Market Cost of Renewable Jet Fuel Adoption in the United States

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Abstract

The US Federal Aviation Administration (FAA) has a goal that one billion gallons of renewable jet fuel is consumed by the US aviation industry each year from 2018. We examine the cost to US airlines of meeting this goal using renewable fuel produced from a Hydroprocessed Esters and Fatty Acids (HEFA) process from renewable oils. Our approach employs an economy-wide model of economic activity and energy systems and a detailed partial equilibrium model of the aviation industry. If soybean oil is used as a feedstock, we find that meeting the aviation biofuel goal in 2020 will require an implicit subsidy to biofuel producers of $2.69 per gallon of renewable jet fuel. If the aviation goal can be met by fuel from oilseed rotation crops grown on otherwise fallow land, the implicit subsidy is $0.35 per gallon of renewable jet fuel. As commercial aviation biofuel consumption represents less than two per cent of total fuel used by this industry, the goal has a small impact on the average price of jet fuel and carbon dioxide emissions. We also find that, as the product slate for HEFA processes includes diesel and jet fuel, there are important interactions between the goal for renewable jet fuel and mandates for ground transportation fuels.

Contents

1. INTRODUCTION

The global aviation industry aims to achieve carbon neutral growth by 2020 and reduce carbon dioxide (CO_2) emissions by 50% relative to 2005 levels by 2050 (IATA, 2009). To achieve these goals, the International Air Transport Association (IATA) has outlined a "four pillar" approach that includes (i) technology, (ii) operations, (iii) infrastructure and (iv) economic measures. Of the four pillars, technology is seen as the most promising option for reducing emissions and includes improved engine technologies, aircraft design, new composite lightweight materials, and use of biofuels that have significantly lower lifecycle greenhouse gas

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(GHG) emissions than conventional fuel (IATA, 2009). Use of renewable jet fuel is also expected to reduce fuel price volatility (IATA, 2010).

The US Federal Aviation Administration (FAA) has set a goal for the US aviation industry to consume one billion gallons of renewable jet fuel each year from 2018 onwards (FAA, 2011, p.10). This goal is an aggregate of renewable fuel targets for the US Air Force, the US Navy and US commercial aviation. The renewable fuel target for commercial aviation represents 1.7% of predicted total fuel consumption by US airlines in 2018. The aviation biofuel goal is set against a backdrop of a renewable fuel standard for ground transportation, which sets minimum annual volume requirements for use of advanced biofuels and total renewable fuels that must be used through 2022.

In this paper, we examine the cost to commercial aviation of meeting the renewable fuel target set out by the FAA. As the cost of renewable jet fuel currently exceeds the price of conventional jet fuel, we assume that the aviation biofuel goal is met by airlines and the military voluntarily purchasing renewable fuel. Our modeling framework uses an economy-wide model of economic activity and energy systems to determine the implicit subsidy to renewable jet fuel producers and the impact of the goal on overall economic activity, and a partial equilibrium model of air transportation to estimate changes in aviation operations.

Our analysis builds on several previous studies of the impact of climate policies on aviation. Hofer *et al.* (2010) and Winchester *et al.* (2013) evaluate the impact of US carbon prices on the aviation industry. The effects of including aviation in the EU ETS are investigated by, among others, Anger (2010), Scheelhaase *et al.* (2010), Vespermann and Wald (2011) and Malina *et al.* (2012). More pertinent for our analysis are studies that consider the use of biofuels in air transportation. Bauen *et al.* (2009) estimate the uptake of biofuels by the global aviation industry between 2010 and 2050. Their analysis considers a range of conversion technologies, feedstocks and carbon prices. Consumption of aviation biofuels is determined by estimates of time-dependent conversation and feedstock costs and deployment of new technologies. The authors' results indicate that biofuels will account for a low proportion of global aviation fuel consumption before 2020, but could make a significant contribution over a longer time horizon. Under a high carbon price with optimistic assumptions regarding the development of biofuel technologies, 100% of global aviation fuel consumption is sourced from biofuels by the early 2040s. With no carbon price and slow development of biofuel technologies, biofuels account for

3% of aviation fuel use in 2030 and 37% in 2050. Sgouridis *et al.* (2011) examine the impact of several policies and strategies for mitigating global CO_2 emissions from air transportation. In their renewable fuels scenarios, the authors assume that the price of biofuels is equal to the price of conventional fuel and specify an exogenous consumption path for biofuels. Sgouridis *et al.* (2011) assume that the proportion of biofuels in total fuel consumption by commercial aviation is 0.5% in 2009 and rises to 15.5% in 2024 in a "moderate" scenario, and to 30.5% in an "ambitious" scenario. Under these assumptions, the authors estimate that biofuels reduce cumulative CO_2 emissions from aviation between 2004 and 2024 by between 5.5% and 9.5% relative to their reference case. Our analysis extends earlier work by explicitly modeling the production and cost of biofuels, including land constraints and competition for resources among sectors, and considering interactions between aviation biofuel strategies and existing biofuel policies.

This paper has six further sections. The next section outlines aviation biofuel pathways. Section 3 provides information on RFS2 and aviation biofuel goals and discusses interactions between renewable fuel targets for ground and air transportation. Our modeling framework and the scenarios we consider are set out in Section 4. Results are presented and discussed in Section 5 and a sensitivity analysis is considered in Section 6. The final section concludes.

2. AVIATION BIOFUEL PATHWAYS

Renewable jet fuel processes currently certified for use in commercial aviation include fuel produced from a Hydroprocessed Esters and Fatty Acids (HEFA) process (also known as Hydrotreated Renewable Jet fuel) and biomass-to-liquid (BTL) via a Fischer-Tropsch (F-T) process.[1] Both these processes produce a product slate that includes diesel, jet fuel and other co-products. BTL production involves vaporizing a mixture of biomass and coal and converting the gas to synthetic liquid fuels through an F-T process. Fuel produced using an F-T process was certified for aviation by ASTM International Standard D7566 in September 2009. A 50% blend of F-T synthetic fuel with conventional fuels is currently used by O.R. Tambo International Airport in Johannesburg for use in commercial aviation (Sasol, 2011).

Under a HEFA process, renewable oil (vegetable oils, animal fat, waste grease and algae oil) is processed using hydrogen treatment (hydroprocessing) to yield a fuel in the distillation range

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[1] Processes expected to be certified in the near future include alcohol-to-jet and synthetic kerosene containing aromatics. Other possible pathways include sugar-to-jet and fuel from pyrolysis processes. See Hileman *et al.* (2013) and OECD (2012) for a comprehensive list of renewable jet fuel processes.

of jet fuel, diesel and naphtha (Pearlson, 2011; UOP, 2005). On July 1, 2011, ASTM approved the jet fuel product slate of HEFA under alternative fuel specification D7566 (ASTM, 2011). HEFA fuel that meets this specification can be mixed with conventional jet fuel, up to a blend ratio of 50%. HEFA is currently the leading process for producing renewable jet fuel and several airlines (including Aeroméxico, Air China, Air France, Finnair, Iberia, KLM, Lufthansa and United) have performed commercial passenger flights with blends of up to 50% renewable fuel produced using this technology (IATA, 2012). In addition to the popularity of HEFA fuel in demonstration flights, Bauen *et al.* (2009) estimate that the near-term uptake of biofuels will be greatest when oil crops are used in a HEFA process. For these reasons, our economic analysis focuses on meeting the FAA aviation biofuel goal using HEFA-derived fuel.

Pearlson (2011) estimates production costs and outputs for a HEFA process using soybean oil as a feedstock. When the proportion of output that is liquid fuel is maximized, a HEFA process with this feedstock produces, by weight, 76.9% (ultra-low-sulphur) diesel, 14.4% jet fuel, 4.7% propane, 2% naphtha and 1.8% liquefied petroleum gas (LPG).[2] In volume terms, five gallons of renewable diesel are produced for each gallon of renewable jet fuel. The product mix can be altered to produce more jet fuel and less diesel, but changing the product slate requires additional processing and increases the proportion of output that is comprised of less-valuable co-products, such a naphtha and LPG. Stratton *et al.* (2011), estimate that, when there is no land use change, the lifecycle CO_2 emissions from HEFA fuel with a soybean oil feedstock relative to emissions from conventional jet fuel range from 31% to 68% with a median estimate of 42%.

Historical and predicted prices (in 2010 dollars) for soybean oil and jet fuel are presented in **Figure 1**. On average, the price of soybean oil was $1.19 more than the price of jet fuel between April 1990 and June 2012 and future predicted soybean oil prices are between $1.07 and $0.66 above the price of jet fuel. These numbers indicate that HEFA production using a soybean oil feedstock is unlikely to be cost competitive with conventional jet fuel in at least the next decade or so.

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[2] HEFA processes also produce outputs that currently have no commercial value (water and CO_2). These co-products are not included in the volume proportions reported above.

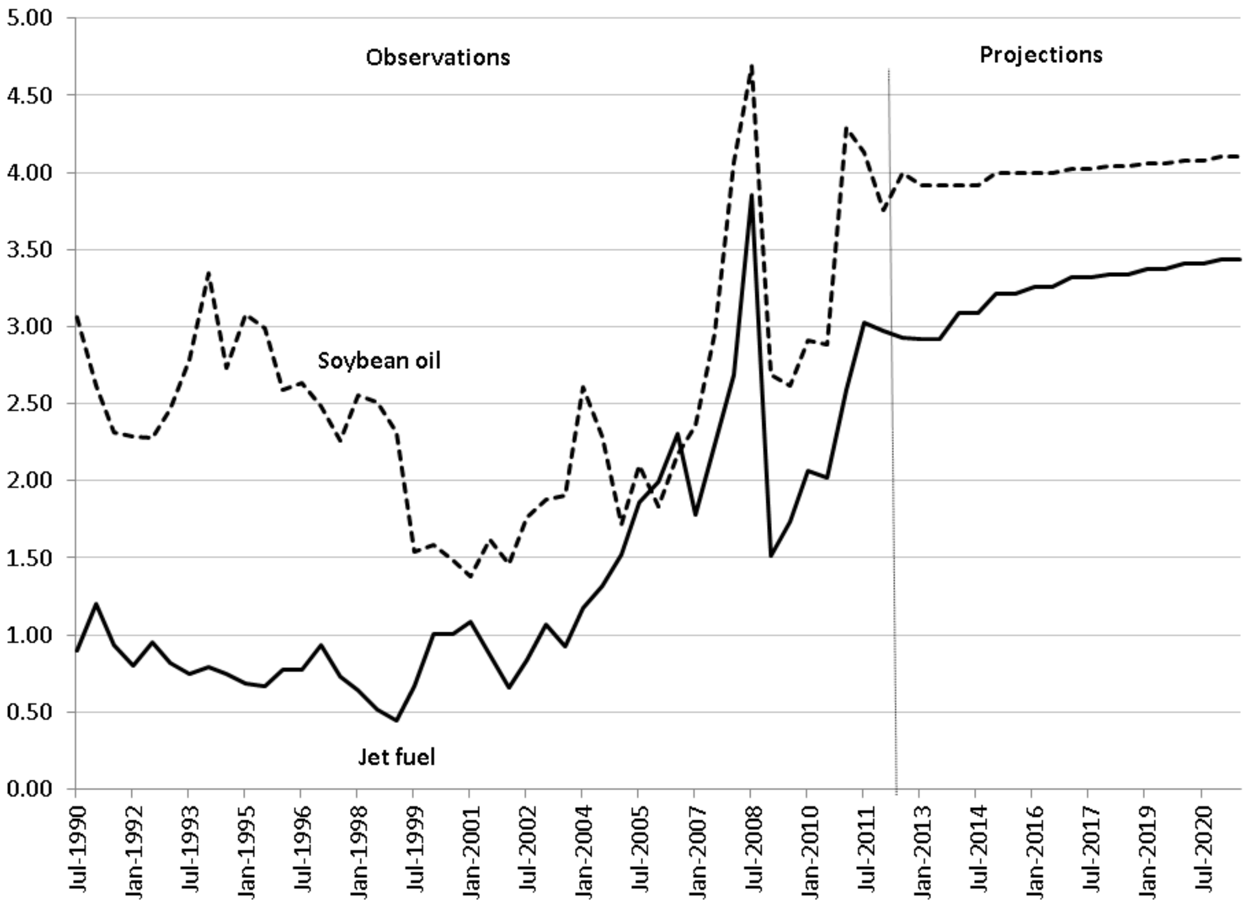

Figure 1. Soybean oil and jet fuel prices, 2010$/gallon. *Source:* Historical jet fuel and soybean oil prices are sourced from EIA (2012b) and World Bank (2012) respectively; and projected jet fuel and soybean oil prices are taken from EIA (2012a) and USDA (2012) respectively.

Potentially low-cost feedstocks for HEFA processes include oilseed crops grown in rotation with other crops on land that would otherwise be left fallow (Shonnard, 2010; EPA, 2012). Two promising rotation crops in the US include *Thlaspi arvense L.* (commonly known as pennycress) and *Camellia sativa* (camelina).[3] Pennycress is a winter annual crop that could potentially be grown in the Midwest in rotation with summer corn and spring soybean crops. Traditionally, land is left fallow between the fall corn harvest and before spring soybean planting. Pennycress requires minimal inputs (fertilizer, pesticides and water), is compatible with existing farm

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[3] Other potential oilseed rotation crops include *Brassica carinata*, *Brassica napus L.* (Canola/Rapeseed), *Linim usitatissimum L.* (Flax), *Sinapis alba L.* (Yellow mustard), *Carthamus tinctorius L.* (Safflower) and *Helianthus annuus L.* (Sunflower).

infrastructure, and could potentially be grown on 40 million acres each year.[4] Camelina is well suited to be rotated with wheat grown in dry areas, where farmers leave land fallow once every three to four years to allow moisture and nutrients to accumulate and to control pests (Shonnard *et al.*, 2010). Camelina is currently grown on 50,000 acres of land in the US. Approximately 95% of current production is used for testing purposes and 5% is used as a dietary supplement or in the cosmetics industry (EPA, 2012). According to EPA (2012), camelina could potentially be grown in rotation with wheat on three to four million acres of land each year that would otherwise be left fallow. When calculating the lifecycle GHG emissions from camelina production, EPA (2012) assumes that there are no direct impacts on land use or food supply. If oilseed rotation crops do not have detrimental effects on pest control and the moisture and nutrient content of the soil relative to leaving the land fallow, the opportunity cost of land used for these crops will be zero. Thus, oil from rotation crops could potentially be produced at a lower cost than oil from conventional crops. Combining estimates on available acres, oil content and yields suggests that, each year, land currently left fallow could be used to produce 2.5 to 6 billion gallons of oil from pennycress[5] and 0.1 to 0.4 billion gallons from camelina (EPA, 2012). However, as many oilseed rotation crops are currently in the early phase of development, there are large uncertainties concerning the production potential and costs for these crops. For example, the upper limit of 6 billion gallons of oil from pennycress is dependent on deployment of technologies currently under development.

3. RFS2 AND AVIATION BIOFUEL GOALS

The current renewable fuels standard in the US has its origins in the 2005 Energy Policy Act, which mandated the production of ethanol from cornstarch through the Renewable Fuels Standard. In 2007, this standard was updated under Title II (“Energy Security through Increased Production of Biofuels”) of the Energy Independence and Security Act (EISA) to create a renewable fuels standard known as RFS2. This standard sets targets for US consumption of renewable fuels by type from 2008 to 2022 that rise over time. By 2022, the target for total

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[4] The pennycress acreage estimate is based on conversations with Terry Isbell, research chemist, Bio-oils Research Unit, Agricultural Research Service, USDA and Professor Win Phippen at the School of Agriculture at Western Illinois University. Pennycress is assumed to be grown in the central corn belt following the corn harvest. The area with rotation potential extends from North of I-70 to South of Minneapolis, Madison and Lansing and East of Sioux City, Iowa to New York and Pennsylvania. Spring pennycress could also be grown well into Canada (from Ontario to Saskatoon).

[5] These estimates assume that pennycress is grown on 40 million acres and draw on yields reported by Moser *et al.* (2009).

biofuel consumption is 36 billion gallons per year. Corn ethanol can contribute a maximum of 15 billion gallons with the balance made up of advanced biofuels. The 2022 minimum mandates for advanced biofuels are one billion gallons for biomass-based diesel, 16 billion gallons for cellulosic fuels, and four billion gallons from undifferentiated advanced biofuels.[6] The renewable fuel mandates are met by assigning each gallon of renewable fuel a renewable identification number (RIN) and requiring importers and domestic fuel producers (refineries) to purchase a certain number of RINs for each gallon of fuel sold for use in ground transportation.[7]

Under the RFS2 mandates, for each type of fuel, the price of RINs will evolve so as to offset the higher production cost of renewable fuels compared to conventional fuels, as outlined in **Figure 2**. For a given biofuel, if the price of conventional fuel is $p*$ and the supply of biofuel is given by (S), the quantity supplied will be q^0, which is below the minimum amount required by the mandate. To meet the mandate, the market RIN value will be r^1 so that producers receive price p^s. If the market equilibrium quantity exceeds the mandated quantity (i.e. the supply curve intersects p^* to the right of the mandate in Figure 2), the RIN value will fall to zero.

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[6] Under current legislation, the Environmental Protection Agency may increase the contribution of biomass-based diesel to the overall goal for advanced biofuels.

[7] One way for obligated parties to meet their RFS2 requirements is to purchase renewable fuels with RINs attached and blend the fuel with conventional fuel. Alternatively, importers and refineries can purchase RINs from other obligated parties that have exceeded their minimum RIN requirements. RINs can also be banked for use in later years.

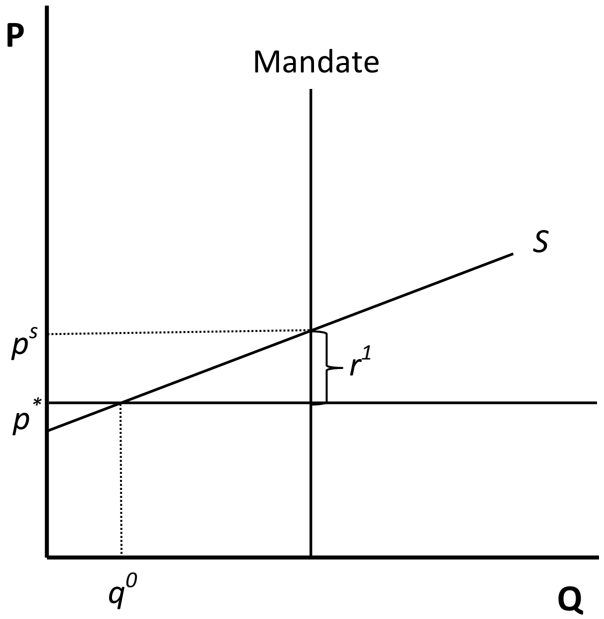

Figure 2. The determination of RIN values under RFS2.

Although obligated parties are not required to surrender RINs for sales of jet fuel, renewable jet fuel is eligible for RINs and can contribute to RFS2 mandates. Fuels produced from renewable oil using a HEFA process qualify for both biomass-based diesel and undifferentiated advanced RINs (but each gallon of fuel can only be assigned a single RIN). As (i) renewable jet fuel can be sold as diesel, (ii) there is very little difference in prices for the two fuels and (iii) separating jet fuel from diesel requires additional processing, RFS2 is unlikely to induce consumption of renewable fuel in the aviation industry.[8]

To help achieve sustainable growth in the aviation industry, the FAA has a goal that one billion gallons of renewable jet fuel is consumed in the US each year from 2018 onward (FAA, 2011). The goal includes renewable jet fuel targets set by the US Air Force (USAF), the US Navy and commercial aviation. The USAF goal is that 50% of domestic aviation operations will use a 50-50 blend of renewable fuel from domestic sources and conventional jet fuel by 2016 (USAF, 2010). The target for the US Navy is that 50% of total energy consumption is from renewable sources by 2020 (US Navy, 2010). According to Carter *et al.* (2011), the US Air Force goal is equivalent to 0.37 billion gallons per year, the Navy goal amounts to 0.28 billion gallons

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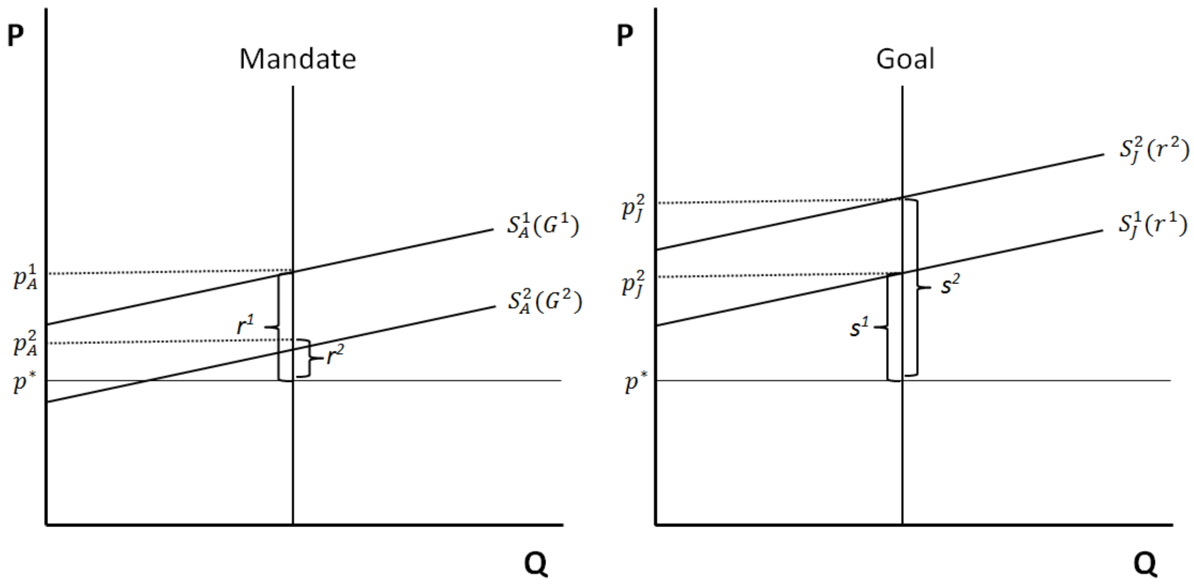
[8] The primary difference between jet fuel and diesel is the number of carbon atoms per molecule (or carbon chain length). Jet fuel typical contains between nine and 16 carbon atoms per molecule while the range for diesel is between nine and 24. As the range of carbon chain lengths for diesel encompasses the jet fuel range, diesel engines can burn jet fuel, but not the other way around (Pearlson, 2011).

per year, and commercial aviation's contribution to the overall goal (which is determined residually) is 0.35 billion gallons per year. Predicted jet fuel consumption by US commercial airlines in 2018 is 20.2 billion gallons (FAA, 2012, p. 104), so the target for commercial aviation represents 1.7% of total fuel consumed by this industry. If the cost of renewable jet fuel remains above the price of conventional fuel and in the absence of blending requirements for sales of jet fuel, the FAA biofuel goal will be met by commercial airlines and the US military voluntarily purchasing renewable fuel.

As HEFA processing of renewable oil produces a product slate that includes diesel and jet fuel, the cost of achieving the aviation goal will be influenced by RFS2 mandates. Specifically, the profitability of producing renewable jet fuel via a HEFA process will not only depend on the price of jet fuel, but also revenue received for co-products, including RIN prices for biomass-based diesel and undifferentiated advanced fuel. These RIN prices will be influenced by the increased supply of renewable diesel induced by renewable jet production to meet the aviation goal.

We illustrate the relationship between the aviation goal and RFS2 mandates and RIN prices in **Figure 3**. For simplicity, and without loss of generality, we assume that there is a single mandate for biomass-based diesel and undifferentiated advance fuel, which we collectively refer to as "other advanced" biofuel. Without an aviation goal ($G^1 = 0$), due to the cost of separating jet from diesel, all qualifying renewable fuel will be sold as other advanced fuel. The market for other advanced biofuel is displayed in Figure 3a. The supply curve for other advanced renewable fuel without a mandate is denoted S_A^1. If the price of conventional (diesel and jet) fuel is p^*, a RIN price equal to r^1 is required to meet the mandate (so that the price received by renewable fuel producers is p_A^1). The market for renewable jet fuel is illustrated in Figure 3b. If other advanced renewable fuel continues to receive a RIN price of r^1, the supply of renewable fuel is given by S_J^1 and an (implicit) subsidy of s^1 is required to meet the aviation renewable fuel goal ($G^2 > 0$). Meeting the aviation goal induces production of other advanced renewable fuels, which causes a shift in the other advanced supply schedule from S_A^1 to S_A^2 in Figure 3a. This supply increase will reduce the other advanced RIN price to r^2. In turn, the lower RIN price will increase the subsidy required to induce jet fuel production, which results in an upward shift of the supply curve from S_J^1 to S_J^2 and renewable jet subsidy of s^2 is required to meet the aviation biofuel goal.



(a) (b)

Figure 3. The market for (a) "other advanced" biofuels, and (b) renewable jet fuel.

Meeting the aviation goal will have a further feedback on the other advanced RIN price (which is not shown in Figure 3). Specifically, as HEFA jet fuel contributes to the other advanced mandate, meeting the aviation goal reduces the quantity of non-aviation other advanced biofuel required under RFS2. This will shift the effective other advanced mandate to the left in Figure 3b and further reduce the RIN price. Ultimately, there will be an additional upward shift in the supply curve for renewable jet fuel and a further increase in the subsidy required to meet the aviation goal. The above analysis indicates that, under the RFS2 mandates, the implicit subsidy required to meet the aviation biofuel goal is larger than the difference between the price of conventional fuel and the cost per gallon of total renewable fuel.

4. MODELING FRAMEWORK

Following Winchester *et al.* (2013) and Malina *et al.* (2012), our modeling approach employs an economy-wide computable general equilibrium (CGE) model and a partial equilibrium model that focuses on the aviation industry (the Aviation Portfolio Management Tool for Economics, APMT-E). We use a CGE model to determine the impact of biofuels policies and goals on biofuel production and costs, RIN prices, fuel prices and GDP. Estimated changes in fuel prices, which are passed through to consumers, and GDP-induced changes in demand are then simulated in APMT-E to determine changes in aviation operations.

4.1 The EPPA-A model

Our CGE model is an augmented version of the Emissions Prediction and Policy Analysis model for Aviation (EPPA-A) as outlined in Gillespie (2011). The EPPA-A model builds on version five of the MIT EPPA model (Paltsev *et al.*, 2005) by separating air transport from other industrial transport (road, rail and sea transport). The EPPA-A model is a recursive dynamic model of the global economy that links GHG emissions to economic activity. The model recognizes the US and 15 other regions, as detailed in **Table 1**. Sectors identified in the model include crops, forestry, livestock, two manufacturing sectors (energy-intensive industry and other industry), air transportation, other industrial transportation, household transportation (which includes privately owned vehicles and purchases of industrial transportation), services and five energy sectors (coal, crude oil, refined oil, gas and electricity). Several energy technologies and sources are specified in the model. For example, electricity technologies include conventional fossil, natural gas combined cycle, and wind and solar generation. Additionally, resources for crude oil and gas include oil and gas from conventional sources, shale oil, oil sands, shale gas and gas from sandstone.

Table 1. Aggregation in the EPPA-A model.

Regions	Sectors	Primary inputs
Developed	Crops	***Non-energy resources***
United States	Livestock	Capital
Canada	Forestry	Labor
Japan	Coal	Crop land
Australia-New Zealand	Crude Oil	Pasture land
European Union	Refined oil	Forest land
Eastern Europe	Aviation fuel	
Russia	Gas	***Energy resources***
	Electricity	Crude oil
Developing	Energy-intensive industry	Shale oil
Mexico	Other industry	Conventional natural Gas
China	Services	Shale gas
India	Air transportation	Coal
East Asia	Other industrial transportation	
Rest of Asia	Household transport	
Africa		
Middle East		
Brazil		
Latin America		

Each good is produced by perfectly competitive firms that assemble primary factors and intermediate inputs using nested constant elasticity of substitution (CES) production functions. All commodities are traded internationally. Crude oil is considered to be homogenous across regions and other goods are differentiated by region of origin following the Armington assumption (Armington, 1969). There is a single representative agent in each region that derives income from factor payments and tax revenue and allocates expenditure across goods and investment to maximize utility. The model is calibrated using economic data from the Global Trade Analysis Project database (Narayanan and Walmsley, 2008) and energy data from the International Energy Agency and is solved through time in five-year increments.

We extend the EPPA-A model by separating jet fuel from the model's aggregate Refined oil sector and including several biofuel production pathways. Biofuel technologies added to the model include corn ethanol, a representative cellulosic technology, a HEFA process, and a generic undifferentiated advanced technology. The HEFA technology is the only pathway that produces jet fuel. Our undifferentiated advanced process includes production from Fatty Acid Methyl Ester (FAME) processes. FAME processes produce biodiesel that qualifies as biomass-based diesel and undifferentiated advanced fuel under RFS2. In March 2012, there were 148 biodiesel plants in the US with total annual production capacity of 1.4 billion gallons (NBB, 2012) and future production of biodiesel is expected to exceed the current minimum mandate (1b gal) for biomass-based diesel under RFS2 (USDA, 2011). If this occurs, some biodiesel will attract biomass-based diesel RINs and some will be assigned undifferentiated RINs, which will equalize RIN values across the two categories. For this reason, and because the future contribution of the biomass-based diesel mandate to the advanced biofuels target is uncertain, we include a single category for both biomass-based diesel and undifferentiated advanced biofuel. As in Section 3, we label this category "other advanced" renewable fuel.

Our parameterization of biofuel technologies, except the HEFA process, follows Gurgel *et al.* (2007) and Gitiaux *et al.* (2012). To characterize HEFA biofuel production, we draw on estimates for plants with a 6,500 barrels per day (BPD) capacity from Pearlson (2011). Production of HEFA fuel in the model combines oilseed crops with capital and labor and other intermediate inputs using a series of nested CES functions, as illustrated in **Figure 4**. In the base data with a soybean oil feedstock, soy oil purchases account for 81% of the cost of production. Other major inputs include hydrogen (Gas), capital and labor.

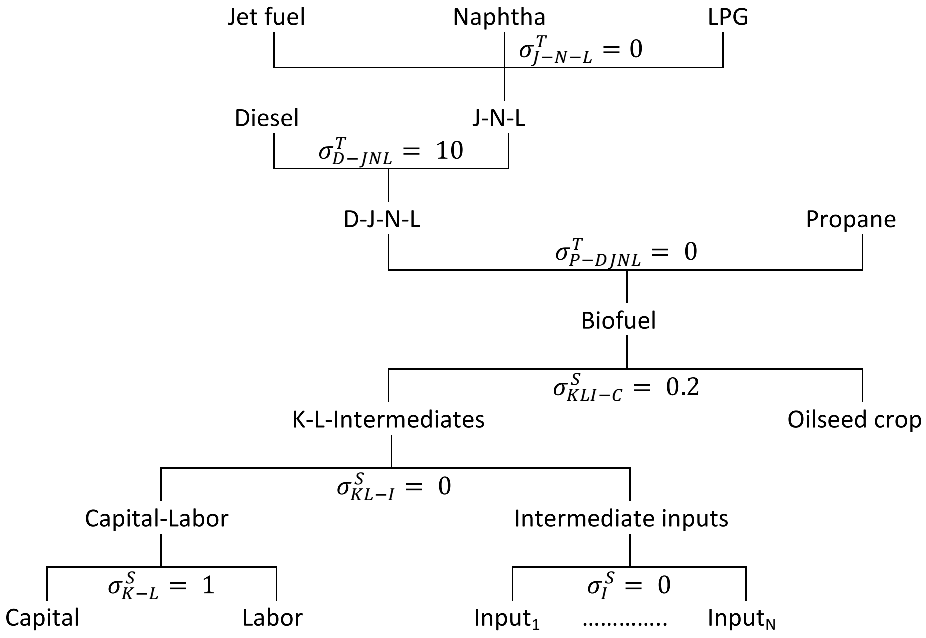


Figure 4: Production of HEFA fuels in the EPPA-A model.

We represent trade-off possibilities among products by a HEFA process using a sequence of nested constant elasticity of transformation (CET) functions. In this framework, product slate trade-offs are influenced by the output nesting structure and elasticities of transformation in the production function. Our representation of trade-off possibilities is calibrated using production under the "maximum distillate" and "maximum jet" alternatives considered by Pearlson (2011). As maximizing the output of jet fuel results in greater production of less-valuable co-products, a jet fuel price premium is needed to induce a higher proportion of this fuel in total output than when total distillate is maximized. In the model, this relationship is captured using a CET function that divides output between diesel and a jet-fuel-naphtha-LPG composite using a CET function with an elasticity value equal to 10. Under this framework, σ_{D-JNL}^{T} represents the elasticity of supply of the jet fuel-naphtha-LPG composite when output is constant. The jet-fuel-naphtha-LPG composite is then allocated to individual products in fixed proportions. Propane and a jet fuel-diesel-naphtha-LPG composite are also a fixed proportion of total output.

Benchmark production value shares, assigned using the "maximum distillate" calculations from Pearlson (2011), are 78.5% for diesel, 15.7% for jet fuel, 2.6% for propane, 2.1% for naphtha and 1.1% for LPG. To fit our sectoral aggregation, diesel and naphtha are sold as Refined oil and propane and LPG are sold as Gas in the model. HEFA production of diesel, jet fuel and naphtha are eligible for other advanced RINs.[9]

To specify biofuel production costs, as is convention in CGE models, for each biofuel, we apply a mark-up factor to all inputs, which determines the cost of biofuels relative to conventional fuels. Our mark-up factors for corn ethanol, representative undifferentiated advanced fuel and cellulosic biofuels draw on Gitiaux *et al.* (2012), Gurgel *et al.* (2007), and existing RIN prices. Our mark-up factor for HEFA production is guided by Pearlson (2011). When the price of soybean oil is $2.46/gal, Pearlson (2011) estimates that the gate cost of HEFA diesel and jet fuel is $3.80/gal for a 6,500 BPD plant operating at maximum distillate.[10] The mark-up factors combined with input cost shares set the cost of production for each biofuel in the base year (2005). In subsequent years, production costs are determined endogenously in the model based on inputs prices and the underlying production functions.

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[9] RINs could also be allocated for LPG and propane, but the cost of recovering these gases for use in transportation is likely to be greater than the RIN values (Pearlson, 2011).

[10] The cost estimates from Pearlson (2011) are for commercial-sale operations. Consequently, we do not specify decreasing production costs as a function of cumulative output.

In biofuel scenarios, we simulate the RIN systems specified under RFS2 and the aviation biofuel goal using a series of permit schemes. Although there are no current plans to mandate the use of renewable jet fuel, a permit system is consistent with airlines and the military voluntarily purchasing renewable jet fuel. Under this interpretation, the amount paid for renewable jet fuel above the price of conventional jet fuel can be interpreted as an implicit subsidy to renewable fuel producers. The operation of the permit systems are depicted in **Figure 5**. For biofuel type j (j represents corn ethanol, other advanced, cellulosic, and jet fuel), a permit belonging to that type is attached to each gallon of fuel produced. For non-aviation fuel, a certain number of permits for each type of biofuel must be turned in for each gallon of fuel used in ground transportation. Similarly, production of aviation fuel requires a fixed proportion of renewable jet fuel permits. The proportion of each non-aviation biofuel in ground transportation fuel is determined by $\alpha_1, \dots, \alpha_I$ (i represents corn ethanol, other advanced, and cellulosic) and the proportion of renewable jet fuel in commercial aviation fuel is determined by choosing α_{CA} and the proportion of renewable aviation fuel purchased by the military is determined by α_{CA}.[11] We simulate biofuel quantities specified in RFS2 and the aviation goal in the model by solving the model iteratively for alternative values of $\alpha_1, \dots, \alpha_R$; α_{CA}; and α_{MA} until the desired biofuel volume requirements are achieved.

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[11] The military is included in the Services sector in the EPPA-A model. As such, we require Services to purchase renewable jet fuel to meet the military aviation biofuel goal.

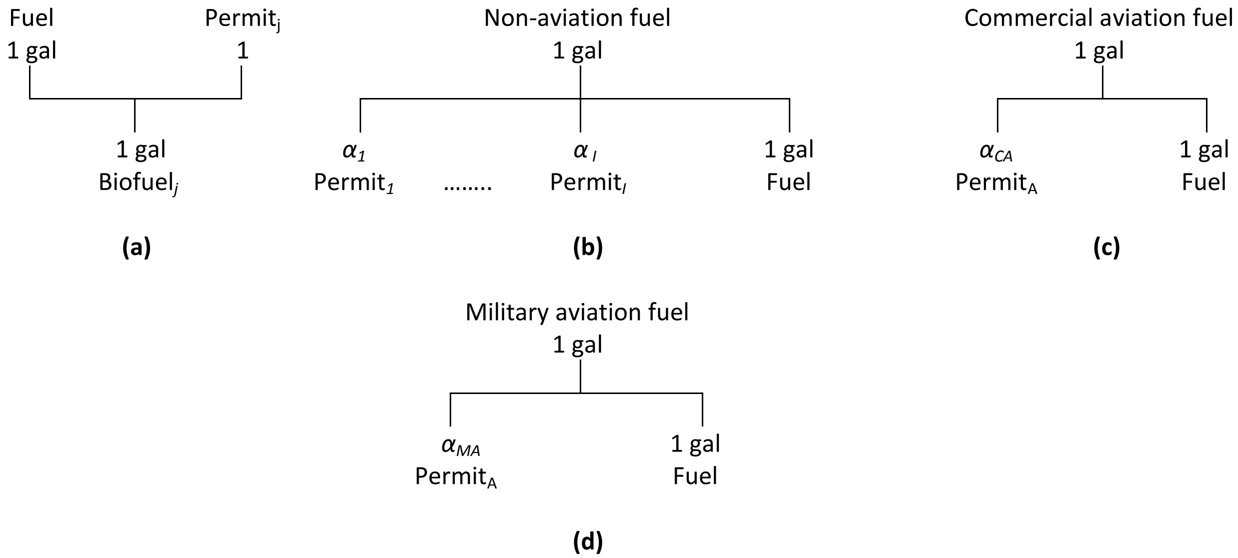

Figure 5. Implementation of RFS2 mandates and the aviation biofuel goal in the EPPA-A model (a) Production of permits (*j* represents corn ethanol, other advanced, cellulosic, and renewable jet fuel), (b) Blending of permits into non-aviation fuel, (c) Blending of permits into commercial aviation fuel, and (d) blending of permits into military aviation fuel.

Each biofuel crop is produced by combining land, materials, energy, capital and labor, as outlined in **Figure 6**. Key responses to relative price changes in the model include substitution possibilities between land and the energy-materials composite, and between capital and labor and the resource-intensive bundle. These substitutions allow land to be farmed more intensively as the land prices increase (e.g., by using more fertilizer and farming equipment). Elasticities of substitution in biofuel crop production are sourced from Gitiaux *et al.* (2012).

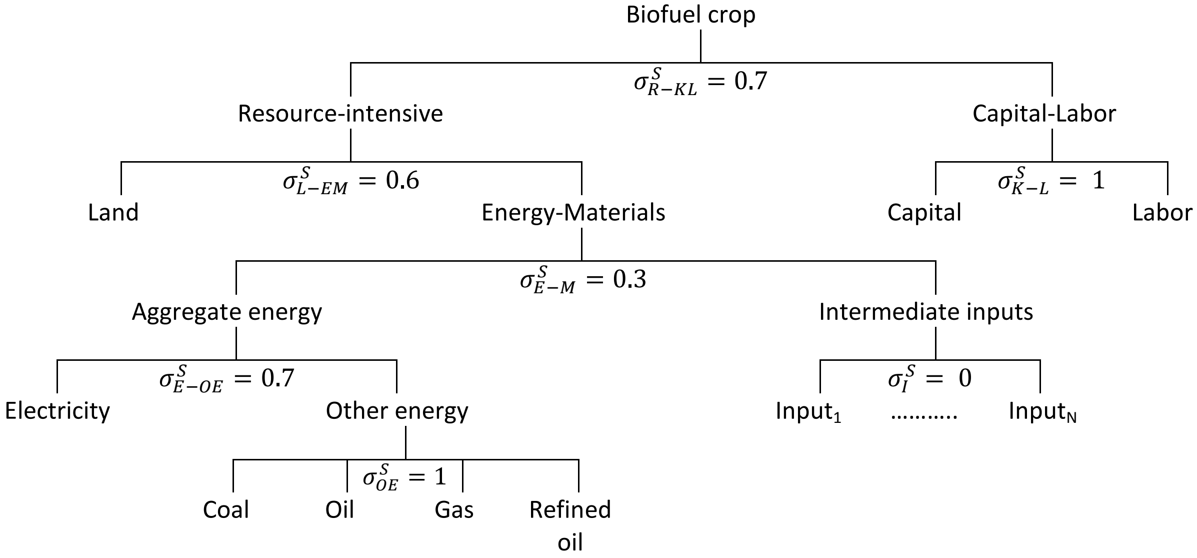

Figure 6: Production of biofuel crops in the EPPA-A model.

As discussed in Section 2, there is the potential for oilseed crops to be grown in rotation with other crops on land that would otherwise be left fallow. Reflecting a productive use for otherwise unused land, in some scenarios, we endow the economy with additional land that can only be used for oilseed rotation crops. Additionally, we set σ^S_{L-EM} and σ^S_{R-KL} equal to zero in production of rotation crops (see Figure 6), so there is a one-to-one mapping between the rotation crop land endowment and oil from rotation crops.

Guided by Wheeler and Guillen-Portal (2007) and EPA (2012), we calibrate the production input costs shares for our representative oilseed rotation crop using value-weighted average production costs for corn and soybeans, excluding land and fertilizer costs. As land has no value for the time that it is left fallow, we assume that the initial cost of land is zero. Once fallow land is used for an oilseed rotation crop, the return to that land is calculated endogenously in the model.

4.2 The APMT-E model

We model the aviation industry using the Aviation Portfolio Management Tool for Economics (APMT-E). APMT-E is one of a series of models developed by the FAA and the Partnership for Air Transportation Noise and Emissions Reduction Center of Excellence. The APMT tool suite is designed to assess the effects of aviation on the environment, and APMT-E focuses on airline responses to policy changes. The model has been used in support of ICAO/GIACC (2009) and ICAO/CAEP (2010) and is outlined by MVA Consultancy (2009).

APMT-E is a global model that determines operations for country pair-stage length combinations. The model identifies 23 route groups (e.g., North Atlantic, Domestic US, North America-South America), nine distance bands (e.g., in kilometers, 0–926, 927–1,853, and 6,483–8,334), ten aircraft seat classes defined by the number of available seats (e.g., 0–19, 20–50 and 211–300) and two carrier types (passenger and freight). In APMT-E, airlines can respond to fuel price increases by raising prices (and flying less) and, when purchasing new aircraft (which are combinations of airframes, engines and seat configurations), selecting more fuel efficient alternatives. The model is calibrated using 2006 data. As the EPPA-A model has a five-year time step and APMT-E is solved annually, we use linear interpolation techniques to generate yearly estimates of changes in fuel prices and GDP. Guided by Gillen *et al.* (2002), we use an income elasticity of demand for air travel of 1.4 to convert changes in GDP to changes in the demand for aviation.

4.3 Scenarios

We simulate a reference scenario and five core policy scenarios. In the Reference scenario, we update the standard benchmark scenario used in the EPPA model by changing oil resources so that simulated jet fuel prices match projections by EIA (2012a). Our first policy simulation (RFS2), models RFS2 mandates for renewable fuels. Remaining scenarios simulate the aviation biofuel goal in tandem with RFS2 targets. The Additional scenario assumes that one billion gallons of renewable jet fuel is produced in addition to the RFS2 targets. Consistent with current legislation, renewable jet fuel contributes to the undifferentiated advanced RFS2 mandate in the Include scenario. A further two scenarios consider renewable fuel from oilseed rotation crops under the assumption that the aviation goal is included within the RFS2 mandates. Guided by our calculations in Section 2, in one scenario (R-Low), we set the quantity of rotation crop land so that three billion gallons of oil are available from rotation crops each year, and in another (R-High) we assume that six billion gallons of oil are produced from rotation crops annually. We also consider sensitivity analyses relating to (i) alternative characterizations of product slate trade-offs in HEFA output, and (ii) fertilizer use for rotation oilseed crops.

5. RESULTS AND DISCUSSION

Results for our core scenarios in 2020 are presented in **Table 2**. In the Reference scenario, the 2020 price of jet fuel (in 2010 dollars) is \$3.41/gal and jet fuel consumption by commercial aviation is 20.8 billion gallons. Corn ethanol is the only renewable fuel produced in the reference scenario. In the RFS2 scenario, decreased demand for ground transportation fuels reduces the (net of RIN value) price of Refined oil. As RINs are not required for sales of jet fuel under RFS2, the price of this fuel decreases to \$3.39/gal. However, as the RFS2 policy reduces GDP and ultimately the demand for aviation, there is a small decrease in aviation operations, as measured by revenue (metric) ton kilometers (RTKs) and available ton kilometers (ATKs). There are also small decreases in fuel use and CO_2 emissions.

Table 2. Core simulation results, 2020.

	Reference	**RFS2**	**Additional**	**Include**	**R-Low**	**R-High**
GDP (Δ relative to ref.)	-	−0.18%	−0.20%	−0.18%	−0.12%	−0.08%
Average jet fuel price (2010\$/gal)	3.41	3.39	3.43	3.43	3.42	3.39
Price of HEFA jet fuel (2010\$/gal)	-	-	6.25	6.08	5.61	3.74
Implicit sub./RIN price (2010\$/gal)						
Renewable jet fuel	-	-	2.86	2.69	2.22	0.35
Other advanced[a]	-	1.88	1.81	1.68	1.29	0
HEFA jet fuel (gal, bil.)						
From soy	0	0	1	1	0.5	0
From rotation crops	-	-	-	-	0.5	1
HEFA diesel production (gal, bil.)	0	1	1.5	1.4	3	4.6
Price of soy oil (2010\$/gal)	2.99	4.25	4.45	4.39	3.97	2.49
Soybean biofuel land (acres, mil.)	0	13.3	70.1	58.9	23.5	0
Aviation metrics						
Operating costs (\$2010, bil.)	267.5	267.3	267.6	267.6	267.5	267.3
Operating revenues (\$2010, bil.)	276.3	276.1	276.4	276.4	276.3	276.1
Revenue tonne km (bil.)	283.4	282.9	282.1	282.1	282.2	282.5
Available tonne km (bil.)	350.0	349.2	348.6	348.6	348.7	349.0
Fuel use (gal, bil.)	20.77	20.74	20.70	20.70	20.71	20.72
Lifecycle CO_2 emissions (Δ relative to ref.)[b]						
Due to reduced fuel use	-	−0.18%	−0.36%	−0.35%	−0.32%	−0.25%
Due to biofuels	-	0%	−0.98%	−0.98%	−0.98%	−0.98%
Total	-	−0.18%	−1.34%	−1.33%	−1.30%	−1.23%

Note: [a] Other advanced biofuels are an aggregate of biomass-based diesel and undifferentiated advanced biofuels; [b] CO_2 emission calculations assume that lifecycle CO_2 emissions from HEFA production are 42% of those from conventional jet fuel.

In the Additional scenario in 2020, meeting the aviation biofuel goal induces production of renewable diesel and decreases the other advanced RIN price (from $1.88 to $1.81) and an implicit subsidy of $2.86 per gallon of renewable jet fuel is required to meet the aviation goal. The average price of jet fuel reported in Table 2 represents the average price paid by commercial aviation when the industry purchases 0.35 billion gallons of renewable fuel (at $3.39 + $2.86 = $6.25/gal) and remaining consumption is conventional fuel (at a price of $3.39/gal). As commercial aviation's purchases of renewable fuel are a small proportion (1.7%) of total fuel purchases, there is only a small increase in the average price of jet fuel. There is also a small decrease in GDP (and aviation demand) relative to the RFS2 due to the additional constraints on the economy. Relative to the reference case, lifecycle CO_2 emissions fall by 1.34% due to reduced fuel use (0.36%) and the use of biofuels (0.98%).[12]

When renewable jet fuel contributes to the RFS2 target (Include), the reduction in the effective mandate for other advanced biofuel results in a further decrease of the RIN price for this fuel. However, the lower total quantity of renewable fuel produced decreases the price of land and ultimately soy oil, so the implicit subsidy to the aviation biofuel ($2.69/gal) is lower than in the Additional scenario. There are only very small differences between the average price of jet fuel and aviation metrics in the Additional and Include scenarios.

In the R-Low scenario, the availability of a low cost option to meet a proportion of the aviation goal reduces the average cost of production. However, as production from soy oil is still required and the market price is determined by the cost of producing the marginal unit, there is only a moderate decrease in the implicit renewable jet fuel subsidy. As farmers are owners of the relatively scarce factor (rotation crop land), they are the major beneficiaries of development of a rotation crop pathway. When 6 billion gallons of oil are available from rotation crops annually (R-High), production of other advanced fuels using this oil exceeds the mandates for these fuels, so the other advanced RIN price is zero. An implicit subsidy is required for HEFA manufacturers to produce a higher portion of renewable jet fuel than at maximum distillate, but due to the low cost of producing fuel from rotation crops, this amount is small ($0.35/gal). The availability of a large quantity of oil from rotation crops also significantly reduces the reduction in GDP due to biofuel policies (including RFS2).

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[12] Following the median estimate of lifecycle emissions without land use change from Stratton *et al.* (2011), our CO_2 emissions calculations assume that lifecycle CO_2 emissions from HEFA fuel are 42% of those from conventional jet fuels.

6. SENSITIVITY ANALYSIS

Important characterizations in our analysis include the ability of HEFA producers to substitute between jet and diesel, and the amount of fertilizer required to grow rotation crops. The key parameter governing product slate trade-offs in HEFA production is the elasticity of transformation between diesel and a composite of jet fuel, naphtha and LPG, σ_{D-JNL}^{T}. We set σ_{D-JNL}^{T} = 10 in our core scenarios and consider values of 5 and 20 for the Include scenario in sensitivity cases. Results are reported in Table 3. When trade-off possibilities between diesel and jet fuel production are low, a higher jet fuel price is required to induce jet fuel production than when there are high trade-off possibilities. Consequently, the implicit subsidy to renewable jet fuel to meet the aviation goal increases (from \$2.69 to \$2.85) when we reduce the value σ_{D-JNL}^{T} and decreases (to \$2.53) when there is greater scope for product slate trade-offs. However, differences in modeling outcomes, particularly for the average jet fuel price, across scenarios are small, indicating that our results are relatively insensitive to alternative values of σ_{D-JNL}^{T} in the range that we consider.

Table 3. Sensitivity analysis results, 2020.

	Product slate trade-offs (Include)		**Fertilizer for rotation crops**	
	$\sigma_{D-JNL}^{T} = 5$	$\sigma_{D-JNL}^{T} = 20$	**R-Low**	**R-High**
Average jet fuel price (2010\$/gal)	3.43	3.43	3.42	3.40
Price of HEFA jet fuel (2010\$/gal)	6.24	5.92	5.61	4.39
Implicit subsidy/RIN price				
Renewable jet fuel (2010\$/gal)	2.85	2.53	2.22	1.00
Other advanced (2010\$/gal)[a]	1.67	1.68	1.29	0.07
HEFA jet fuel (gal, bil.)				
From soy	1	1	0.5	0
From rotation crops	-	-	0.5	1
HEFA diesel production (gal, bil.)	2.4	0.7	3.5	3.5
Price of soy oil (2010\$/gal)	4.44	4.34	3.97	2.75
Soybean biofuel land (acres, mil.)	59.1	58.7	23.5	0

Note: [a] Other advanced biofuels are an aggregate of biomass-based diesel and undifferentiated advanced biofuels.

Our second set of sensitivity analyses examines alternative assumptions for the use of fertilizer when growing rotation crops. Fertilizer was not required for rotation crops in the core scenarios. In alternative cases for the R-Low and R-High scenarios, we assume that rotation crops require the same amount of fertilizer per acre as corn production. This increases the cost of rotation crop production by 35% and results in the cost of HEFA production with a rotation crop feedstock exceeding the price of conventional fuel. In the R-Low scenario, as renewable fuel with a soy oil feedstock is used to supply the marginal unit, as in our core scenario, there is little difference between results with and without fertilizer use. When a large quantity of rotation crop land is available (R-High) and fertilizer costs are included, fuel from rotation crops continues to be used to meet both the aviation goal and the other advanced mandate. Increased production costs result in an increase in the implicit subsidy to renewable jet fuel (from $0.35 without fertilizer costs to $1.00 with such costs) and a small increase in the average jet fuel price, relative to in the corresponding core scenario. This analysis indicates that our findings are sensitive to rotation crop production costs when the aviation goal is met by fuel derived from rotation crop oil.

7. CONCLUSIONS

We examined the cost to US commercial aviation of meeting the FAA's aviation biofuel goal of consuming one billion gallons of renewable jet fuel each year from 2018 onwards. We began by analysing interactions between the aviation biofuel goal and an existing renewable fuel standard for fuels used in ground transportation (RFS2). If a renewable jet fuel pathway produces a product slate that includes renewable diesel, encouraging production of renewable jet fuel will increase the supply of other renewable fuels and decrease RIN prices for these fuels. To compensate producers for lower RIN prices, the implicit subsidy to aviation jet fuel will need to be larger than the difference between the cost of production per gallon of total distillate and the price of conventional jet fuel. However, encouraging production of advanced renewable fuel (both jet fuel and diesel) will not induce consumption of renewable fuel in air transportation. As jet fuel can be sold as diesel (at approximately the same price) and there are additional costs associated with separating jet fuel and diesel, jet fuel will be sold as diesel under mandates for ground transportation fuels.

Our analysis considered renewable jet fuel production via HEFA processes. These processes produce a mixed product slate that includes diesel, naphtha and gases, in addition to renewable jet fuel. Feedstocks considered include soybean oil and (in some simulations) a representative rotation oilseed crop grown on otherwise fallow land. Our modeling framework employed an economy-wide model and a partial equilibrium model of the aviation industry.

We found that, without the development of an oilseed rotation crop, meeting the aviation biofuel goal will require an implicit subsidy to renewable fuel producers of \$2.69/gal of jet fuel and increase the average price of jet fuel by \$0.04/gal. As renewable jet fuel accounts for 1.7% of total fuel use by commercial aviation, meeting the aviation biofuel goal had only a small impact on CO_2 emissions. When a rotation oilseed crop was considered as a feedstock, the outcome was influenced by the amount of oil available from this crop. If renewable oil from rotation crops can only meet a fraction of demand for renewable jet production, the price of renewable jet fuel was determined by the cost of production using a soybean oil feedstock, and the implicit subsidy to renewable jet producers was \$2.22/gal. When there is sufficient rotation crop oil to meet the aviation goal, the implicit subsidy to renewable jet fuel producers was only \$0.35/gal.

Overall, our analysis revealed that renewable jet fuel pathways producing higher fractions of jet fuel (as a proportion of total distillate) may be a more cost-effective way of meeting the aviation goal, even if they have higher production costs per gallon of total distillate than pathways producing a lower proportion of jet fuel. Similarly, a cellulosic pathway may be more cost effective than a non-cellulosic pathway with lower production costs, as relatively large cellulosic mandates mean that inducing production of these fuels will have a relatively small impact on the cellulosic RIN price. Our results also showed that development of a rotation crop grown on otherwise fallow land has the potential to significantly reduce the cost of achieving biofuel goals.

We close by noting that, as we did not consider the full suite of pathways potentially available in 2018, our calculations may overestimate the cost of meeting the aviation biofuel goal. Including more feedstocks, such as canola oil, animal fat and waste grease, will likely lower the cost of producing renewable jet fuel. Additionally, processes to produce alcohol-to-jet and synthetic kerosene containing aromatics are expected to be certified by the end of 2013. The addition of these processes and other new technologies may also lower the cost renewable jet consumption.

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