discount rate, barring changes in that key price. Conversely, an input BEP higher than current or likely prices for that input indicates a favorable project. We do this on the output side for the price of crude oil, which drives the prices received for all of our fuel products, and on the input side for the price of pennycress seed oil, expressed as a percent of the soybean oil price. There are two versions of the crude oil BEP, one which assumes that the crude oil price is constant in real terms (the "constant crude oil BEP" below), and another which assumes that its real price grows at 2.25% per year over the life of the plant, which we call a "starting crude oil BEP".

Two other measures we generate of the proposed plant's financial viability are variations on the idea: If all the other prices we model (except for RINs) remain unchanged, how much would the price of crude oil (and thereby the prices of fossil jet, diesel, and gasoline) have to increase in order for our plant to break even? To answer this question, we drive all of our fossil fuel prices using regression on the price of jet fuel, which we vary in each iteration to set the NPV for that iteration to zero. We allow RINs to vary based on the implied price for fossil diesel fuel, which, as we have seen, defines one endpoint for the "gap" that D4 and D5 RINs cover. All other price projections remain unchanged. The price of jet fuel is used to drive the price of diesel fuel, and the price of diesel fuel drives the price of gasoline. Thus all our fossil fuel prices move together in an "index" of sorts, driven by the jet fuel price. The price of diesel fuel, along with the forecasted price for soybean oil, drives RINs prices. We could just as easily have used the diesel fuel or gasoline prices as the "driver". The important point is that these prices move together as we change one of them in each iteration to find a breakeven price. We then use EIA data on the wholesale prices of crude oil (EIA, 2018a) and jet fuel (EIA, 2018b) to establish a regression relationship between these prices that allows us to report our breakeven price in terms of the price of crude oil. For details, see table 8 below. We do not allow any of these linked prices to take negative values, even if implied by the regression relationships.

Table 8: Robust OLS of historical annual real wholesale crude oil prices (averages of Brent and West Texas Intermediate) on annual real wholesale jet fuel prices, 1990-2017

	Real wholesale crude oil prices, 2017 $/barrel
Real wholesale jet fuel prices, 2017 $/gal	34.1*** (0.569)
Constant	0.733 (0.750)
Observations	28
R-squared	0.993

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

We carry out two versions of this procedure. In one, we are finding a breakeven constant real price of crude oil, which is constant in real terms in every year of a given iteration. The same cell is referenced for the real jet fuel price in every year of the model. This approximates the EIA's "Low Oil Price" projection scenarios (EIA, 2018a). In the other, we are finding a breakeven starting price for crude oil, which then grows by 2.25% in real terms throughout the life of the plant. In this version, only the first year's jet fuel price directly references the cell whose value we are changing to find the breakeven point. The real jet fuel price in every subsequent year is equal to the previous year's real jet fuel price, multiplied by one plus the 2.25% growth rate. This procedure approximates the expectations of the EIA's "Reference Case" crude oil price projections (EIA, 2018a). As explained above, the prices of diesel fuel, gasoline, and D4 and D5 RINs all vary based on the stipulated jet fuel price.

Our pennycress seed oil BEPs are used to investigate the feasibility of more-favorable pricing regimes for pennycress oil, given the cost structures of the rest of the supply chain, and to understand how far such cases diverge from our base pricing assumption. We calculate two such BEPs, a breakeven buying price for pennycress oil as an input, from the perspective of the biofuels producer, and a breakeven selling price from the perspective of a pennycress seed processor. Pennycress oil is not yet commercially produced or traded, and so we cannot yet know how it would be priced in a real market. Some link between its price and the price of soybean oil seems likely, however, due to significant co-movement between the prices of commodity vegetable oils and due to its substitutability with soybean oil for the purposes of fatty acid methyl ester (FAME) biodiesel production (Moser et al., 2009; Moser, 2012; Drenth et al., 2014; Moser, 2016; Yu, Bessler, and Fuller, 2006; and Moser, Evangelista, and Isbell, 2016). For this reason, and in order to facilitate comparison to our base assumption, we measure our pennycress seed oil BEPs as a percent of the projected price of soybean oil.

The procedure for obtaining the buying price BEP from the perspective of the biofuels producer is simple. A single parameter is defined that is multiplied by the soybean oil price in every period to yield the buying price of pennycress oil at the biofuels facility. The price of soybean oil used to help determine RINs prices remains unchanged by this parameter. This factor is expressed in percentage terms, and its value is changed in each iteration of the model to drive that iteration's pioneer or n^{th} CH facility's NPV to zero. These values are stored after each iteration of the model, and then compiled into a distribution of breakeven pennycress oil buying prices, expressed as a percent of projected soybean oil prices.

To calculate the selling price BEP for pennycress oil from the perspective of the seed processor, we lean on TEAs of pennycress seed production and processing conducted by researchers affiliated with the University of Tennessee, Knoxville, and led by Dr. Burton English (Trejo-Pech et al., 2019; and Markel et al., 2018). We combine parameters from their work with our price projections and financial assumptions to build a discounted cash flow model for a representative pennycress seed processor, using our projected DDGS prices as proxies for prices of pennycress meal sold as an animal feed additive. The processor's other source of revenue is selling pennycress oil. We then follow a procedure identical to that used for the CH facility's pennycress BEP. A single, constant factor is defined that is multiplied by the soybean oil proxy price received by the seed processor in every period of each iteration. That parameter is expressed in percentage terms, used to drive the NPV of the seed processing facility to zero in each iteration of the model, with the resulting values from each iteration stored and compiled into a distribution of seed processor's pennycress oil selling BEPs.

Results

On the following pages, we present tables summarizing the results of our stochastic analysis. In order to save space, we only present detailed results tables for our Iowa-located scenarios, as Indiana results differ only marginally. Commentary on the results of each metric precedes the associated tables. Particular emphasis is given to the 90th percentile values for distributions of breakeven prices, as these are the values that would result in the modeled facility's at least breaking even in 90% of cases, and is therefore taken as a possible benchmark for interest from a risk-averse investor. We then discuss which scenarios produced the most favorable results, and which scenario variables appear to have the greatest impact on a plant's financial performance. Overall, our results show that a greenfield CH aviation biofuels production facility like the one modeled here is not financially viable under current economic conditions, even with existing policy supports. However, there are indications that a greenfield CH facility that maximizes its renewable diesel production at the expense of renewable jet fuel could be a highly attractive investment under certain conditions.

Net Present Values

Distributions of net present values (NPVs) demonstrated a similar degree of variability in returns across scenarios, with nearly identical standard deviations of roughly $40 million and max-to-min ranges around $200 to $300 million in all cases. They differ from each other primarily when it comes to where they are centered. Distribution means ranged from roughly negative $61 million to $84 million (2017 USD). Six of our sixteen scenarios (three for each site) resulted in NPV distributions with mean values greater than zero.

Table 9: Net present value results for Iowa site, 2017 US $, negative values in parentheses

Scenarios			mean	st. dev.	min	max
Pioneer	BTC	Jet and Diesel	($20,455,173.96)	$40,009,288.68	($156,024,575.33)	$135,665,243.72
Pioneer	BTC	Max Diesel	$56,656,596.15	$40,008,849.57	($84,698,968.86)	$198,099,460.28
Pioneer	NO BTC	Jet and Diesel	($61,386,044.63)	$39,252,164.41	($191,067,319.50)	$90,530,786.50
Pioneer	NO BTC	Max Diesel	($32,783,039.65)	$38,540,613.53	($150,638,098.31)	$108,077,791.79
Nth	BTC	Jet and Diesel	$7,357,196.67	$39,983,217.61	($127,932,016.19)	$163,580,044.03
Nth	BTC	Max Diesel	$84,467,488.88	$39,984,748.25	($56,758,913.79)	$226,252,992.39
Nth	NO BTC	Jet and Diesel	($33,573,674.00)	$39,226,033.37	($163,210,644.57)	$118,445,586.82
Nth	NO BTC	Max Diesel	($4,972,146.92)	$38,515,581.70	($122,698,043.25)	$136,231,323.89

Breakeven Jet Fuel Incentive

Our breakeven jet fuel incentive metric is the amount of additional real, constant, per-gallon revenue over projected jet fuel prices that would be needed for the project to break even. This might take the form of a tax credit like the Biodiesel Blender Tax Credit (BTC), for example. The degree of variation in these estimates is high, as may be seen by comparing distribution means and standard deviations below. In all cases, the standard deviation is greater than half of the mean. Were our interest in using these mean values to predict the true level of the breakeven jet fuel bonus, then this would make our results statistically insignificant. Our interest, however, is in using these results to identify a cutoff level of support that would render an investment in a greenfield aviation biofuels facility like the one modeled here relatively safe, despite the high degree of variability. Thus, we focus on the 90th percentile values of these distributions. Additional fuel producer revenue of $0.40 to $0.85 per gallon of jet fuel (in constant 2017 US dollars) would be sufficient to make a plant like the one modeled here into an attractive investment in any of the scenarios we considered, as can be seen below. Real wholesale jet fuel prices were at $1.85 per gallon (2017 USD) in July 2019, which means that this level of support would represent an increase of roughly 20 to 40 percent in the base price received by producers of renewable jet fuel, in addition to payments for the values of California Low Carbon Fuel Standard (LCFS) credits and D4 Renewable Identification Numbers (RINs).

We can get an idea of the minimum percentage increase in jet fuel price required for aviation biofuels to break even, on average, by comparing the lowest mean incentive required ($0.21 per gallon, 2017 USD) to the mean projected jet fuel price in the first year of our model, which is $1.87 per gallon (2017 USD). This gives a low-end price increase estimate of roughly 11%. Repeating the same procedure for the worst-performing pathway gives an estimated required price increase of 26%.

Table 10: Breakeven jet fuel incentive results for Iowa site, 2017 US $ per gallon

Scenarios			mean	st. dev.	min	max	90th percentile
Pioneer	BTC	Jet and Diesel	$0.30	$0.20	$0.00	$1.14	$0.58
Pioneer	NO BTC	Jet and Diesel	$0.50	$0.25	$0.00	$1.43	$0.84
Nth	BTC	Jet and Diesel	$0.21	$0.16	$0.00	$0.93	$0.43
Nth	NO BTC	Jet and Diesel	$0.35	$0.21	$0.00	$1.23	$0.65

Breakeven Crude Oil Price

Mean values and standard deviations for our crude oil breakeven prices are somewhat variable from one scenario to another. One interesting pattern that emerges from these results is that the standard deviations for scenarios in which the BTC continues its recent behavior are higher than "No BTC" scenarios, while their mean values are lower. At least some of this increase in variation is likely due to our stochastic implementation of the BTC. Another possibility may be that factors other than the price of crude oil exert more influence on financial outcomes in these scenarios.

Our 90th percentile results tell a clearer story than the mean and standard deviation results. They indicate that starting crude oil prices around \$100-\$130 real 2017 USD per barrel with 2.25% real annual price growth or constant crude oil prices between \$130 and \$170 real 2017 USD per barrel would make the modeled greenfield CH biofuels facility an attractive investment, assuming that input price levels remain as projected here. A real crude oil price of \$100 per barrel (2017 USD) would be in the 85th percentile of all historical crude oil prices from 1987 to 2017, while \$130 per barrel would be in the 99th percentile (EIA, 2018a). Any of these would imply diesel fuel prices greater than the highest value of our 2018 projections.

Looking at the mean results for the best-performing scenario that produces both renewable jet and renewable diesel can give us an idea of the minimum percentage increase in crude oil price that would be required to make aviation biofuels production profitable, on the mean. An nth plant in Iowa with the BTC in place has a mean breakeven starting crude oil price of \$86.60 per barrel (2017 USD). The mean first-year crude oil price implied by our stochastic forecast was \$64.67 per barrel (2017 USD). Refiner's cost for a barrel of crude was roughly \$55.73 per barrel (2017 USD) in August 2019. In percentage terms, then, a price increase of at least 31% over projection or 52% over actual prices would be required for aviation biofuels production to break even, on average.

Our projections follow those of the EIA, and crude oil prices when the analysis was conducted were on the low end of their projections, and therefore on the low end of ours. This explains a curious feature of our results: The probability-of-loss and breakeven jet fuel incentive metrics paint a much more optimistic picture than do the starting and constant crude oil breakeven prices. Our implied projections of crude oil prices, while still substantially lower than these BEP results, are nearer to the breakeven levels than actual prices have been since the projection model was built.

Table 10: Breakeven constant crude oil price results for Iowa site, 2017 US $ per barrel

Scenarios			mean	st. dev.	min	max	90th percentile
Pioneer	BTC	Jet and Diesel	$124.47	$34.59	$0.81	$200.05	$161.63
Pioneer	BTC	Max Diesel	$89.69	$47.31	$0.78	$184.53	$146.34
Pioneer	NO BTC	Jet and Diesel	$141.56	$23.72	$1.03	$207.68	$170.84
Pioneer	NO BTC	Max Diesel	$134.59	$26.56	$0.86	$201.83	$165.61
Nth	BTC	Jet and Diesel	$112.66	$40.86	$0.84	$195.60	$156.05
Nth	BTC	Max Diesel	$69.54	$46.78	$0.82	$178.88	$138.56
Nth	NO BTC	Jet and Diesel	$136.12	$25.24	$0.85	$204.16	$166.87
Nth	NO BTC	Max Diesel	$128.92	$30.02	$0.97	$197.66	$161.61

Table 11: Breakeven starting crude oil price results with 2.25% real annual price growth for Iowa site, 2017 US $ per barrel

Scenarios			mean	st. dev.	min	max	90th percentile
Pioneer	BTC	Jet and Diesel	$96.54	$26.18	$0.79	$155.09	$124.24
Pioneer	BTC	Max Diesel	$65.50	$34.71	$0.77	$136.12	$108.48
Pioneer	NO BTC	Jet and Diesel	$111.00	$17.88	$0.97	$161.80	$132.78
Pioneer	NO BTC	Max Diesel	$104.56	$20.25	$0.83	$157.49	$128.03
Nth	BTC	Jet and Diesel	$86.60	$30.60	$0.82	$150.84	$118.92
Nth	BTC	Max Diesel	$53.74	$34.19	$0.80	$130.11	$100.98
Nth	NO BTC	Jet and Diesel	$105.77	$19.26	$0.83	$157.80	$128.58
Nth	NO BTC	Max Diesel	$99.02	$22.79	$0.92	$153.25	$124.24

Breakeven Pennycress Oil Prices

All of our BEPs for pennycress seed oil are measured as a percent of the price of soybean oil, for the sake of comparison, and to account for the fact that the prices of commodity oils tend to exhibit significant degrees of co-movement (Yu, Bessler, and Fuller, 2006). Six scenarios in total had 50th percentile scores over 100%. These were the same scenarios that had positive mean NPVs. From 10th percentile values of the other scenarios we see that discounts of 2-6% over soybean oil prices would make fuel conversion a very safe investment, indeed. From figure 6 we see that the crushers would be able to accommodate these discounts with a high degree of safety, themselves, as the 90th percentile of their minimum selling price distribution is roughly 94% of the soybean oil price.

Table 12: Biofuels producer's breakeven cost of pennycress oil at an Iowa site, as a percent of projected soybean oil prices

Scenarios			50th percentile	st. dev.	min	max	10th percentile
Pioneer	BTC	Jet and Diesel	98.75%	2.32%	93.04%	112.69%	96.36%
Pioneer	BTC	Max Diesel	103.19%	2.75%	96.10%	118.53%	100.35%
Pioneer	NO BTC	Jet and Diesel	96.40%	2.04%	91.54%	108.47%	94.29%
Pioneer	NO BTC	Max Diesel	98.05%	2.16%	93.07%	110.11%	95.82%
Nth	BTC	Jet and Diesel	100.34%	2.48%	94.29%	115.30%	97.79%
Nth	BTC	Max Diesel	104.78%	2.91%	97.39%	121.17%	101.79%
Nth	NO BTC	Jet and Diesel	97.98%	2.20%	92.79%	111.08%	95.71%
Nth	NO BTC	Max Diesel	99.64%	2.32%	94.36%	112.74%	97.26%

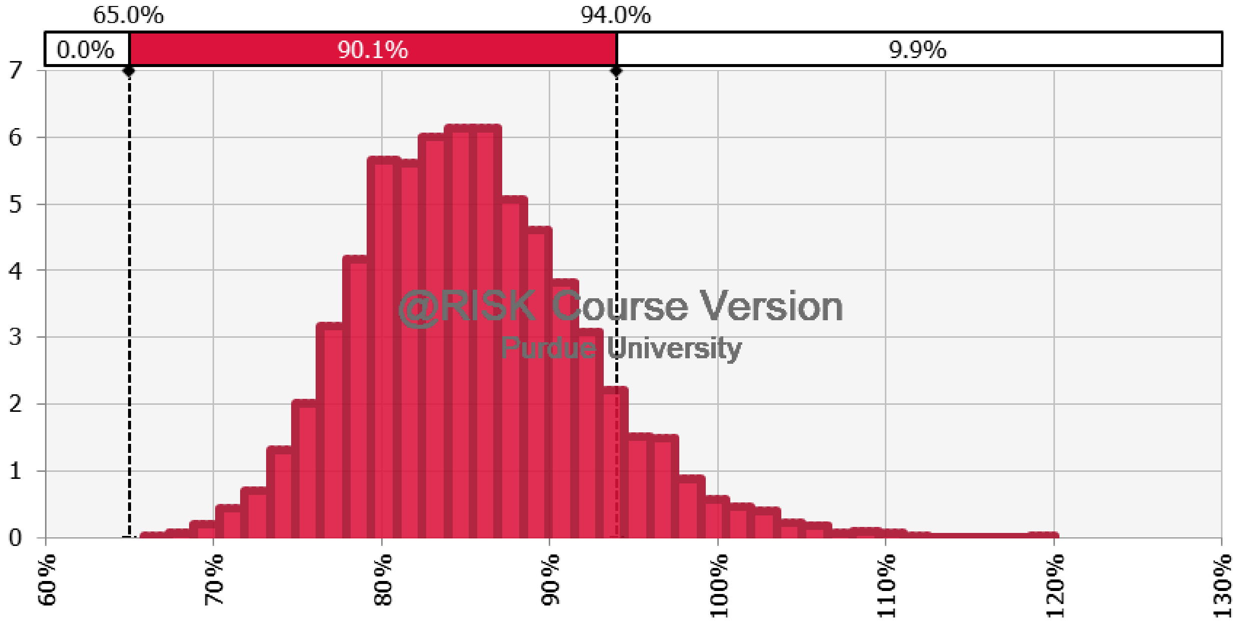

Figure 6: Seed processor's breakeven selling price of pennycress oil, as a percent of projected soybean oil prices

Ranking Scenarios and Identifying Key Variables

Including both the Iowa and Indiana siting options, we examined sixteen greenfield scenarios in our study, allowing us to compare the relative impacts of four binary variables on the project's financial performance. As previously stated, in none of these scenarios would a greenfield CH aviation biofuels facility represent a financially viable investment.

Many of the lessons to be drawn from our results are unsurprising: nth plants performed marginally better than pioneer plants, and scenarios based on Iowa's relatively lower electricity prices yielded more favorable results than otherwise equivalent scenarios using Indiana's electricity prices. More interesting are the results pertaining to the impact of the BTC's status and the plant's choice of product mix. Table 13 below presents a snapshot of the results for all sixteen scenarios, ranked by increasing probability of loss (POL) from top to bottom. Other metrics are presented alongside POL, and the ranking of scenarios would have been similar if any of these other results had been used as criteria, as can be seen from the consistent “good-to-bad” green-to-red color coding in the table. The four binary variables that define each scenario are listed on the left-hand side of the table, arranged left to right from most influential to least, as will be explained below.

Table 13: Ranking of scenarios based on probability of loss (P.O.L.), with impacts on other metrics also shown. Color gradients show ranking of scenarios based on each metric. Green is good; red is bad.

Scenarios				Net Present Value, 2017 US $		Breakeven Jet Fuel Incentive, 2017 US $ per gallon			Breakeven Starting Crude Oil Price, 2017 US $ per barrel		
				P.O.L.	50th percentile	50th percentile	75th percentile	90th percentile	50th percentile	75th percentile	90th percentile
BTC	Max Diesel	Nth	Iowa	1.5%	$ 83,590,161.80				$ 51.08	$ 83.11	$100.98
BTC	Max Diesel	Nth	Indiana	1.6%	$ 81,887,811.81				$ 52.72	$ 83.10	$101.70
BTC	Max Diesel	Pioneer	Iowa	7.2%	$ 55,803,693.79				$ 70.60	$ 94.29	$108.48
BTC	Max Diesel	Pioneer	Indiana	7.9%	$ 54,046,649.15				$ 71.41	$ 94.77	$108.78
BTC	Jet and Diesel	Nth	Iowa	44.0%	$ 5,894,064.75	$ 0.18	$ 0.30	$ 0.43	$ 93.60	$108.75	$118.92
BTC	Jet and Diesel	Nth	Indiana	45.6%	$ 4,102,271.02	$ 0.18	$ 0.31	$ 0.44	$ 93.88	$109.10	$119.36
NO BTC	Max Diesel	Nth	Iowa	56.7%	$ (6,260,778.50)				$101.70	$113.88	$124.24
NO BTC	Max Diesel	Nth	Indiana	58.1%	$ (8,033,461.99)				$101.88	$114.23	$124.40
BTC	Jet and Diesel	Pioneer	Iowa	70.2%	$ (21,862,090.22)	$ 0.27	$ 0.43	$ 0.58	$100.87	$114.44	$124.24
BTC	Jet and Diesel	Pioneer	Indiana	71.9%	$ (23,657,912.12)	$ 0.28	$ 0.44	$ 0.59	$101.21	$114.76	$124.58
NO BTC	Max Diesel	Pioneer	Iowa	80.2%	$ (34,032,436.07)				$106.48	$118.20	$128.03
NO BTC	Jet and Diesel	Nth	Iowa	80.6%	$ (35,062,900.73)	$ 0.33	$ 0.50	$ 0.65	$107.16	$119.05	$128.58
NO BTC	Max Diesel	Pioneer	Indiana	81.5%	$ (35,880,355.60)				$106.83	$118.47	$128.32
NO BTC	Jet and Diesel	Nth	Indiana	81.7%	$ (36,830,843.82)	$ 0.34	$ 0.50	$ 0.66	$107.41	$119.29	$128.86
NO BTC	Jet and Diesel	Pioneer	Iowa	93.4%	$ (62,878,755.12)	$ 0.49	$ 0.68	$ 0.84	$112.19	$123.50	$132.78
NO BTC	Jet and Diesel	Pioneer	Indiana	93.9%	$ (64,618,190.43)	$ 0.50	$ 0.69	$ 0.85	$112.45	$123.79	$133.04

With the results arranged in this way, we can see which scenario variables generally proved to be relatively more important. If a single scenario variable’s impact always outweighed all the others’, then the scenarios would be ranked by that variable first, and then by the other three. This would result in seeing all the scenarios in which that variable took its more-favorable value ranked above all the scenarios in which it took its less-favorable value, and the column for that variable would contain two solid blocks in table 13 above. This is very nearly the case for the “BTC / NO BTC” variable. Its large impact on the project’s financial success is to be expected. As modeled here, the default “BTC continues” scenario results in added nominal revenues of $0.50 per gallon of renewable diesel in years for which it is reinstated retroactively, which occurs in 40% of all years. For a plant like this one rated to process 5000 barrels of feed oil per day, this equates to roughly \$13 million dollars of revenue per year in nominal terms. In years in which it is in effect ex-ante, at least some of that value gets absorbed by the model in the form of lower RINs prices, as indicated in tables 5 and 6.

If a scenario variable were always less influential than all the other variables, then the scenarios would be ranked by that variable last, after the impacts of all the other variables had been accounted for. This would result in a simple one-by-one alternating pattern between the values of that scenario variable, as is very nearly the case for our "Iowa / Indiana" variable above. That this variable should be relatively unimportant to our model is not surprising, since a slight difference in electricity prices comprised the sole distinction between the two sites in this analysis. The product slate choice and n^{th} versus pioneer distinctions appear to have roughly equivalent impacts on the ranking of our scenarios. Still, the choice of product slate can be shown to be of greater practical importance to the "go – no go" decision for the proposed biofuel facility. Four scenarios had probabilities of loss lower than 10%, and the fifth-best scenario's POL was 44.0%. These four scenarios included two pioneer plants and two n^{th} plants, but all four of them had "max diesel" product slates. According to our analysis, then, a greenfield CH biofuels facility using a vegetable oil feedstock that is priced equivalently to soybean oil is a favorable investment under current policy only if it maximizes its output of renewable diesel fuel at the expense of renewable jet fuel.

Discussion

Our results show that aviation biofuels production at a greenfield CH plant fed by pennycress seed oil is not economic under current market and policy conditions. Our breakeven metrics for a renewable jet fuel policy incentive, crude oil prices, and the input cost of pennycress oil indicate this could change if one of the following were to occur:

- A crude oil price increase of at least 31-52%
- A jet fuel price increase of at least 11-26%
- A pennycress oil price discount of 2-6% from soybean oil prices
- Some combination of the above

These findings are heavily influenced by current policy design.

Support for the conclusion that the pathway considered would not be economic under current conditions can be drawn from the results for NPVs, POLs, breakeven jet fuel incentives, and crude oil BEPs. Starting with the NPV results, we see in table 9 that no scenario in which jet fuel was produced resulted in a mean NPV that was significantly higher than zero. Moving to POL, we see that the best-performing scenario for a plant producing both jet fuel and diesel fuel would still be expected to earn less than the stipulated rate of return in 39.6% of all cases. The breakeven jet fuel incentive results contained in table 10 show that the mean level of policy support needed for a jet-fuel-producing plant was positive in all cases. Finally, the mean crude oil BEP results presented in tables 10 and 11 for plants that produced renewable jet fuel are all greater than \$84 per barrel (2017 USD), which would be in the 78th percentile of historical prices from 1987 to 2017, and would imply a diesel fuel price in the 94th percentile of our projections for 2018. The composite refiner acquisition cost of crude oil was \$55.73 per barrel in August of 2019 (2017 USD) (EIA, 2018a; and OECD, 2018).

Price Sensitivities

The relative sensitivities of our results to the factors listed above are somewhat counterintuitive. One would not expect for larger price changes to be required for crude oil than for jet fuel, since changes to the crude oil price impact the prices received for all three of the fuel products that our plant would produce, and since renewable jet fuel makes up only 33-39% of our plant's total output volume. It is similarly surprising that our results would appear to be so much more sensitive to changes in input price than to changes in output price. This is but one example among many of the determinative impacts of policy on the economics of biofuels production, as all of these counterintuitive results can be traced back to the interactions between these prices and the markets for D4 and D5 RINs. In the model of RIN price discovery that we use in this analysis, the gap between the market prices of soybean oil and No. 2 diesel fuel is the driver of the D4 RIN price, which, in turn, drives the price of the D5 RIN. Thus, if the price of diesel fuel rises relative to the price of soybean oil, then RIN prices fall. This mechanism has the effect of buffering our biofuels producer's profitability from changes in the crude oil price, since those changes get passed on to the diesel fuel price, and then (in the opposite direction) to RINs prices. Changes to the price of jet fuel, however, are not assumed to generate countervailing movements in RINs markets, since renewable jet fuel comprises a small fraction of RFS compliance. This explains our finding that a producer of aviation biofuels would be more sensitive to a movement of the jet fuel price than to a movement of the crude oil price, if the jet fuel price movement were independent of the prices of other fossil fuels, especially diesel fuel. Such an "independent" movement of the jet fuel price might arise from the initiative of the large airlines that are responsible for the majority of jet fuel consumption, from a policy support targeted at renewable jet fuel, or from a decrease in the relative demand for road transport fuels resulting from the increased prevalence of electric cars.

Similarly, the aviation biofuels producer modeled here appears to be starkly more sensitive to changes in the input price than changes in the prices of outputs. This is also due to the current functioning of RINs markets, as modeled here. Our analysis considers the case of pennycress seed oil, a novel biofuel feedstock, which we assume would make up a relatively small portion of the total biofuel feedstock market. Based on this assumption, the aforementioned blend gap driving RINs prices would continue to be set by the price of soybean oil, the higher-volume “marginal” input to biofuels production in the US. Decreases in the price of pennycress oil, then, behave similarly to independent movements of the jet fuel price: they do not generate a countervailing movement in RINs values. The ratio between the volume of pennycress oil used by our plant and the volume of renewable jet fuel it produces is roughly 3:1, which accounts for most of the difference we see in sensitivity between the two prices.

As to a 2-6% “discount” for pennycress oil versus soybean oil, our crusher’s perspective pennycress oil output BEP results (See figure 6.) indicate that, in a vacuum, a pennycress oil price that low would make the entire pennycress-fed, CH aviation biofuels pathway economic, as long as the RFS and LCFS continue. By “in a vacuum”, we mean to exclude the possibility that soybean oil biodiesel producers would bid up the market price of pennycress oil to match the price of soybean oil, in which case crushers would earn negative economic profits by selling the oil at a lower price. This “vacuum” might take the form of contracting between pennycress seed crushers and CH aviation biofuels producers, backwards vertical integration from the biofuels producers, or high transaction costs for biodiesel producers, perhaps due to a thin market for pennycress in the early stages of commercialization. Alternatively, a market price gap between pennycress oil and soybean oil might result from seasonal price effects, since pennycress harvest precedes soybean harvest by four to six months, or from the functional properties of the oils, themselves. This could be because of an as-yet unidentified functional deficiency in pennycress oil for the purposes of biodiesel production. A functionality-based price gap could also arise from pennycress oil’s inedible nature if enough of it were produced to significantly shift the aggregate supply of vegetable oil to the biofuels sector. In this case, edible oils such as soybean oil could face a higher effective demand than inedible oils, due to their use in food.

Diesel Fuel vs. Jet Fuel and the BTC

The BTC plays a significant role in the financial viability of the plant modeled here. The only scenarios to exhibit positive mean NPVs assumed that the operation of the BTC continued to reflect its recent behavior throughout the life of the plant. If we examine results for otherwise-equivalent pairs of "BTC" and "NO BTC" scenarios in table 9, we can see that the BTC's continuation adds roughly $41 million to the mean NPV of "Jet and Diesel" scenarios and roughly $89 million to the NPVs of "Max Diesel" scenarios (2017 USD). A similar comparison of the POLs in table 13 shows that the continuation of the BTC reduces the probability of earning less than the stipulated rate of return by roughly 20-40 percentage points for plants that produce renewable jet fuel and by 50-70 percentage points for "max diesel" plant configurations. This is noteworthy, since the presence of the RFS has called into question the usefulness of the BTC as a policy measure (Irwin, 2017). While the BTC might be a source of unnecessary windfall profits for fatty acid methyl esters (FAME) biodiesel producers (Irwin, 2017), it appears important to the financial health of producers of high-quality "drop-in" biofuels via the CH process modeled here, or via any such process that has relatively higher production costs than would a FAME process.

Finally, we can observe that if our model facility maximizes its output of renewable diesel fuel at the expense of renewable jet fuel, it performs markedly better. Most of this effect is due to renewable diesel's qualifying for the BTC, whereas renewable jet fuel does not. Compare the mean NPVs in table 9 for otherwise-identical "Max Diesel" and "Jet and Diesel" scenarios that include the BTC. They reveal that maximizing renewable diesel production at the expense of renewable jet fuel production was worth about $77 million (2017 USD) of mean NPV in such cases. To isolate the portion of that value that results from fossil diesel fuel's higher market price, we can compare the mean NPVs for matched pairs of "NO BTC" scenarios in those same tables. The results indicate that, without the BTC, maximizing renewable diesel output added roughly $28 million to mean NPV (2017 USD). This points to roughly $49 million (2017 USD) of NPV that renewable jet fuel-producing plants would surrender, on average, due solely to the fact that jet fuel does not qualify for the benefits of the BTC. Even so, "leveling the playing field" between middle distillate fuels, in terms of policy, would still leave an average value of $28 million (2017 USD) that biofuels plants would forfeit by choosing to produce renewable jet fuel. Both the policy environment and historic market conditions stack the deck in favor of maximizing renewable diesel output.

Practical Implications

This analysis shows that, even with other policies such as the RFS and LCFS in place, the biodiesel BTC remains an important factor for the economics of producing drop-in biofuels at greenfield sites. This may be because low-cost FAME biodiesel technology currently "sets the curve" when it comes to the values of D4 and D5 RINs. That is certainly how we model those prices here, and if we are right to do so, then that presents a few practical implications for biofuel producers using CH or other similar technologies. First, it implies that it may be worthwhile for them to join in with the "biodiesel lobby" in their efforts to ensure the BTC's survival. Second, it highlights the importance of identifying opportunities to market high-quality biofuels at a premium over their lower-quality analogs. The RFS doesn't distinguish between FAME biodiesel and high-quality renewable diesel from CH or HEFA processes, even though the latter may be used at much higher percentages in final fuel blends (Mawhood et al., 2016). The RVOs mandated by the RFS would need to be substantially higher than their current levels for that difference to become significant for compliance purposes. The 2018 biodiesel RVO, for example, was set at 2.1 billion gallons (EPA, 2017), which equated to roughly 3.5% of total sales of ultra-low-sulfur diesel fuel in that year (EIA, 2019b). Even so, some buyers may be interested in a fuel blend that contains a higher proportion of biofuels, and these buyers may be willing to pay a premium for higher quality products.

Our study indicates that, even if a pathway like the one modeled here were financially viable, a rational, profit-maximizing biofuels producer would probably choose not to produce any significant amount of renewable jet fuel. This may be the most significant hurdle to the commercial production of aviation biofuels, regardless of crude oil prices, feedstock prices, or policy: likely due at least in part to large airlines' buying power in the market for jet fuel, the price of diesel fuel is consistently higher than the price of kerosene-type jet fuel (EIA, 2018b; and EIA, 2018c). Further, they are chemically similar enough that production processes like CH allow for jet production to be foregone in favor of diesel production. Producing renewable jet fuel instead of renewable diesel fuel results in losing money. Unless the stable, long-running price relationship between these two fuels (EIA, 2018b; and EIA, 2018c) is disrupted by developments like the growing electrification of ground-based transport, only an actor with a firm vested interest in producing renewable jet fuel would be likely to do so.

This leaves those who have such a vested interest in using renewable jet fuel with three options for encouraging its production. They can push for additional policy incentives that specifically target aviation biofuels, perhaps along the lines of the biodiesel BTC, they can contract to buy renewable jet fuel from a biofuels producer at a significant premium over fossil jet fuel, or they can integrate backwards into biofuels production, and perhaps all the way to feedstock processing or growing. Our results support the idea that each step of such a vertically-integrated system could generate sufficient margin to pay its costs, thus showing an accounting profit, but the system's economic profits would likely be negative as a result of foregoing one or more higher-value opportunities along the way.

Limitations

For all of our analysis, we rely heavily on the assumption that current and historical market behavior continues to be typical for the 23-year project life. The future is unpredictable, and so this assumption could lead us to conclusions that do not represent the reality of future events. For our stochastic price projections, we assume that the autocorrelations and real growth rates within each series and the correlations between series observed in the sample period remain constant for the 23-year project life. This implies two limitations to our research. First, if any of these observed characteristics were to undergo significant change in the next 23 years, then our projections would no longer reflect the behaviors of the real prices. Second, 2017 is the last year in which our model uses historical price data, which means that we rely on projected prices starting in 2018. Since real prices for crude oil and soybean oil in 2018 and 2019 have been on the low end of their historical ranges, our projections based on those historical ranges tend to "overshoot" those prices. This fact negatively impacts the usefulness of our crude oil BEP results, which are based on projections of the soybean oil price that are somewhat higher than current market prices for soybean oil. Comparing our crude oil BEP results to either the historical distribution of real crude oil prices or to the distribution of our projections of the crude oil price in 2018 is likely to be more instructive than a naïve comparison to current market prices.

The model of D4 RINs pricing we rely on for our projections is intuitively appealing, and appears to perform reasonably well, but it has not yet been rigorously proven. It is possible that RINs markets do not, in fact, function the way we assume that they do. This would undermine the validity of our results. Even if our model of RINs pricing does reflect the real operations of those markets, we make further assumptions that also must hold for our results to be reliable, namely, that soybean oil FAME biodiesel continues to act as the marginal gallon in the D4 and D5 "buckets" of the RFS and that the ratios of those RVOs to US biodiesel production capacity remains steady. If either of these fails to hold for the life of the project considered, our estimates of RINs prices may no longer reflect reality.

Our identification of DDGS as a proxy for pennycress seed meal prices is based on shadow prices drawn from a linear program, and not from real market data. This could hardly be avoided, as there is no real market data for the price of pennycress seed meal. Even so, this approach at modeling the potential demand for this product is limited by several things which we do not take into account, such as international trade or general equilibrium effects of pennycress meal production. The fact that our pennycress meal shadow prices are mechanistically determined by the system of given prices in our model may also introduce issues with endogeneity that would call into question our use of OLS to identify DDGS as a predictor of pennycress prices. A more robust approach might have been able to avoid these issues, but would have been beyond the scope of this study.

Another important limitation of our analysis is that we assume that pennycress seed oil would be priced as a perfect substitute for soybean oil. This assumption might or might not be representative of how pennycress oil would actually be priced; it relies on an assumption that the market for pennycress oil as a biofuel feedstock would be reasonably competitive, and that pennycress supply would not be so large as to begin to significantly shift the supply-demand balance in the market for biofuels feedstocks. Further, by making this market-based assumption about the pricing of pennycress seed oil, we are explicitly not considering the case of a vertically-integrated system. Such a system could perhaps cover its costs while producing aviation biofuels under current conditions, and thus run an “accounting profit”, and investing in such a system might be a valid decision for reasons related to corporate social responsibility, public relations, or other strategic concerns, regardless of the market value of pennycress oil. It should be noted, however, that a vertically integrated system that undervalues one of its throughputs may show an accounting profit, but it ignores relevant opportunity costs, and thus cannot yield an economic profit. If our base assumption regarding the pricing of pennycress oil is correct, then it would always be more profitable to sell it at the market price than to “buy” it from yourself at a lower-than-market price in order to run an accounting profit on your own biofuels production activities.

Both of the above limitations rest on the fact that we assume that pennycress would be supplied and used in the marketplace in ways that are closely analogous to existing commercial oilseeds like soybeans and canola. In fact, the pennycress supply chain might prove to be quite different. Pennycress meal might be best used for purposes other than animal feed, and pennycress oil might be best used for purposes other than biofuel production. New markets could emerge, like the market for the ethanol byproduct DDGS in the early 2000s. The offseason nature of pennycress compared to soybeans might cause them to be priced and consumed in very different ways. Existing commercial oilseed crops are the best model we have for how pennycress might behave if produced commercially, but we cannot guarantee that the analogy we rely on between those crops and pennycress will prove reliable.

Policy is inherently unpredictable, yet in analyses such as ours, it is often necessary to make assumption about the futures of relevant policies, and we certainly do so here. We assume that both the RFS and the LCFS continue for the life of the investment. Further, we assume that the current balance between the levels of those mandates and the relevant production capacities (whether production of biofuels in the case of the RFS or "production" of carbon reductions in the case of the LCFS) remains stable at current levels through the life of the plant. These two policies play a central role in our analysis, and so any change in either of them would have drastic implications for our results.

Finally, it is important to note that we diverge from McGarvey and Tyner (2018) in not considering a "brownfield" case, in which the plant modeled is located on a site which already possesses some industrial infrastructure. Capital requirements would be reduced in such a case compared to the ground-up greenfield case we consider. Estimates of the magnitude of these reductions exist in the literature (De Jong et al., 2015), and they are large enough that they would likely have a significant impact on our results, if applied. However, the actual magnitude of any savings from a brownfield location is highly site-specific, making such generalizations of little practical value, and their impact on a project's predicted financial performance, though large, is highly predictable. Any savings to the total capital investment necessary for a project simply shift its distribution of expected NPVs to the right by roughly the dollar amount of the savings. Thus, in our view, the fundamental economics are best represented by the greenfield setting, with any deviations from those assumptions handled on a case-by-case basis.

Suggestions for Further Research

Our analysis shows that the economic viability of producing aviation biofuels from pennycress seed oil using CH technology is highly sensitive to the cost of pennycress oil; a 2-6% decrease to our base price assumption is sufficient to radically improve projected financial outcomes. Further, we lean on the work of other researchers to find evidence that such price decreases would not be likely to threaten the financial viability of pennycress production and processing. At this stage, a more thorough, rigorous investigation of the likely market valuation of inedible oilseed cash cover crops such as pennycress could make an important contribution to our understanding of biofuels pathways like the one modeled here. General equilibrium modeling using a framework like the Global Trade Analysis Project (GTAP) model might serve as a good jumping-off point.

Our analysis also shows that, even if a facility like the one modeled here were economically viable, a rational, profit-maximizing owner of such a facility would choose to forego production of renewable jet fuel in order to maximize output of renewable diesel. This clarifies the options facing actors in the civil aviation industry for using biofuels to reduce their carbon footprints: in the absence of additional policy supports, they may either pay high enough prices for renewable jet fuel to match the price of renewable diesel fuel, plus the expected value of the BTC, or they may integrate backwards into biofuel production. A relevant line of research, then, would compare the costs and benefits of these options with those of other mitigation strategies, such as purchasing carbon offsets or investing in advances in airplane and engine design.

Our analysis is based on an assumption that conversion to liquid transport fuels would represent the “highest and best” use of pennycress seed oil, but this assumption may not be valid. Further research by chemical engineers into potential higher-value co-products is therefore warranted. For example, pennycress oil contains high levels of erucic acid (Moser et al., 2009), which may have a higher value in other industrial applications than in fuel production (Van Dyne and Blase, 1990). The possibility of isolating some or all of the erucic acid from pennycress oil prior to converting it into biofuels was discussed with ARA engineers, but the details of such a process were not worked out at the time this study was conducted. Further research into biofuel co-products from novel oilseed feedstocks may completely change the picture presented in studies like ours of such pathways’ economic viability.

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