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Drop-in ready jet biofuel from carinata: A real options analysis of processing plant investments

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Abstract

A promising feedstock for large-scale production of sustainable jet biofuel is the inedible oilseed *Brassica carinata* (referred to simply as "carinata"), but transitioning to large-scale fuel production entails significant economic uncertainty and requires substantial up-front capital requirements for biorefinery construction. Furthermore, for carinata and other feedstocks attempting to compete within the established fossil jet fuel market, historically volatile aviation fuel prices affect the economic feasibility and return of biorefinery investments. In this study, we assess the impact of jet fuel price volatility on the return on investment in a carinata biorefinery employing a real options analysis (ROA). The key advantage of ROA over traditional net present value (NPV) analysis is that it simultaneously assesses the optimal timing for investments and the impact of jet fuel price dynamics on the likelihood of positive economic returns from investments in processing plants. Given the nonstationary nature of jet fuel prices and the presence of structural breaks, the price series are modeled as a geometric Brownian motion. Taking into account the volatility of jet fuel price, the ROA price threshold for a profitable investment is 45% greater than the NPV threshold. The ROA model identifies the necessary market conditions for a profitable investment and highlights the importance of considering market price dynamics before making substantial capital investments in a carinata biorefinery.

KEYWORDS

aviation fuel, biorefinery, carinata, economic feasibility, jet biofuel, net present value, real options analysis

1 | INTRODUCTION

The aviation industry is a significant component of the global economic system with an estimated total annual economic impact of $2.7 trillion (direct, indirect, and induced tourism contributions), which accounts for 3.6% of the global gross domestic product (ATAG, 2018). Although technological improvements and retirements of older airplanes have led to significant increases in fuel efficiency (70% improvement relative to 1960; FAA, 2015) and reduction in CO_2 emissions per seat kilometer (50% relative to 1990), the aviation industry remains a global contributor of greenhouse gasses. In 2017, it was estimated that the global aviation industry contributed about 2% (859 million tons) of total anthropogenic CO_2 emissions and 12% of transport-related CO_2 emissions (ATAG, 2018). Given the carbon emissions profile of the aviation industry and expectations that air traffic volume will double by 2039 (FAA, 2019), an array of industry, government, and international initiatives are striving to reduce the environmental impacts of aviation while fostering the continued growth of this globally critical industry.

A significant effort in that direction is the development and commercialization of sustainable bio-based aviation fuels which have been estimated to potentially reduce emissions by up to 80% during their full lifecycle compared to petroleum-based fuels (IATA, 2021). In the United States, two key programs aiming to advance the use and economic competitiveness of sustainable aviation fuels through a partnership among airplane manufacturers, airline companies, government agencies (USDA and DOE), and the military are Farm to Fly 2.0 and the Defense Production Act Title III Advanced Drop-in Biofuels Production Program. The goal of these programs (and similar initiatives globally) is to develop and deploy cost-competitive "drop-in" ready renewable jet fuels that meet the same specifications as petroleum jet fuel and do not require engine modifications or performance or safety compromises.

One promising feedstock for large-scale production of drop-in ready jet biofuel is *Brassica carinata*, a non-edible oilseed crop that can be grown in rotation during summer in colder climates or during winter in milder climates, like the Southeastern United States, as a cover crop on land typically fallowed prior to soybean, cotton, peanut, and corn cultivation (Christ et al., 2020). On a small scale, carinata oil has been refined to produce jet biofuel and successfully tested in commercial flights (Lane, 2018). However, like all emerging biofuels, transitioning from small- to large-scale production of carinata jet fuel has challenges and economic uncertainties throughout the supply chain from field to sky.

One key economic uncertainty, which is explored in this study, is the investment cost of developing the carinata oil refining capacity needed to move the feedstock forward as a large-scale jet biofuel source. The oil-to-jet fuel catalytic conversion process has already been successfully piloted and licensed for commercialization by Applied Research Associates and previous studies (Chu et al., 2017; McGarvey & Tyner, 2018) have explored the economic feasibility of a carinata biorefinery employing a traditional net present value (NPV) approach. Although NPV analysis is commonly employed to assess economic feasibility by weighing the tradeoff between significant upfront sunk costs and future revenue over the lifetime of a project, NPV does not directly consider the impact of uncertainty in price dynamics that ultimately can affect project viability. As a result, NPV analysis is usually accompanied with a simulation study to investigate the impact of volatility. Given that jet biofuels operate in a competitive marketplace (in the absence of government-imposed volume mandates), they must compete with conventional aviation fuels on a price basis. Hence, it is critical to appropriately model and incorporate the dynamics of petroleum-based aviation fuel prices into the economic feasibility of biorefineries. More simply stated, given that revenues from a carinata biorefinery are dependent on uncertain and stochastic aviation fuel prices, failure to incorporate dynamic fuel pricing into an economic feasibility assessment can potentially lead to incorrect evaluations of commercial viability.

To assess the impact of stochastic aviation fuel prices on the economics of investing in a carinata biorefinery, in this study, we evaluate investment decision-making by using real options analysis (ROA) and compare our findings to those with traditional NPV analysis. As shown by Dixit and Pindyck (1994), ROA is a more appropriate method than traditional NPV analysis for evaluating investment decisions involving possibility to delay irreversible upfront investment costs and a stochastic price environment. ROA can account for stochastic prices of aviation fuel prices that will affect future revenue, replacement irreversibility (once expenditures are made to construct a biorefinery, it is difficult to recoup those costs if the plant is shut down), and the possibility of delaying the investment until future market price conditions become conducive. This leads to two key advantages of ROA over traditional NPV analysis: (1) ROA calculates the optimal timing (price thresholds) for investing in a carinata processing plant; and (2) ROA assesses the impact of jet fuel prices and volatility on the likelihood of positive economic returns on the processing plant investment. However, it is also important to note two weaknesses of ROA: The model is significantly more complex compared to a traditional NPV feasibility analysis and sufficiently rich market price data (jet fuel prices) are required to operationalize the model.

Given these advantages, ROA has been used to evaluate a range of energy investment decisions, such as biofuels (Kern et al., 2017; Liu et al., 2018; Schmit et al., 2009, 2011; Xian et al., 2015), solar and wind (Abadie & Chamorro, 2014; Gazheli & van den Bergh, 2018; Reuter et al., 2012), land use change for energy production (Gazheli & Di Corato, 2013; Song et al., 2011;), and nuclear power (Kiriyama & Suzuki, 2004; Rothwell, 2006; Zhu, 2012). Previous studies that have considered both NPV and ROA estimates to evaluate investment decisions have revealed that the differing approaches may potentially lead to very different conclusions regarding viability (Gonzalez et al., 2012; Santos et al., 2014), highlighting the importance of considering price dynamics. For example, considering the entry and exit decisions for dry-grind corn ethanol plants, Schmit et al. (2009) employed an ROA framework and found for a large plant that gross margins on ethanol required for entry under ROA are more than 200% greater than those implied under NPV. Gonzalez et al. (2012) indicate similar findings for ethanol plant investment decisions as ROA consistently suggests greater caution for making investments by yielding a larger inaction gap. Moreover, the effect of time consistency of governmental policies on investment decisions for biofuel production is revealed under ROA such as in Liu et al. (2018), who found a disruptive federal tax credit policy on biodiesel can lead to a significant negative impact on investment decisions. In addition to aiding decision-making about biofuel plant design, ROA has been employed to investigate the value of operational flexibility subject to commodity price dynamics (Kern et al., 2017).

Recent literature has extended ROA models to investigate opportunities for blended energy or green technologies. Employing ROA to analyze blended energy, such as cofiring wood pellets with coal, points to hedging the investment portfolio by reducing the market uncertainty embedded in the stochastic nature of individual energy prices. The resulting positive option value may induce an incentive to adopt an investment project despite higher costs (Vedenov et al., 2006; Xian et al., 2015). Overall, previous literature indicates that economic analysis employing an NPV framework can lead to substantially different feasibility assessments compared to ROA. This potential divergence between NPV and ROA is contingent on the specific nature of the price dynamics affecting the profitability of the investment, hence necessitating a specific analysis for a given investment decision. In this study, we build upon the previous body of work to explore for the first time how volatility in the aviation fuel market influences investment decisions in a jet biofuel refinery using carinata as feedstock.

2 | MATERIALS AND METHODS

To model the investment decision in an ROA framework and contrast optimal decisions with an NPV framework, we first develop the investment decision for a carinata biorefinery in a real options framework by following Dixit and Pindyck (1994), which yields a series of equations defining the market conditions for firm entry, mothballing, reactivation, and exit in a setting of stochastic prices. Then, we employ collected data on capital expenditures, operating costs, and jet fuel prices to calibrate the model and obtain an ROA versus NPV comparison.

2.1 | Carinata biorefinery investment decision in a real options framework

Real options analysis is built on the notions of uncertainty, which is captured by stochastic processes, irreversibility, and the ability to wait to make an investment decision. Stochastic processes combine the dynamics of a series with uncertainty, and in such combined models, the current state determines the probability distribution of future states, not the actual value (Dixit & Pindyck, 1994). Thus, a dynamic model with uncertainty built in provides more flexibility. Brownian motion (BM) is such a process with desired properties that is commonly used in investment theory. The main features of a BM are: (a) It is a Markov process, meaning the probability distribution of all future values of the process depends on its current value as all past information is already embedded in the current value; (b) It has independent increments, hence the probability distribution of a change in the process over a time interval is independent of non-overlapping time intervals; and (c) Changes in the process over a time interval are normally distributed. Even though these three properties may seem restrictive to fit in real-world price series, it is not unreasonable to assume that changes in the logarithm of price series are normally distributed (Dixit & Pindyck, 1994). This simply implies that the logarithm of price series, instead of the price series itself, can be modeled as a BM.

We consider a risk-neutral firm evaluating an investment opportunity in a carinata biorefinery plant, whereby the firm can pay a lump sum cost K (capital cost) per unit of output to construct the plant. When the option to invest is exercised and entry is made (the investment is made and the biorefinery is constructed), the firm acquires a biorefinery that produces annually a fixed amount of jet biofuel from carinata oil. It is assumed that the operation of the plant entails a cost flow C (operating cost) per unit of output. Once in operation, the firm has the option to abandon the project at a cost of E_X per unit of output. Since some of the capital cost can be recovered on exit, that positive liquidation value would reduce the total exit cost and can even result in a negative exit cost. When the firm exercises the option to delay investment in such a processing plant to a future potential date, the active project can be viewed as a composite asset with the firm holding the option to abandon.

Active firms also have the option to temporarily suspend their operations (mothballed state) and reactivate in the future based on the market conditions. Mothballing requires a sunk cost E_M per unit of expected output, which is typically much lower than the initial capital cost of construction. In addition, a mothballed firm incurs a maintenance cost flow of M per unit of output to maintain the existing capital. The plant can be reactivated in the future at an additional sunk cost R per unit of output. Mothballing rather than permanently shutting down would only make sense if the maintenance cost M is lower than the operating cost of an active plant C and if the reactivation sunk cost R is lower than the sunk cost of the initial investment K.

As mentioned earlier, one key economic feature explored in this study is that the return on investment from a carinata oil refinery is dependent on market jet fuel prices. Therefore, for a given carinata supply capacity, the optimal timing of investment and mothballing in terms of jet fuel prices and the price thresholds for an active firm and an idle firm are interlinked and determined simultaneously. As is traditional in

ROA, the firm is assumed to be a price taker and the stochastic process of jet fuel price P follows a geometric Brownian motion (GBM):

$$\mathrm{d}P = \alpha P \mathrm{d}t + \sigma P \mathrm{d}z,$$

where α is the drift rate and σ is the volatility parameter. The term dz denotes an incremental Wiener process and dt is a time interval.

The optimal entry, mothballing, reactivation, and exit strategies are determined by the price thresholds for jet fuel, P_E, P_M, P_R, and P_X, respectively. Furthermore, we assume that over an interval of lower revenue levels (0, P_{E}), there is no initiation of the investment in a carinata biorefinery. Active state prevails over the range (P_{M}, ∞), and mothballed state continues over some range of prices (P_{X}, P_{R}). The optimal strategy for an active firm is to remain in operation, but mothball the plant once prices fall to P_M. If prices rise to P_R, then the firm will reactivate the plant going back to the active state. However, it will be optimal to exit the market permanently once prices fall to P_X. These price triggers determine the optimal timings for initiation of a project (invest in a processing plant), as well as for suspension of an active one (mothballing), reactivation of a suspended project, and termination of an active one (permanently close down a processing plant) as a response to the stochastic process of jet fuel price over time interval dt.

The value of the firm conditional on its current status is a function of the exogenous state variable P. Let V_0 represents the value of an idle firm, V_1 represents the value of an active firm, and V_M represents the value of a mothballed firm. The Bellman equations for V_0, V_1, and V_M are then $rV_0dt = E(dV_0)$, $rV_1dt = E(dV_1) + (P - C)dt$, and $rV_M = E(dV_M) - Mdt$, respectively, where r is the discount rate of return representing the minimum rate of return required on the project and $\alpha < r$. Given the fact that there is no cost incurring for an idle firm, the total expected return for the firm is equal to the expected rate of capital appreciation, $E(dV_0)$. The total expected return for an active firm is equal to the expected capital gain plus net revenue from the investment. Finally, the total expected return for a mothballed firm is equal to the expected capital gain of the mothballed plant less ongoing maintenance costs.

Applying Ito's lemma to dV_0 and substituting the Bellman equation for V_0 yields $\mathrm{d}V_0 = V_0'(\alpha P\mathrm{d}t + \sigma P\mathrm{d}z) + \frac{1}{2}V_0''(\alpha^2P^2\mathrm{d}t^2 + \sigma^2P^2\mathrm{d}z^2 + 2\alpha\sigma P^2\mathrm{d}t\mathrm{d}z)$. After taking the expectation of this equation and substituting it into the Bellman equation for V_0 results in $\frac{1}{2}\sigma^2P^2V_0'' + \alpha PV_0' - rV_0 = 0$. The general solution to this differential equation is $V_0 = A_1P^{\beta_1} + A_2P^{\beta_2}$, where A_1 and A_2 are constants to be determined and β_1 and β_2 are roots of the quadratic equation $\frac{1}{2}\sigma^2\beta(\beta - 1) + \alpha\beta - r = 0$ given by:

$$\beta_1 = \frac{1}{2} - \frac{\alpha}{\sigma^2} + \sqrt{\left(\frac{1}{2} - \frac{\alpha}{\sigma^2}\right)^2 + \frac{2r}{\sigma^2}} > 1,$$

$$\beta_2 = \frac{1}{2} - \frac{\alpha}{\sigma^2} - \sqrt{\left(\frac{1}{2} - \frac{\alpha}{\sigma^2}\right)^2 + \frac{2r}{\sigma^2}} < 0.$$

Given that V_0 vanishes as P approaches zero, the coefficient A_2 becomes zero (Dixit & Pindyck, 1994). Therefore, subject to the boundary conditions, the solution for the idle firm over the interval (0, P_{E}) is $V_0 = A_1P^{\beta_1}$.

Applying the same procedure to the Bellman equation for V_1 yields $\frac{1}{2}\sigma^2P^2V_1'' + \alpha PV_1' - rV_1 + P - C = 0$. The general solution to this differential equation is $V_1 = B_1P^{\beta_1} + B_2P^{\beta_2} + \frac{P}{r-\alpha} - \frac{C}{r}$, where B_1 and B_2 are constants to be determined. The first two terms, $B_1P^{\beta_1} + B_2P^{\beta_2}$, represent the value of the option to abandon and the last two terms, $\frac{P}{r-\alpha} - \frac{C}{r}$, represent the value of the active project when the firm has to keep it operational regardless of any losses. As P approaches ∞, the probability of abandonment becomes very small, leading to the value of the exit option to diminish and the coefficient B_1 becomes zero. As a result, the solution for the active firm over the interval (P_{M}, ∞) is given by $V_1 = B_2P^{\beta_2} + \frac{P}{r-\alpha} - \frac{C}{r}$. Similar procedure for V_M leads to the general solution given by $V_{\mathrm{M}} = D_1P^{\beta_1} + D_2P^{\beta_2} - \frac{M}{r}$, where D_1 and D_2 are constants to be determined.

When the jet fuel price reaches the entry threshold P_E, the investing firm pays the lump sum cost of K per unit of output to exercise the investment option. At the entry threshold P_E, the corresponding value matching and smooth pasting conditions are:

$$V_0|_{P=P_{\mathrm{E}}} = V_1|_{P=P_{\mathrm{E}}} - K, \quad V_0'|_{P=P_{\mathrm{E}}} = V_1'|_{P=P_{\mathrm{E}}}.$$

For mothballing, these conditions are

$$V_1|_{P=P_{\mathrm{M}}} = V_{\mathrm{M}}|_{P=P_{\mathrm{M}}} - E_{\mathrm{M}}, \quad V_1'|_{P=P_{\mathrm{M}}} = V_{\mathrm{M}}'|_{P=P_{\mathrm{M}}}.$$

For reactivation, value matching and smooth pasting condition at the threshold P_R are

$$V_{\mathrm{M}}|_{P=P_{\mathrm{R}}} = V_1|_{P=P_{\mathrm{R}}} - R, \quad V_{\mathrm{M}}'|_{P=P_{\mathrm{R}}} = V_1'|_{P=P_{\mathrm{R}}}.$$

Finally, when the price is lower than the exit threshold P_X, the mothballed firm pays cost E_X to exercise the abandonment option. The corresponding value matching and smooth pasting conditions are:

$$V_{\mathrm{M}}|_{P=P_{\mathrm{X}}} = V_0|_{P=P_{\mathrm{X}}} - E_{\mathrm{X}}, \quad V_{\mathrm{M}}'|_{P=P_{\mathrm{X}}} = V_0'|_{P=P_{\mathrm{X}}}.$$

Substituting the functional forms of V_0, V_1, and V_M into the value matching and smooth pasting conditions yields the following eight equations, which determine the optimal entry, mothballing, reactivation, and exit jet fuel price thresholds for a carinata processing plant investment decision under ROA:

$$-A_1P_E^{\beta_1} + B_2P_E^{\beta_2} + \frac{P_E}{r-\alpha} - \frac{C}{r} - K = 0,$$

$$-\beta_1A_1P_E^{\beta_1-1} + \beta_2B_2P_E^{\beta_2-1} + \frac{1}{r-\alpha} = 0,$$

$$-B_2P_M^{\beta_2} - \frac{P_M}{r-\alpha} + \frac{C}{r} + D_1P_M^{\beta_1} + D_2P_M^{\beta_2} - \frac{M}{r} - E_M = 0,$$

$$-\beta_2B_2P_M^{\beta_2-1} - \frac{1}{r-\alpha} + \beta_1D_1P_M^{\beta_1-1} + \beta_2D_2P_M^{\beta_2-1} = 0,$$

$$-D_1P_R^{\beta_1} - D_2P_R^{\beta_2} + \frac{M}{r} + B_2P_R^{\beta_2} + \frac{P_R}{r-\alpha} - \frac{C}{r} - R = 0,$$

$$-\beta_1D_1P_R^{\beta_1-1} - \beta_2D_2P_R^{\beta_2-1} + \beta_2B_2P_R^{\beta_2-1} + \frac{1}{r-\alpha} = 0,$$

$$-D_1P_X^{\beta_1} - D_2P_X^{\beta_2} + \frac{M}{r} + A_1P_X^{\beta_1} - E_X = 0,$$

$$-\beta_1D_1P_X^{\beta_1-1} - \beta_2D_2P_X^{\beta_2-1} + \beta_1A_1P_X^{\beta_1-1} = 0.$$

2.2 | Carinata biorefinery investment decision in a NPV framework

Following Gonzalez et al. (2012), the entry and exit thresholds for a carinata processing plant under the NPV criteria are derived from the net return flows. Returns from an active project for year i are defined as:

$$\pi_i = P(1+\alpha)^i - C.$$

The present value of this return flow over an infinite time horizon is then:

$$\sum_{i=1}^{\infty} \frac{\pi_i}{(1+r)^i} = \frac{P(1+\alpha)}{r-\alpha} - \frac{C}{r}.$$

For an investment to stay active, the present value of the net return should exceed the lump sum cost, $\frac{P(1+\alpha)}{r-\alpha} - \frac{C}{r} - K > 0$. If the present value of the net return is lower than the scrap value of the firm, $\frac{P(1+\alpha)}{r-\alpha} - \frac{C}{r} < -E_X$, the active firm should abandon the project. Thus, the entry (E) and exit (X) price thresholds under the NPV approach are given by:

$$\mathrm{NPV}_E = \left(\frac{r-\alpha}{1+\alpha}\right)\left(K + \frac{C}{r}\right),$$

and

$$\mathrm{NPV}_X = \left(\frac{r-\alpha}{1+\alpha}\right)\left(\frac{C}{r} - E_X\right).$$

2.3 | Data

Parameterization of the real options and NPV models requires two key costs (initial investment and operating cost) per unit of output expressed in \$/gallon of jet fuel and estimates of the drift and volatility parameters for the jet fuel price process. Initial investment cost corresponds to the expenses incurred at the initial construction period including site preparation, building of the plant, land rental, construction contingency, engineering and permitting, and electrical and utilities. Operating cost refers to the cost incurred during production such as feedstock, input, and processing costs, labor, repairs and maintenance, insurance, marketing, and depreciation. Exit costs are contingent upon the liquidation value of the assets which are typically assumed to be a portion of the initial investment cost in the plant. Few previous engineering studies have explored the cost of constructing and operating a jet biofuel processing plant utilizing carinata as a feedstock. McGarvey and Tyner (2018) consider a pioneer brownfield plant employing both new and repurposed equipment producing various products with an initial investment cost of \$114 million and daily jet fuel production of 65,500 gallons, approximately 30% of which are assumed to be made from carinata oil. Chu et al. (2017) consider a larger scale plant with 105.14 million gallons of annual jet fuel production with an initial investment of \$443 million (in 2019 dollars) for a brownfield facility and annual operating expenses of \$315 million (in 2019 dollars) inclusive of the cost of carinata feedstock. We use these estimates from Chu et al. (2017) as our baseline values for investment and operation costs. It is important to note that studies focused on biofuels from established market traded feedstocks (such as corn ethanol) model either both processes (feedstock and fuel prices) or the gross margin as a stochastic process (Gonzalez et al., 2012; Schmit et al., 2009). Carinata in the United States is currently produced and sold on a contract basis; hence, historical market price data do not exist and thus modeling the gross margin is not feasible.

Following Schmit et al. (2009), the sunk exit costs are defined as 25% of the investment costs, $E_X = -0.25 \times K$. The sunk costs associated with mothballing and reactivation are defined as 5% and 10% of the investment cost, respectively, $E_M = -0.05 \times K$ and $R = -0.10 \times K$. Finally, the maintenance cost of a mothballed firm is defined as 2.5% of the initial sunk cost, $M = -0.025 \times K$. Table 1 summarizes the baseline costs per unit of jet biofuel output.

Monthly price data (February 2012–October 2019) for US Gulf coast kerosene-type jet fuel are obtained from the Energy Information Administration. Over this timeframe, jet fuel prices (nominal) ranged between \$0.93 and \$3.09 per gallon, with an average monthly price of \$2.12 per gallon, as illustrated in Figure 1.

TABLE 1 Baseline cost parameters for ROA and NPV models

Sunk cost	\$/gallon	Flow cost	\$/gallon	Interest cost	%
Investment cost (K)	4.21	Operating cost (C)	3.00	Discount rate (r)	7
Mothballing cost (E_M)	0.21	Maintenance cost (M)	0.10		
Reactivation cost (R)	0.42				
Exit cost (E_X)	−1.05				

Note: Values are in 2019 dollars. All costs are expressed in dollars per gallon of jet fuel produced.

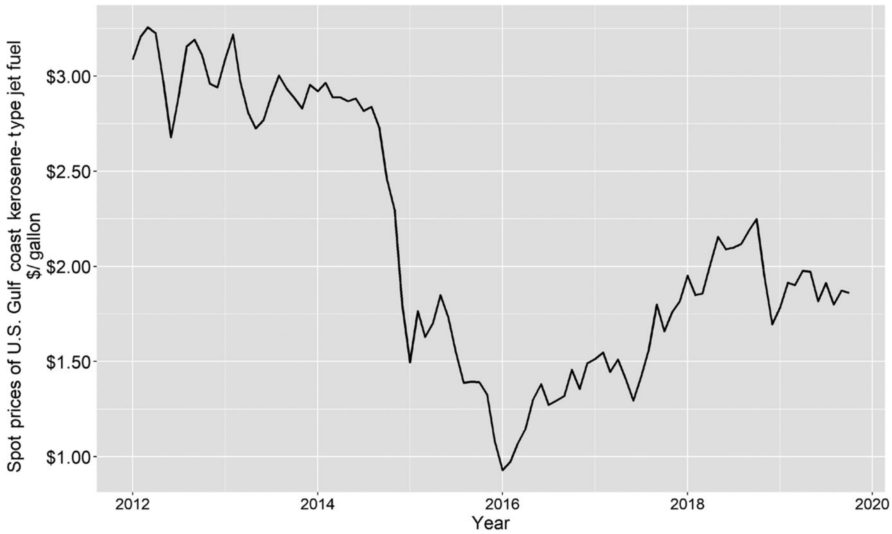

FIGURE 1 Monthly U.S. Gulf Coast kerosene-type jet fuel price
Source: EIA

Prior to estimating the GBM parameters for jet fuel prices, structural break tests and unit root tests are conducted. Following Fuller (2009), we employed an augmented Dickey–Fuller test and failed to reject (with a p-value of 0.93) the existence of a unit root, indicating that the series was nonstationary. Moreover, following Andrews (1993) and Andrews and Ploberger (1994), we detected one structural break in November 2014 with a 95% confidence interval from October to December 2014. The collapse in fuel prices was mainly driven by a plunge in the Brent oil price in 2014 due to an increased supply glut that failed to trigger demand growth in a slowing global economy (Khan et al., 2017). Successive pessimistic economic perspectives on the future oil market also yielded sustained declines in the price of oil (Baumeister & Kilian, 2016). Hence, in order to investigate the impact of changing price characteristics on the price thresholds, two sample periods were selected: (1) the series after the breakpoint, January 2015–October 2019; and (2) the entire series, February 2012–October 2019. For each period, the ROA and NPV models were run and compared to assess the impact of failure to appropriately account for changes in the underlying data generation process.

The drift and volatility parameters were computed as the sample mean and standard deviation of the difference between the natural logarithm of two consecutive prices, that is, $\Delta \ln(P_t) = \ln P_t - \ln P_{t-1}$. For the sample period 2015–2019, the variable $\ln P$ is assumed to follow a BM with monthly drift rate of 0.003 and volatility parameter of 0.125. The resulting annual GBM parameter estimates for variable P are $\hat{\alpha} = 0.003 + 0.125^2 = 0.011$ and $\hat{\sigma} = 0.125$. The GBM parameter estimates for the entire sample window of 2012–2019 were derived in a similar fashion. Given these sample means and standard deviations for the variable $\ln P$, the resulting annual GBM parameter estimates, $\hat{\alpha}$ and $\hat{\sigma}$, were −0.022 and 0.114, respectively. Therefore, the sample period 2012–2019 suggests a potential decline in prices in the long run. However, if one focuses on the recent post-break time frame 2015–2019, a rising price series with slightly more fluctuations is expected in the long run. A summary of these parameters for the sample periods with and without consideration of a structural break is detailed in Table 2.

3 | RESULTS

Table 3 presents entry and exit jet biofuel prices for the NPV and ROA models, as well as the price thresholds for mothballing and reactivating the biorefinery. The results are presented considering jet fuel price dynamics post the structural break in 2014, as well as for the entire sample period of 2012–2019, ignoring the presence of a structural break. As seen in Table 3, there is a significant difference in the jet fuel price thresholds required for a profitable investment in a carinata processing plant under ROA as compared to NPV.

TABLE 2 Annual drift rate and instantaneous volatility for geometric Brownian motion

	Full sample February 2012–October 2019	Post-structural break January 2015–October 2019
GBM parameters for variable *P*		
Drift rate, α	−0.022	0.011
Volatility parameter, σ	0.114	0.125

Note: Monthly drift and volatility parameters obtained from monthly data were converted to annual values.

TABLE 3 Jet fuel price thresholds for a carinata processing plant under ROA and NPV

Price thresholds	Post-structural break January 2015–October 2019	Full sample February 2012–October 2019
P_E	$4.00	$4.22
P_R	$3.31	$3.37
P_M	$2.50	$2.59
P_X	$2.30	$2.72
NPV_E	$2.76	$4.42
NPV_X	$2.57	$4.12

Note: P_E, P_R, P_M, and P_X are the trigger prices for entry, reactivation, mothballing, and exit obtained with the ROA analysis. NPV_E and NPV_X are trigger prices for entry and exit obtained with the NPV analysis.
Abbreviations: NPV, net present value; ROA, real options analysis.

Furthermore, contrasting entry and exit thresholds for the two jet fuel price sample windows leads to different relative magnitudes between the NPV and ROA thresholds due to the presence of a positive drift rate for 2015–2019 and a negative drift rate for 2012–2019.

Under the baseline parameter assumptions, a carinata processing plant producing jet biofuel is investable at a jet fuel price threshold of $4.00 per gallon under the ROA framework, which is 1.5 times higher than the corresponding NPV price threshold of $2.76 per gallon during the post-structural break time period 2015–2019. At the time of this study in February of 2021, jet fuel market prices were approximately $1.45 per gallon, indicating that under both ROA and NPV models, the necessary conditions for profitable investment in a biorefinery are not met without the inclusion of RIN credits for sustainable aviation fuels. Exit thresholds under ROA and NPV were estimated to be $2.30 and $2.57 per gallon, respectively, indicating that a firm operating a carinata processing plant should optimally exit later under the ROA framework. The ROA model estimated that a firm should enter the mothballed state when jet fuel prices fall to $2.50, which is similar to the estimated price threshold for exit under NPV. This captures the option value of potentially reactivating the biorefinery if price conditions improve rather than immediately exiting and capturing the liquidation value of the plant. Overall, the substantial difference in estimated price thresholds between the NPV and ROA models highlights the impact of considering the stochastic dynamics of jet fuel prices in the investment decision.

If we fail to consider the structural break in the jet fuel price series and use the price data of the entire 2012–2019 period, the drift is negative (−0.022) and the volatility parameter is smaller (0.114 vs. 0.125) in the ROA model. In this case, the ROA entry price threshold ($4.22) is smaller than that under NPV ($4.42). This relationship is the opposite of that found under the post-break period, where the drift is positive and volatility parameter is higher. That is, under ROA, which incorporates the stochastic nature of jet fuel prices into the investment decision, the fuel price required for a profitable investment is lower than the price under NPV. It is worth noting that changes in the drift and volatility parameters have opposite effects on the ROA entry prices. When the drift parameter decreases, idle firms will wait longer to invest to take advantage of possible gains from higher returns in the future. In addition, the value of staying in the active mode decreases, making currently operating firms more eager to exit. As a result, ROA entry and exit prices both increase. A lower volatility parameter decreases the value of waiting to invest, resulting in a lower ROA entry price. The value of staying active decreases in this case as well, leading to a higher ROA exit price. Therefore, the difference in the ROA entry price found for the entire sample and for the post-break sample is due to a combined effect of drift and volatility changes.

Similarly, the exit price threshold under ROA ($2.72) is lower than that under NPV ($4.12). These results mean that investment in a carinata processing plant should be made sooner under ROA compared to NPV and, once the plant is operating, it should continue to operate under a wider range of prices under ROA. Interestingly, the entry and exit price thresholds under ROA for both sample periods (2012–2019 vs. 2015–2019) are very similar ($4.22 vs. $4.00 for entry price; $2.72 vs. $2.30 for exit price), and the same is true for the inaction gap between ROA entry and exit prices ($1.50 vs. $1.70). The negative drift in the full sample period implies that idle investments in a carinata processing plant be delayed or that active investments be terminated sooner. In this case, the ROA mothball price threshold is less than the exit price threshold, implying that the plant should exit and trigger the liquidation value without entering into a mothballed state with the prospect of improving price conditions. In contrast, NPV entry and exit price thresholds vary much more between the two sample periods. Both ROA entry and exit prices during 2012–2019 are 1.6 times higher than the NPV values calculated for the period 2015–2019. Both entry and exit thresholds under NPV increase by 60% as the drift rate declines to −0.022. However, ROA provides insight into this investment decision by investigating threshold behavior changes to the volatility rate. Taking the decline in the volatility parameter (0.125 vs. 0.114) into account, ROA suggests to increase the threshold for entry by only 5.5% and the exit threshold by 18%.

Overall, these findings indicate that failing to account for the stochastic nature of prices and the ability to delay investment decisions can lead to a significantly different decision as to when to invest in a carinata processing plant and when to mothball or abandon an operating carinata plant. Under the baseline scenario, we find ROA entry thresholds to be 1.5 (during 2015–2019) and 0.9 (during 2012–2019) times the NPV entry thresholds and ROA exit thresholds to be 0.9 (during 2012–2019) and 0.7 (during 2015–2019) times the NPV exit triggers. Moreover, failure to consider changes in the underlying price dynamics, such as structural breaks, can lead to markedly different investment thresholds.

To further illustrate the impact of volatility on optimal price thresholds, Figure 2 presents estimates of the price thresholds over a range of volatilities with the drift rate fixed at zero. At low levels of volatility, entry and exit thresholds implied under both NPV and ROA are similar. It is also the case that at volatility levels less than 10% the option to mothball does not make economic sense, and simply exiting the industry rather than suspending the operation becomes optimal. This is because the odds of improved prices in the future are low (Schmit et al., 2009). However, as the volatility increases, both the ROA entry and reactivation thresholds increase, whereas the mothball and exit thresholds decrease. This result reflects that the value of the option to invest increases with volatility and, therefore, idle firms will optimally wait longer to invest. In contrast, active firms find it more profitable to stay active longer in the market before exercising the option to exit. Due to the absence of direct consideration of this dynamic in a static NPV analysis, the disparity between optimal investment decisions under ROA and NPV increases in a more volatile price environment.

3.1 | Sensitivity analysis

Using the biorefinery investment and operation cost estimates of Chu et al. (2017) and the mothballing, reactivation, and exit cost assumptions of Schmit et al. (2009), the previous section presented point estimates for the price thresholds. To assess the sensitivity of price thresholds to the various assumptions, this section considers costs over a wider range of values. All results are presented assuming the drift and volatility parameters for jet fuel prices from the post structural

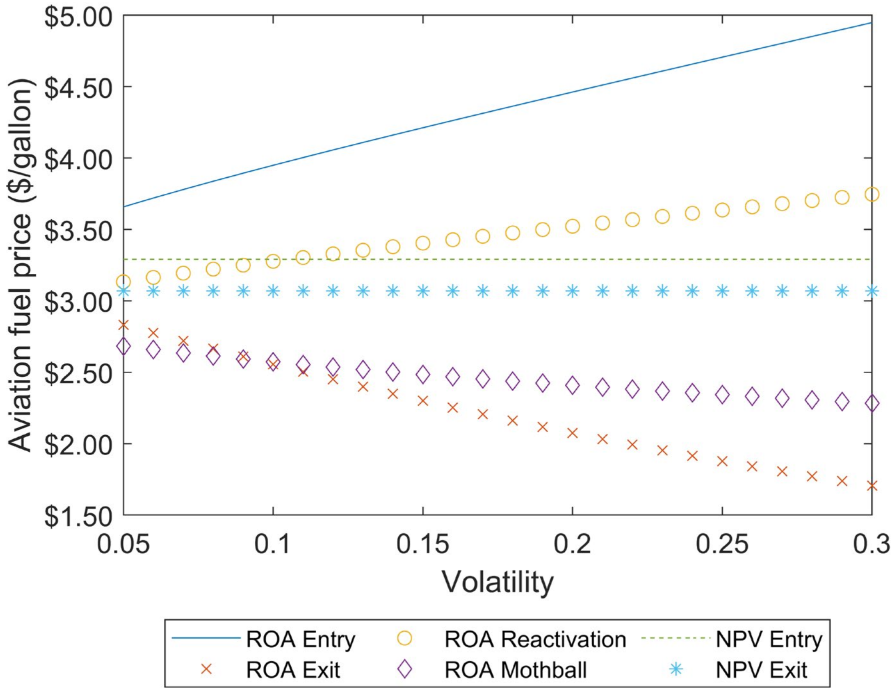

FIGURE 2 Sensitivity of price thresholds to volatility

break period 2015–2019. Our qualitative results remain the same under the assumption of a zero drift rate. Corresponding figures are available from the authors upon request.

Figure 3 presents price thresholds for operating expenses 30% lower or greater than the baseline value of \$3.00 per gallon of aviation fuel produced from carinata. As would be expected, both NPV and ROA price thresholds are positively related to the operating cost. Over the entire range of operating costs, the relationship $P_E > P_R > NPV_E > NPV_X > P_M > P_X$ is preserved with the divergence between ROA and NPV entry and exit thresholds increasing (in absolute terms) as operating costs increase.

The baseline cost parameters based on the economic analysis by Chu et al. (2017) considered an initial investment cost of \$443 million for the construction of the biorefinery. Figure 4 presents entry and exit prices under higher and lower initial investment expenses. It is important to note that the assumptions on the exit, mothball, and reactivation costs as a percentage of the initial investment cost are maintained in this sensitivity analysis. As expected, entry price

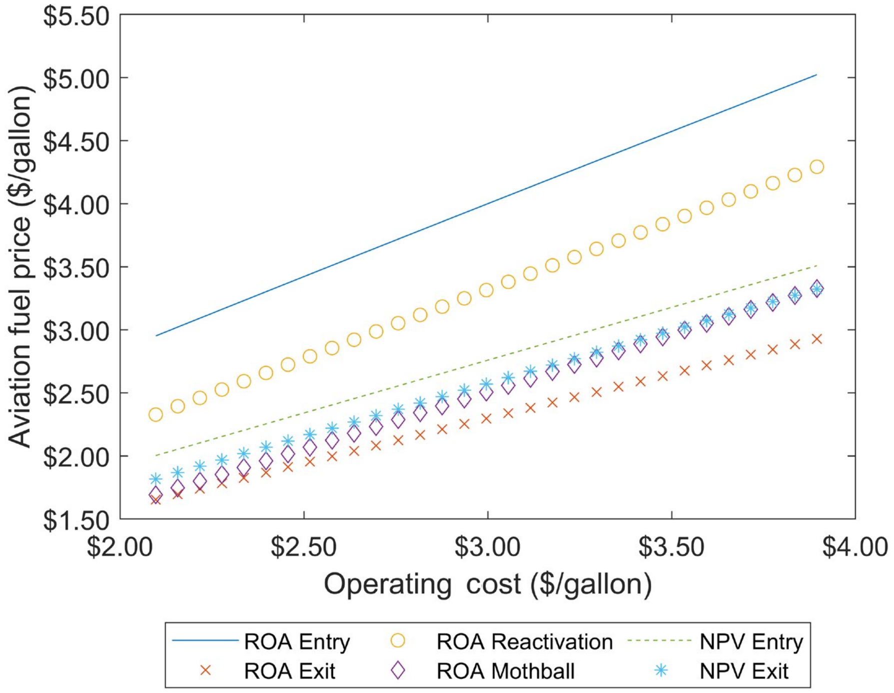

FIGURE 3 Sensitivity of price thresholds to operating cost

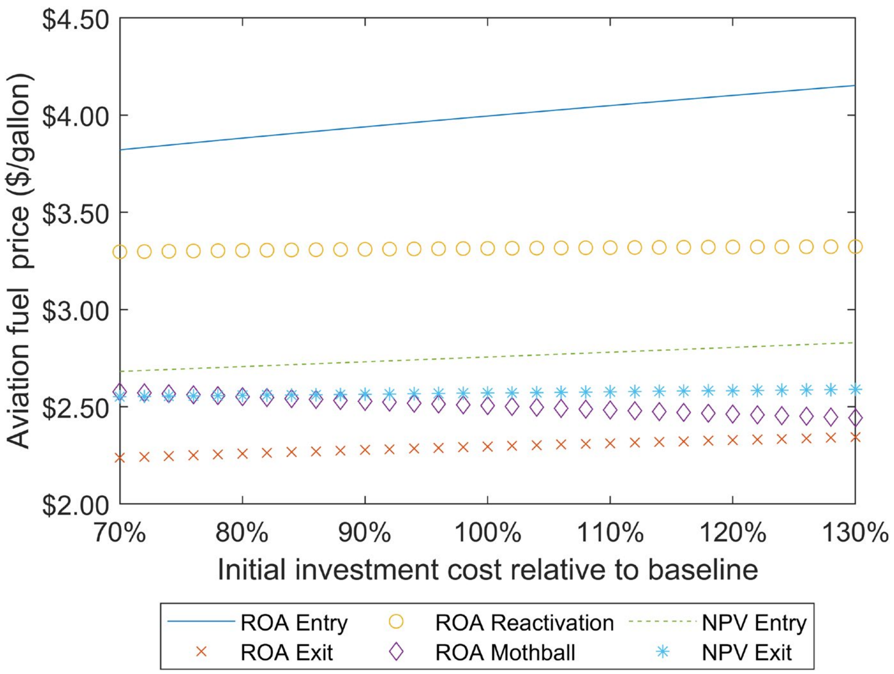

FIGURE 4 Sensitivity of price thresholds to initial investment cost

thresholds (NPV and ROA) are positively related to the initial investment cost. That is, for a positive economic return on the biorefinery, higher aviation fuel prices are required to take on a more expensive initial outlay of capital. Due to the assumption that the liquidation value of the biorefinery is a percentage (25%) of the initial investment cost, the exit price thresholds for both the NPV and ROA models are also increasing with the investment cost.

Assessing the impact of the assumed liquidation value of a biorefinery upon exiting the market, Figure 5 presents price thresholds ranging from 0% to 50% of the initial capital cost (the baseline value was 25%). The most significant impact of various biorefinery liquidation values is on the exit price threshold under the ROA model. As the liquidation value increases (as an investor can recoup more of their initial construction expenses by selling the facility), the ROA exit price

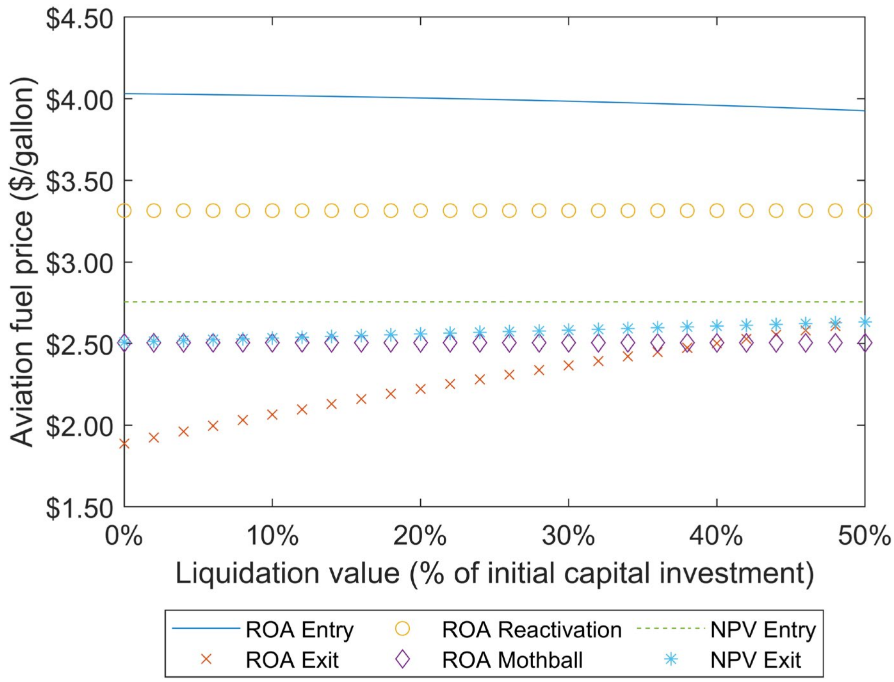

FIGURE 5 Sensitivity of price thresholds to liquidation value (exit cost)

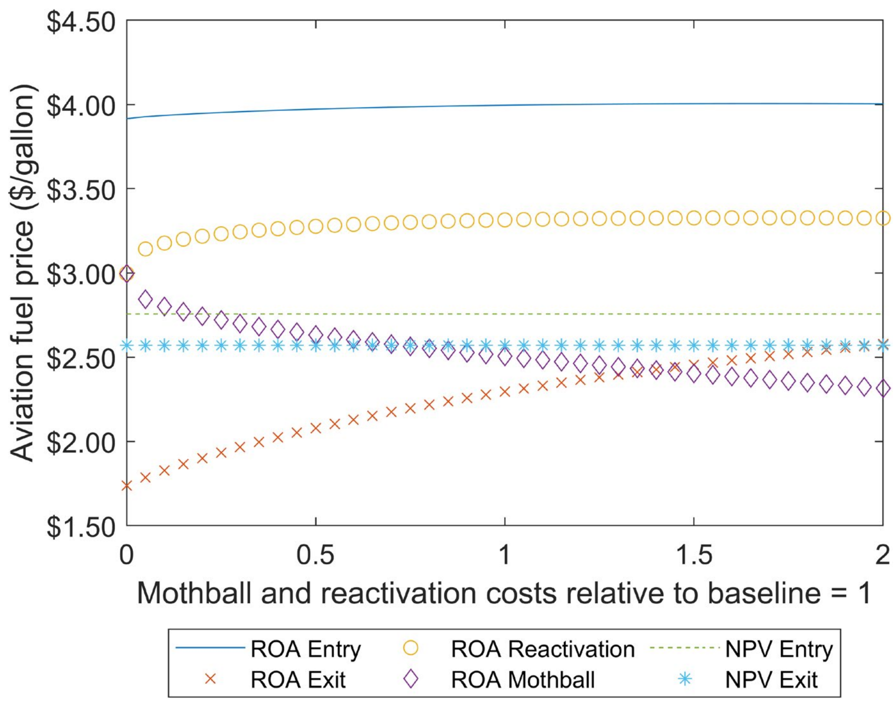

FIGURE 6 Sensitivity of price thresholds to mothball and reactivation costs

increases reflecting the higher value of trigger for this option. As can be seen, at sufficiently high liquidation values, the ROA exit threshold is greater than the mothball price threshold, implying that it is optimal to exit and recoup the liquidation value rather than enter the mothball state and wait to see if price conditions improve for reactivation.

Figure 6 presents price thresholds over a range of parameter values for mothball and reactivation costs. In the baseline model presented in the previous section, it was assumed that mothballing a biorefinery incurs a sunk cost of 5% of the initial investment cost and a maintenance expense of 2.5%, whereas reactivating the plant from a mothballed state incurs a sunk cost of 10% of the initial investment. Using these costs as baseline, Figure 6 presents price thresholds when these costs are varied ±100%. In line with expectations, as mothball and reactivation costs increase, the price threshold for mothballing decreases and the reactivation price threshold increases. This drives an increasing wedge between both states for the biorefinery and reduces the likelihood that a plant will enter the mothball state and, once entered, that it will be reactivated. Similar to the results presented in Figure 5, if the mothball expense becomes sufficiently high, an active firm will choose to exit and trigger the liquidation value of the biorefinery without entering the mothball state to recoup the initial investment and reinvest elsewhere.

4 | DISCUSSION

Biofuels produced from nascent feedstocks, like any other new entrant into an industry, face significant challenges achieving the scale necessary to successfully compete with conventional fossil fuels in order to ultimately deliver their environmental, economic, and national security benefits. To be competitive and take advantage of economies of scale requires substantial investment in refining capacity, an investment that inherently involves risk. This study, focused on the production of sustainable jet biofuel from *B. carinata*, showed that the methods used to assess the economic feasibility and timing of investment in a large-scale biorefinery could lead to very different conclusions on viability. Although the NPV is a widely employed method for evaluating investment opportunities, it fails to consider price dynamics and the ability to delay investments. Our analysis reveals for the base scenario that by employing ROA, which models jet fuel price dynamics as a GBM, the implied jet fuel price threshold for investing in a biorefinery is more than 45% greater than what is found through the traditional NPV analysis. Furthermore, we show the importance of capturing major shifts in the stochastic nature of market prices that may occur. Our analysis reveals that failure to consider a structural break in the jet fuel price series leads to widely different industry entry and exit thresholds.

The differential between NPV and ROA thresholds for profitable investment in a biorefinery that converts carinata oil into jet biofuel highlights several policy incentives that could be implemented to foster and support the development of a sustainable jet biofuel industry. Our analysis shows that policy initiatives that reduce jet fuel price volatility faced by a carinata biorefinery, such as long-term contracts or price guarantees for bio-based aviation fuels, can aid in reducing the threshold required for biorefinery investment. As a result, such policy will facilitate longer term known or fixed price contracts between a carinata biorefinery and both private airline carriers and military aviation agencies. Moreover, given the substantial sunk costs of constructing a biorefinery, policy initiatives such as favorable loan terms and tax credits aimed at supporting investments in renewable energy sources would, as shown in the sensitivity analysis assessing the impact of investment costs, reduce the threshold jet fuel price required under both NPV and ROA models for profitable investment. As also shown in the sensitivity analysis, initiatives that would reduce the operating costs for the production of aviation fuel from carinata would also improve the viability of a biorefinery. Continued funding of public and private efforts to improve carinata seed varieties, particularly new hybrid varieties currently in development, to enhance yields would aid in reducing the cost of aviation fuel production from carinata. Overall, for renewable feedstocks like carinata to successfully transition to a large-scale production and compete/displace petroleum-based jet fuels, our analysis indicates that incorporating the dynamics of jet fuel prices into the investment decision process via ROA is important to consider. Policy initiatives that can reduce investment and operating costs, as well as dampen the effects of jet fuel price volatility on revenues to a carinata biorefinery, will aid the development of large-scale jet biofuel production to reduce the carbon emissions of the aviation sector.

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DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available from the corresponding author upon request.

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