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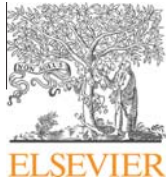Building E19, Room 411
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Economic and emissions impacts of renewable fuel goals for aviation in the US ☆

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A R T I C L E   I N F O

A B S T R A C T

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 economic and emissions impacts of 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 from airlines 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 2% 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, under the pathways we examine, the cost per tonne of CO_2 abated due to aviation biofuels is between $50 and $400.

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 (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 to 2022.

In this paper, we examine the economic and emissions impacts of the fuel target set out by the FAA and evaluate the cost effectiveness of the goal. Our modeling framework uses an economy-wide model of economic activity and energy systems to

determine the additional cost of renewable jet fuel relative to conventional fuel 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 Emissions Trading Scheme 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 conversion 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 US mandates for biofuels used in ground transportation and aviation biofuel goals, and discusses interactions between these targets. 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 (ASTM, 2011).[1] Both these processes produce a product slate that includes diesel, jet fuel and other co-products (Pearlson et al., 2013). 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 of jet fuel, diesel and naphtha (Pearlson et al., 2013; 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 et al. (2013) estimate 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-sulfur) 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 as 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%.[3]

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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. (2014) and OECD (2012) for a comprehensive list of renewable jet fuel processes.

[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.

[3] Lifecycle CO_2 emissions for biofuels include all emissions associated with the production of that fuel, including emissions from energy sources used for sowing, harvesting, fertilizer production, transportation and processing. Lifecycle CO_2 emissions for conventional jet fuel include emissions from extraction, transportation, refining and combustion.

On average, the price of soybean oil was $1.19 more than the price of jet fuel between April 1990 and June 2012 (EIA, 2012b and World Bank, 2012) and predicted future soybean oil prices are between $1.07 and $0.66 above the price of jet fuel (EIA, 2012a and USDA, 2012). 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.

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 et al., 2010; EPA, 2012). Two promising rotation crops in the US include *Thlaspi arvense L.* (commonly known as pennycress) and *Camellia sativa* (camelina).[4] 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 agricultural inputs (fertilizer, pesticides and water), is compatible with existing farm infrastructure (Moser et al., 2009), and could potentially be grown on 40 million acres each year.[5] 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 (although payment for activities such as sowing and harvesting are still required). 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 2.5–6 billion gallons of oil from pennycress[6] and 0.1–0.4 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 fuel 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 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.[7] 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. 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.

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) HEFA 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

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[4] 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).

[5] 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).

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

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

[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 et al., 2013).

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 0.37b gallons per year, the Navy goal amounts to 0.28b gallons per year, and commercial aviation's contribution to the overall goal (which is determined residually) is 0.35b gallons per year. Predicted jet fuel consumption by US commercial airlines in 2018 is 20.2b 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. Voluntary purchases of renewable fuel at a higher cost than conventional fuel is equivalent to a government policy that subsidizes production of renewable jet fuel and taxes purchases of conventional jet fuel, where the per-gallon subsidy is chosen to induce the desired level of production and the per-gallon tax is chosen so that the total tax revenue is equal to the total cost of the subsidy. For this reason, we refer to the additional per gallon cost of purchasing renewable jet fuel relative to conventional fuel as an implicit subsidy from airlines to renewable fuel producers.

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 on revenue received for co-products and RINs. These RIN prices will be influenced by the increased supply of renewable diesel induced by renewable jet production to meet the aviation goal.

To illustrate interactions between RFS2 mandates and the aviation biofuels goal, without loss of generality, we construct a simple example and assume that there is a single mandate for biomass-based diesel and undifferentiated advance fuel, which we collectively refer to as "other advanced" biofuel (which has an RFS2 mandate of 4.5 billion gallons in 2020). In our example, a HEFA pathway produces five gallons of diesel for every one gallon of jet and, for simplicity, changes in the product slate are not possible. If the price of conventional (jet and diesel) fuel is $3 per gallon and the cost of renewable fuel production using the HEFA process is $4 per gallon of total distillate, producing one billion gallons of jet fuel to meet the aviation goal will require six billion gallons of renewable fuel. As this amount exceeds the RFS2 other advanced mandate, the other advanced RIN price will be zero. Additionally, as each gallon of total distillate costs $4 and sells for $3, an implicit renewable jet subsidy of $6 per gallon will be required to offset losses on total production of jet and diesel fuel. That is, payments for renewable jet fuel effectively cross-subsidize renewable diesel production.

When product slate trade-offs are possible, motivated by the increase in the price of renewable jet fuel, HEFA producers will increase the proportion of jet fuel in total output, so it is unlikely that the other advanced mandate will be exceeded. Nevertheless, as product slate trade-offs are limited, increased renewable diesel supply will decrease the other advanced RIN value.[9] Ultimately, in our modeling scenarios we expect the implicit subsidy for renewable jet fuel production to be higher than the difference between the per unit cost of HEFA production and the price of conventional jet 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).[10] 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.

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

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[9] Although producing renewable jet fuel via a HEFA processes will increase the supply of other advanced fuel (a rightward movement of the other advanced supply curve), the equilibrium quantity of other advanced fuel will not change as long as the mandate is binding. However, renewable diesel produced jointly with aviation biofuel replaces high-cost alternatives, which reduces the RIN price needed to meet the other advanced mandate.

[10] A public release version of the EPPA model is available at <http://globalchange.mit.edu/research/IGSM/eppadl>.

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		

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 6500 barrels per day (BPD) capacity from Pearlson et al. (2013). 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 Fig. 1. 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.

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 et al. (2013) and the CET calibration procedure outlined by Rutherford (2012). 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^T_{D-JNL} 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 et al. (2013), 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.[11]

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[11] 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 et al., 2013).
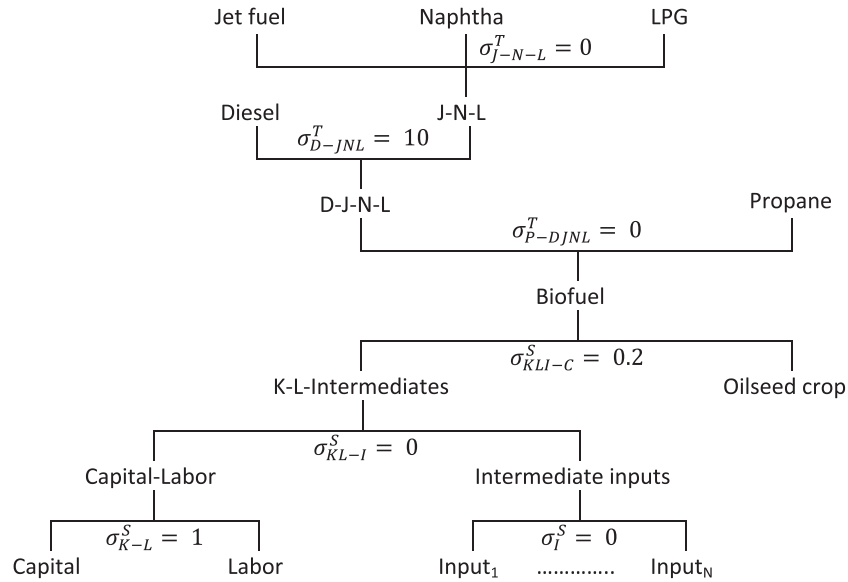
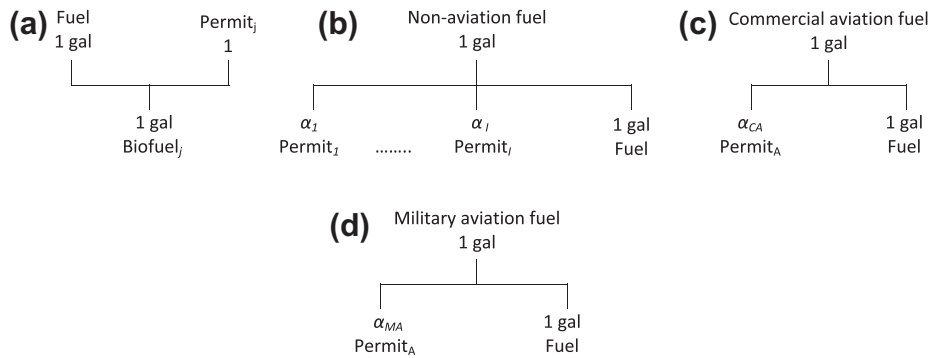**Fig. 1.** Production of HEFA fuels in the EPPA-A model.

Fig. 2. Implementation of RFS2 mandates and the aviation biofuel goal in the EPPA-A model: (a) Production of permits (j = 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.

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 et al. (2013). When the price of soybean oil is $2.46/gal, Pearlson et al. (2013) estimate that the gate cost of HEFA diesel and jet fuel is $3.80/gal for a 6500 BPD plant operating at maximum distillate.[12] 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.

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 Fig. 2. For biofuel type j (j = 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-

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[12] The cost estimates from Pearlson et al. (2013) are for commercial-sale operations. Consequently, we do not specify decreasing production costs as a function of cumulative output.
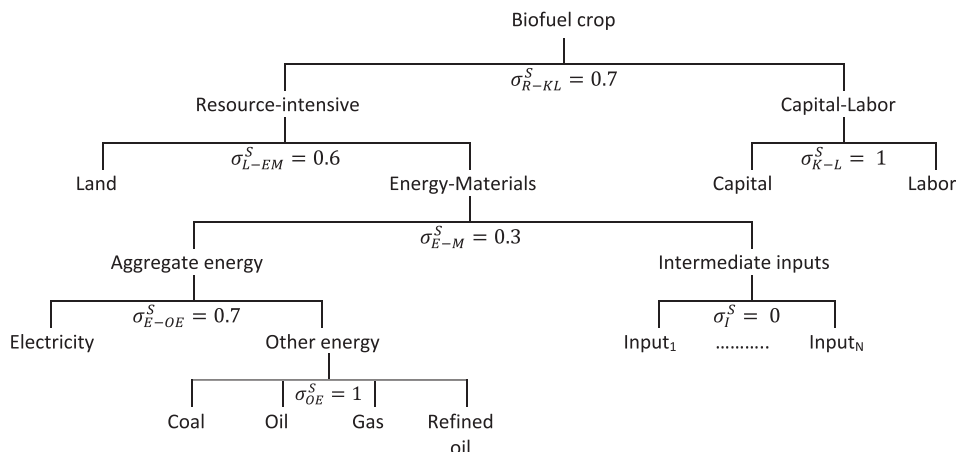
Fig. 3. Production of biofuel crops in the EPPA-A model.

aviation biofuel in ground transportation fuel is determined by $\alpha_1, \ldots, \alpha_I$ (i = 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_{MA}.[13] We simulate biofuel quantities specified in RFS2 and the aviation goal in the model by solving the model iteratively for alternative values of $\alpha_1, \ldots, \alpha_R$; α_{CA}; and α_{MA} until the desired biofuel volume requirements are achieved.

Each biofuel crop is produced by combining land, materials, energy, capital and labor, as outlined in Fig. 3. 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).

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_{L-EM}^S and σ_{R-KL}^S equal to zero in production of rotation crops (see Fig. 3), so there is a one-to-one mapping between the rotation crop land endowment and oil from rotation crops.[14]

In addition to requiring land, our representative rotation crop requires other inputs for activities including sowing and harvesting just like conventional crops. However, a difference from conventional crops is that, following Moser et al. (2009), fertilizer is not required to grow rotation crops (although we do consider fertilizer in a sensitivity analysis). 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, 927–1853, and 6483–8334), 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-

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[13] 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.

[14] We assume that using land usually left fallow for a rotation oilseed crops has no impact on the productivity of this land when it is used to grow other crops. If growing an oilseed rotation crop decreased yields for other crops, the cost of a HEFA production using an oilseed rotation crop would be higher than in our analysis.

Table 2
Scenarios considered.

Name	Description
Reference	No biofuel mandates or goals
RFS2	RFS2 mandates for fuels used in ground transportation
Additional	Aviation renewable fuel goal in addition to RFS2 mandates
Include	Aviation renewable fuel goal nested within RFS2 mandates
R-Low	Include scenario with a representative oilseed rotation crop, low availability
R-High	Include scenario with a representative oilseed rotation crop, high availability

Note: In the R-Low and R-High scenarios, respectively, 3 billion and 6 billion gallons of oil are available from rotation crops each year.

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 (which equal changes in national income) to changes in the demand for aviation.[15]

4.3. Scenarios

We simulate a reference scenario and five core policy scenarios, which are summarized in Table 2. In the Reference scenario, we update the standard benchmark scenario used in the EPPA-A 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. In 2020, these targets are 15 billion gallons for grain-based ethanol, 10.5 billion gallons for cellulosic fuels, and 4.5 billion gallons for other advanced fuels (including biomass-based diesel). Other 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 3 billion gallons of oil are available from rotation crops each year, and in another (R-High) we assume that 6 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.

Key variables of interest in each scenario include the change in GDP, the price of renewable jet fuel, the other advanced RIN price, the implicit subsidy from airlines to renewable fuel producers, the price of soy oil, and changes in aviation operations and CO_2 emissions. As renewable fuel mandates and goals are small proportions of total energy consumption, we expect these targets to have a small impact on GDP. Following the analysis in Section 3, we anticipate that adding the aviation goal on top of the aviation mandates, as in the Additional scenario, will reduce the RIN price for other advanced biofuels and require a relatively large implicit subsidy for the production of renewable jet fuel. In the Include scenario, the nesting of the aviation goal within the RFS2 mandates will, relative to the Additional scenario, reduce the total amount of biofuel produced, which will lower land costs and ultimately RIN prices and the implicit renewable jet fuel subsidy. The availability of oilseed crops grown on otherwise fallow land will further decrease RIN prices and the implicit subsidy to renewable jet fuel, with larger decreases when the availability of rotation crop land is high (R-High) than when availability of this land is low (R-Low). Turning to aviation operations, as the renewable jet fuel goal for commercial aviation represents a small proportion (~1.7%) of total fuel consumed by this industry, we expect the additional cost of purchasing biofuels to have a small impact on overall fuel costs, aviation operations and emissions.

5. Results

Results for our core scenarios in 2020 are presented in Table 3. 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 20.8b gallons. Relative to 2012, aviation operations as measured by available tonne kilometres increases by 34% but, reflecting fuel efficiency improvements, fuel use increases by only 25%. As renewable jet fuel is more expensive than conventional fuel, there is no production of renewable jet fuel. This is true for all biofuels except corn ethanol.

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 tonne kilometers and available tonne kilometres. There are also small decreases in fuel use and CO_2 emissions. Use of soy oil to make ground transportation fuels increases the price of this commodity relative to the reference scenario.

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[15] This elasticity is applied to income changes within each time period (i.e., when population is constant).

Table 3
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 ($2010, bil.)	276.3	276.1	276.4	276.4	276.3	276.1
Revenue tonne km (bil.)	283.4	282.9	282.1	282.1	282.2	282.5
Available tonne km (bil.)	350.0	349.2	348.6	348.6	348.7	349.0
Fuel use (gal, bil.)	20.77	20.74	20.70	20.70	20.71	20.72
Lifecycle CO_2e emissions (Δ relative to reference)[b]						
Due to reduced fuel use	–	−0.18%	−0.36%	−0.35%	−0.32%	−0.25%
Due to biofuels	–	0%	−0.98%	−0.98%	−0.98%	−0.98%
Total	–	−0.18%	−1.34%	−1.33%	−1.30%	−1.23%
CO_2e abatement cost (2010$/t)						
Direct effect[c]	–	–	429.70	404.14	333.54	52.59
Direct and indirect effects[d]	–	–	401.92	378.03	317.11	50.83

[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.

[c] Abatement costs due to the direct effect are calculated by dividing the additional cost of renewable fuel purchases (relative to conventional fuel) by the reduction in lifecycle CO_2e emissions from replacing conventional fuel at constant operations.

[d] Abatement due to direct and indirect effects costs are calculated by dividing the additional cost of renewable fuel purchases by emissions reductions from replacing conventional fuel with renewable fuel, more efficient airline operations, and reduced demand for aviation services.

In the Additional scenario in 2020, meeting the aviation biofuel goal induces greater 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 cost per gallon of jet-diesel composite from our HEFA process is $2.23 more than the price of conventional fuel so, as highlighted in Section 3, inducing jet fuel production requires airlines to partially subsidize renewable diesel production by paying a high price for renewable jet fuel.

The average price of jet fuel reported in Table 3 represents the average price paid by commercial aviation when the industry purchases 0.35b gallons of renewable fuel (at $3.39 + $2.86 = $6.25/gal) and 20.35b gallons of 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 proportional 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 replacing 0.35b gallons of conventional fuel with renewable jet fuel (0.98%).[16]

When renewable jet fuel contributes to the RFS2 target (Include), relative to the Additional scenario, the reduction in the effective mandate for other advanced biofuel decreases the other advanced RIN price (from $1.81 to $1.68). The reduced requirement for total biofuels also decreases land prices and ultimately the price of soy oil (from $4.45/gal to $4.39/gal). As a result, the implicit subsidy to aviation biofuel ($2.69/gal) is also lower than in the Additional scenario. As in the Include scenario, the higher implicit renewable jet subsidy relative to the other advanced RIN price reveals that airlines must partially cross subsidize the production of renewable diesel to induce production of aviation biofuels. There are only very small differences between the average price of jet fuel and aviation metrics and CO_2 emissions 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 HEFA 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

[16] 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.

Table 4
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

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

owners of the relatively scarce factor (rotation crop land), they are the major beneficiaries of development of a rotation crop pathway. Relative to the Include scenario, the price of HEFA jet fuel decreases from $6.08 to $5.61. This results in small increases in aviation operations, total fuel use and emissions.

When six 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 still 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). As renewable jet fuel is a small proportion of total fuel consumption by commercial aviation, the significant reduction in the price of renewable jet fuel results in only a small reduction in the average price of jet fuel, relative to the Include scenario. The lower average jet fuel price results in a smaller reduction in fuel use and emissions due to the aviation biofuel goal.

5.1. CO$_2$ abatement costs

Purchasing renewable fuel will reduce emission through direct and indirect channels. First, renewable fuel consumption will directly reduce emissions by displacing conventional fuel use. Second, as renewable fuel is more expensive than conventional fuel, the increase in fuel costs will indirectly reduce emissions by inducing airline efficiency improvements and (assuming costs are pasted through to consumers) reducing demand for aviation services.

Emissions reductions due to the direct effect will depend on the cost and lifecycle CO$_2$ equivalent (CO$_2$e) emissions of renewable jet fuel relative to those for conventional fuel.[17] Stratton et al. (2011) estimate that the lifecycle emissions from conventional jet fuel are 80.7 g of CO$_2$e per megajoule (0.0115 tonnes of CO$_2$e per gallon) and those from HEFA jet fuel derived from soy oil where there is no land use change are 33.89 g of CO$_2$e per megajoule (0.0048 tonnes of CO$_2$e per gallon). Accordingly, each gallon of conventional fuel replaced by renewable fuel reduces CO$_2$e emissions by 0.0067 tonnes and airlines need to purchase 150.2 gallons of renewable fuel in order to abate one tonne of CO$_2$e. Emissions abatement due to indirect effects are influenced by the availability and cost of new, more fuel-efficient technologies and the responsiveness of the demand for aviation services to changes in airfares, which are determined in the AMPT-E model in our analysis.

CO$_2$e abatement costs are presented in Table 3. As emissions reductions are similar across scenarios, abatement costs across scenarios are driven by differences in production costs for renewable fuel. In the Additional and Include scenarios, abatement costs (through direct and indirect channels) are around $400 per tonne of CO$_2$e. When a rotation oilseed feedstock is available, abatements cost are $317 and $51 per tonne when there is, respectively, low and high availability of rotation crop oil. In all scenarios, reflecting the small proportion of biofuels in total fuel purchases and ultimately small changes in the average price of jet fuel, there is only a small decrease in abatement costs due to indirect effects.

Two important limitations to our analysis should be stressed. First, we did not consider the full suite of pathways potentially available in 2018. 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 in the near future. The addition of these processes and other new technologies may also lower the cost of renewable jet fuel consumption. Second, CGE models produce point estimates that depend on a number of parameter assumptions and do not reflect uncertainty in parameters used to calibrate the model. We address this limitation in the next section by examining the sensitivity of our results to key parameter values.

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[17] CO$_2$e units for GHG gases are calculated by multiplying units by global warming potential (GWP) weights, which measure the ability of gases to trap heat in the atmosphere relative to the heat-trapping capability of CO$_2$ over a 100 year period.

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^T_{D-JNL}. We set $\sigma^T_{D-JNL} = 10$ in our core scenarios and consider values of five and 20 for the Include scenario in sensitivity cases. Results are reported in Table 4. 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 HEFA jet fuel to meet the aviation goal increases (from $2.69 to $2.85) when we reduce the value σ^T_{D-JNL} 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^T_{D-JNL} in the range that we consider.

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 and discussion

We examined the economic and emissions impact of meeting the FAA's aviation biofuel goal of consuming one billion gallons of renewable jet fuel each year from 2018 onwards. Our analysis considered a HEFA process from renewable oils. We found that, without the development of an oilseed rotation crop, meeting the aviation biofuel goal will require an implicit subsidy from airlines to renewable fuel producers of $2.69/gal of jet fuel and increase the average price of jet fuel by $0.04/gal. 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. 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 in all scenarios.

Our analysis also revealed that, as a HEFA process produces other renewable fuel in addition to jet fuel, there are important interactions between the aviation biofuel goal and US mandates for renewable fuels used in ground transportation. Specifically, inducing aviation biofuel production increases the supply of other renewable fuels and drives down RIN prices for these fuels. To compensate producers for lower RIN prices, the implicit subsidy for renewable 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.

In evaluating the cost effectiveness of the policy, we found that the cost of the goal per tonne of CO_2e emissions abated was around $400 when soybean oil was used as a feedstock, and was approximately $50 per tonne under optimistic assumptions regarding the development of oilseed rotation crops. These costs would increase if the goal was expanded to induce larger emissions reductions due to pressure on land prices, and are much higher than the costs of emissions reduction options available through market-based measures. In mid-2013, emission allowances in the EU Emissions Trading System (ETS) were trading at just under $5 per tonne of CO_2e and the futures price for 2018 was around $7. Another low-cost avenue for aviation to contribute to emissions reduction is the purchase of Certified Emissions Reductions (approved credits from projects that reduce emissions in developing countries) issued under the Clean Development Mechanism. Both the purchase of emissions permits and Certified Emissions Reductions would result in aviation contributing to emission reductions by funding abatement in other sectors. A global ETS for aviation would induce emissions reductions at a lower cost than relying only on biofuels, as such a system would allow improvements in technology and infrastructure (in addition to biofuels) to contribute to emissions reductions. However, as the costs of abating emissions in aviation is high relative to other sectors (Winchester et al., 2013), the cost per tonne of abatement is likely to be higher than if the aviation ETS is linked to a cap-and-trade program with broad sectoral coverage. In summary, at expected carbon prices over the next decade and under the pathways considered in this study, we conclude that the biofuel goal for US aviation is an expensive emissions abatement option relative to alternatives. However, development of other biofuel pathways may reduce emissions abatement costs.

Acknowledgements

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