Feasibility Analysis of Regional SAF Production: A Case Study in Virginia

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By

Curtis D. Davis

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Abstract

Because the aviation sector of the economy is difficult to decarbonize, large investments are being made in developing and scaling sustainable aviation fuel (SAF) technology. The *Inflation Reduction Act* brought new federal tax credits for SAF into effect as of August 2022. At the state level, extra incentives may be desired to persuade companies and airlines to invest in SAF infrastructure. This study analyzed SAF production in Virginia via two biomass-to-energy conversion platforms, gasification Fischer Tropsch (GFT) and pyrolysis, as applied to two organic feedstocks: woody wastes and municipal solid wastes. Previously validated analysis models, including the Freight and fuel Transportation Optimization Tool from the U.S. Department of Transportation and techno-economic assessments from the *Aviation Sustainability Center* (ASCENT) (funded by the Federal Aviation Administration), were used to evaluate possible SAF supply chain implementation at the county scale in Virginia. Systems boundaries encompassed feedstock collection and transportation, conversion, and fuel upgrading and transport. Key model outputs were minimum product selling price (MPSP) ($/gallon) and life-cycle global warming potential (GWP) (g CO_2eq/MJ). These data were used to compare hypothetical SAF production in Virginia with relevant benchmarks and to assess what impact state-level investments of different magnitudes and/or different modes would have on economic performance relative to conventional jet fuel. Results suggest that a median case, representative "pilot" GFT facility in Virginia will require financial incentives of approximately $3.61 per gallon, in addition to existing incentives, to be cost-competitive with fossil fuels. A median case, representative pilot pyrolysis facility will require financial incentives on the order of $0.75 per gallon of SAF. These amounts correspond to Pittsylvania County, which was found to be a typical case among five selected counties. Specific SAF prices were found to vary by location due to transportation logistics. Other favorable locations

for pilot facilities include Alleghany, Buckingham, Greensville, and Tazewell Counties. Incentives to close the price gap between SAF and fossil jet fuel could be structured in different ways (i.e., tax credits, loan forgiveness, etc.) to benefit different stakeholders (e.g., feedstock producers, conversion facilities, etc.). Similarly, production facilities could be sited in different geographic locations to benefit different regions and take advantage of feedstock resources and transportation infrastructure access. Having delivered cost projections for SAF from GFT and pyrolysis processes, it was also possible to compare the two platforms and evaluate to what extent the recent changes to federal SAF incentives are structured to efficiently motivate the full decarbonization of SAF supply chains. Results from this study highlight a misalignment of environmental and economic impacts under current federal incentives; whereby, it is not economically efficient to pursue GWP reductions to the fullest extent possible via existing technology platforms. Finally, though Virginia was used as a case study for this analysis, it is anticipated that the methodology is replicable for other states or regions.

1.0 Introduction

The accelerating pace and increasingly severe impacts of climate change make it urgent that our society moves away from fossil fuels and finds alternative, lower-carbon energy sources.[1] Aviation and heavy freight transport are among several sectors that are especially difficult to decarbonize via electrification; aviation, in particular, emits about 2% of total anthropogenic CO_2.[2] Therefore, governments and other stakeholders require other means of reducing carbon emissions from these activities, while also working towards related goals such as protecting air and water quality, promoting human and ecosystem health, managing waste, improving the quality of life for traditionally marginalized groups, etc. It is of particular interest to explore the economic and environmental sustainability performances of biomass- and waste-to-energy systems that could deliver many of these priorities concurrently. These evaluations should take into consideration the specific biophysical and sociotechnical characteristics of the regional context in which they will be implemented.[3]

Federal agencies, regional (state/municipal) governments, and commercial airlines are urgently interested in the commercialization of sustainable aviation fuels (SAF). Multiple federal agencies released the SAF Grand Challenge Roadmap in 2022, which explored methods for the U.S. government to help de-risk technologies and supply chains, prioritize engagement with stakeholders, and generally reduce barriers to SAF production and scaling.[4] Low-carbon SAFs produced from domestically sourced biomass feedstocks are critical for ensuring sustainable commercial and military aviation, which are vital to economic prosperity and homeland security.[4] SAFs are drop-in fuels that are designed to power existing aircraft without necessary modifications at blend ratios of up to 50% with fossil jet fuel.[5] Our research group has previously partnered with the Virginia Department of Transportation (VDOT) to evaluate supply chain readiness for SAF production in Virginia.[6] This study now seeks to understand how much SAF could be produced in Virginia per year, and at what economic and environmental costs via various possible fuel production pathways. Notably, Virginia ranks among the top ten states for jet fuel consumption per year, but it currently produces and consumes no SAF.[7,8] It also produces large quantities per year of woody/forest residues and is a net importer of municipal solid waste (MSW), both of which are of interest for conversion into SAF via thermochemical processing.[9,10] For these reasons, Virginia serves as a good case study for understanding the logistical and incentive readiness of scaling SAF within a state.

There are currently seven ASTM D7566-qualified pathways for converting biomass feedstocks into SAF.[11,12] These seven pathways are also approved to be CORSIA-eligible fuels (CEFs). The Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) is an internationally adopted framework that requires airlines to offset emissions from international travel beyond 2019 levels, and CEFs are a method for compliance.[12] CEFs must be produced from renewable (bio-based) or waste feedstocks not derived from lands designated as high carbon stock. They must also exhibit life-cycle greenhouse gas (GHG) emissions at least 10% below the fossil jet fuel baseline of 89 g CO_2e/MJ for “well to wake” system boundaries (Figure 1).[12]

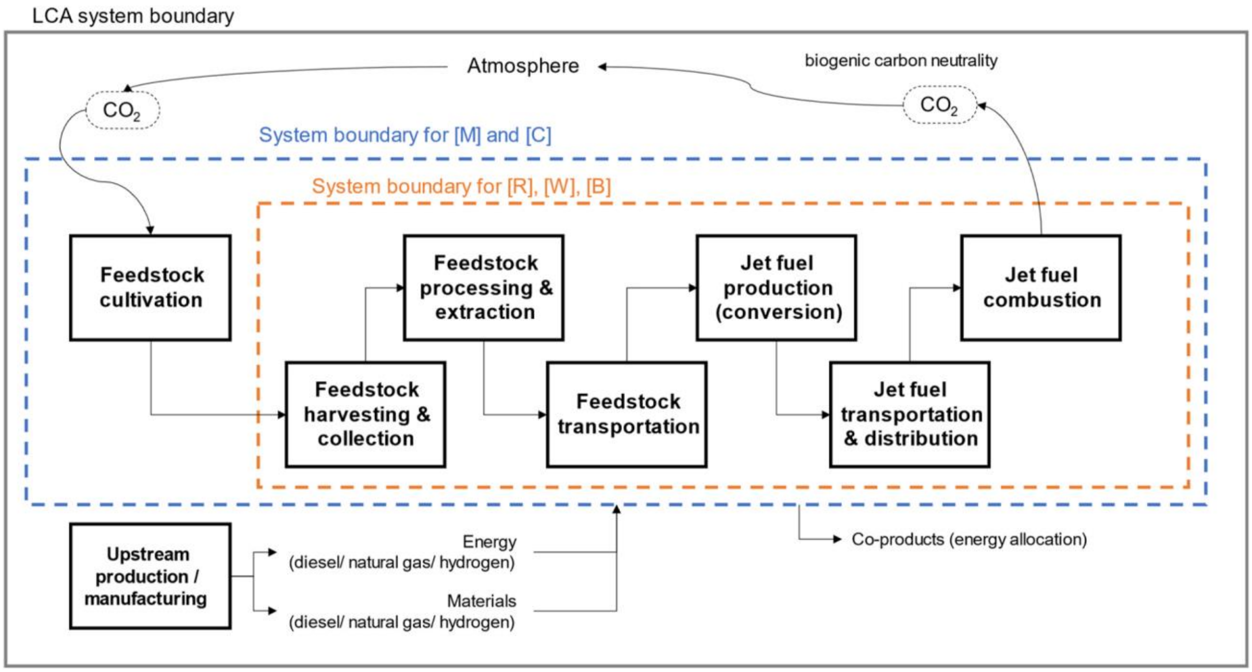

Figure 1. *System boundaries for core LCA of CORSIA SAF.*[12]

Based on outcomes from previous VTRC-funded work,[6] it was decided that thermochemical pathways would be the likeliest candidates for near-term commercialization in Virginia. Previous work also found that SAF could bring substantial economic benefits to Virginia, especially given that feedstocks and transportation infrastructure are available. The previous study suggested that more research was needed into the development of productive feedstocks and that policies such as subsidies could help give a critical boost to the industry.[6] It was subsequently determined that there was especially urgent interest in the gasification and Fischer Tropsch (GFT) pathway leveraging woody wastes and/or MSW as feedstocks. Accordingly, modeling efforts for the current case started by focusing on GFT processing of woody wastes and MSW, addressing both pilot facilities and longer-term mature installations (see Figure 2). Technical descriptions of each conversion pathway of interest are summarized in the following paragraphs.

GFT is a process that converts carbon-rich feedstocks into syngas and then into liquid hydrocarbons. Biomass is first reduced in size and dried before being gasified in an updraft or downdraft gasifier (dryer feedstocks are more optimal to reduce energy involved in drying).[13] The bio-syngas contains CO, H_2, CO_2, N_2, and CH_4, and it goes through a cleaning process where impurities are removed. Impurities can be organic (tars, benzene, etc.), inorganic (O_2, NH_3, etc.), or physical (dust, soot, etc.).[13] Once the bio-syngas has been cleaned, it goes through the Fischer-Tropsch process which uses catalytic processes and converts the gas into a liquid. This process converts the CO and H_2O into CO_2 and H_2. Water gas shifts can also occur to correct the ratio of CO to H_2.[13]

GFT is in use at a pilot-scale facility in Nevada operated by Fulcrum Bioenergy. This facility processes MSW feedstock into SAF which is then used by California airports.[14] Virginia already produces and imports large quantities of MSW per year, and an eighth mega-landfill (3500+ tons per day) was recently proposed for construction in historically economically disadvantaged and underserved Cumberland County.[15] It is appealing to imagine that MSW could be transformed into a valuable resource for producing SAF, whereby the drawbacks of community landfills (odor, noise, possible groundwater contamination, etc.) could be potentially offset via economic opportunities and benefits arising from transitioning waste management facilities into energy production facilities.

Pyrolysis is a different method of converting carbon-rich feedstocks into liquid fuels. Biomass is heated in a non-reactive atmosphere; varying temperatures, pressures, residence times, and heating rates lead to different physical and chemical compositions of the process outputs.[16] Thermal decomposition of the biomass typically begins at about 350°C to 550 °C and is raised to between 700°C and 800°C. During this exposure to high heat and pressure, the biomass breaks down into gases, vapors (tars and oils), and char.[16] Slow pyrolysis has higher residence times but shorter heating rates and lower temperatures than fast pyrolysis. Fast pyrolysis generally produces more oil and less char and gas.[16]

GFT and pyrolysis result in different co-products and different energy inputs, primarily that pyrolysis produces large quantities of char in addition to the bio-oil. Additionally, an important difference between the two is that GFT conversion of several feedstocks into SAF is currently ASTM-certified.[11,12] However, there is also merit to pyrolysis as a "bridge" between current and future SAF production. It is widely acknowledged that the GFT platform, though more appealing in the long term based on its GWP, has been slow to commercialize. When meeting with a major airline earlier this year, their executive was quick to point out that "not a single drop of GFT fuels is being produced in the US right now." That has since changed, now that Fulcrum Bioenergy is up and running, but its long delays illustrate the remaining technical challenges associated with the GFT platform.[14] It is posited that the establishment of a pilot pyrolysis facility could help grow feedstock supply chains, create robust markets for other distillates (i.e., diesel), and give time for GFT technology to fully develop in Virginia. Thus, pyrolysis of both MSW and woody waste feedstocks was also analyzed in this case study (see Figure 2).

It is anticipated the SAF produced in Virginia will still not be cost-competitive with fossil jet fuel despite recent increases to federal incentives, as this has been historically observed by other research.[17] It is also unknown what amount of in-state jet fuel consumption could be transitioned to SAF sourced from Virginia. Therefore, this study sought to answer two overarching questions:

1. What are the best pathways and conversion locations for supplying SAF at scale in Virginia, and how much can be produced? How much would SAF cost?

2. What amount and in what format would the state need to incentivize SAF to help it compete economically with fossil jet fuel? How does this tradeoff with environmental performance metrics?

These questions of interest are applied to a set of two conversion processes, each consuming two possible feedstocks, with an assessment of both pilot facilities and longer-term scenarios once the technologies have matured (Figure 2).

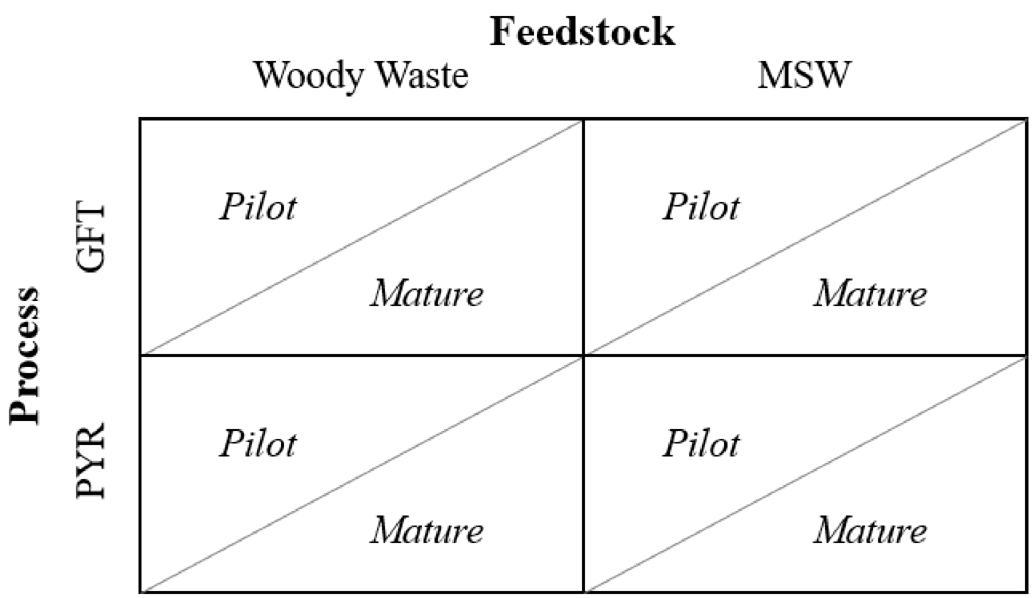

Figure 2. *Combinations of SAF production platforms and feedstocks evaluated in this study, with consideration of both pilot facilities and mature installations. PYR is pyrolysis, which is a thermochemical pathway closely related to hydrothermal liquefaction (HTL).*

2.0 Methods

Supply chain and transportation logistics analyses for SAF production were performed via adaptation of two existing, previously validated modeling tools funded by the US federal government; namely, the *Freight and fuel Transportation Optimization Tool* (FTOT) from the U.S. Department of Transportation (USDOT), and a series of open-source techno-economic assessment (TEA) models for SAF production from the *Aviation Sustainability Center* (ASCENT) [funded by the U.S. Federal Aviation Administration (FAA)]. These modeling frameworks provided a starting place to analyze and optimize transportation, operational, and capital costs of SAF production at various locations. Data from both models were integrated into an overarching techno-economic analysis (TEA) implemented via spreadsheet in Microsoft Excel. Systems boundaries included all of the sub-processes shown in Figure 1. Key outputs from the integrated modeling framework were life-cycle global warming potential (GWP) in g CO_2e/MJ and minimum product selling price (MPSP) in $/gal.

The following subsections provide detailed information about how inputs were selected for use in each constituent model to produce final estimates for the key metrics of interest. Sub-topics are ordered to approximate the sequence of unit processes shown in Figure 1.

2.1 Feedstock Availability

NREL's Biofuels Atlas was used to get county-by-county data for woody waste feedstock availability by year.[9] This class of materials includes forest residues, primary and secondary mill residues, and urban wood. Forest residues include "logging residues and other removable material left after carrying out silviculture operations and site conversions"; primary mill residues include "wood materials (coarse and fine) and bark generated at manufacturing plants (primary wood-using mills) when round wood products are processed into primary wood products"; secondary mill residues include “wood scraps and sawdust from woodworking shops – furniture factories, wood container and pallet mills, and wholesale lumberyards”; urban wood includes “wood material from MSW (wood chips and pallets), utility tree trimming and/or private tree companies, and construction and demolition sites.”[9]

These quantities were compiled into one total quantity of woody waste per county or independent city in Virginia, in units of dry tonnes per year. Dry weights were used as inputs for feedstock-to-fuel conversion ratios, but a mid-range water content of 20% was assumed for the calculation of transportation impacts. Per Han et al.[18], GREET uses water contents of 50% at the time of harvest, but prior to transport, natural drying is assumed, and the water content of forest residue is reduced to 20%. This moisture content is also assumed for primary mill residue and urban wood, but a lower range (15-20%) is assumed for secondary mill residue.[19] These water contents were both increased and decreased by 5% in scenario runs to determine the variability based on changes in the assumed water content.

MSW availability changes from year to year, so Virginia’s most recent solid waste report at the time of modeling was used.[10] This report includes the total amount of MSW collected from in-state and out-of-state, and it details individual landfills with the tonnage of MSW and other wastes.

2.2 Feedstock and Fuel Transportation – FTOT Analyses

The FTOT model was used to evaluate impacts arising from the transport of feedstocks, from known origin locations (Section 3.1) to candidate conversion facility sites, and fuel, from the candidate conversion facilities to the desired consumption site at Dulles International Airport (IAD). For simplicity, each county’s feedstock and candidate conversion site were mapped to the GIS coordinates of its population centroid. The large number of possible conversion site locations, assuming up to one each in 134 total Virginia counties and independent cities, made the optimization too computationally expensive to evaluate all possible counties in a single run. Therefore, 24 randomized sets of 45 counties were evaluated in individual runs. For each run, FTOT identified what set of production facilities delivered the lowest overall transportation cost while still meeting fuel demand requirements. Model demand at IAD was set to match the total supply in a given FTOT run to avoid unmet demand penalties; however, the demand used in each run was different from the actual demand at IAD. The real demand was estimated to be about 1 million gallons per day, based on communication with officials from the airport's fuel supplier.[20] FTOT also reported total GWP impacts for feedstock and fuel transportation within the optimized network from each run. The analysis of various county combinations was repeated at three different sizes of hypothetical conversion facilities (300K, 500K, and 750K tonnes of feedstock per year), to ensure that county selection results were robust to this parameter. The set of 20-40 counties selected for siting of a conversion facility (depending on the size of the facilities) was recorded for all 24 sets of county combinations, to determine which counties were picked by FTOT most frequently. Finally, the county prioritization results arising from the randomized optimization process were filtered based on input from relevant stakeholders (e.g., Commercial Aviation Alternative Fuels Initiative, UT Institute of Agriculture)[21,22] and insights from previously published work.[6] More information about how to use FTOT is available in Appendix A.1 and FTOT's public GitHub page.[23]

FTOT computed feedstock and fuel transport costs and GWP from the county of origin to various candidate conversion sites based on population centroids. It was also necessary to account for the likely distances between each county centroid and where the feedstock was actually collected. These "last-mile" adjustments were implemented in the spreadsheet model integrating results from the various constituent sub-models (i.e., FTOT and the ASCENT TEAs). Transportation distances within each county of origin were computed by estimating the radius of the circle circumscribing the area of that county. Corresponding cost and GWP impacts were computed by multiplying the masses of feedstock from each county by the county-specific radii. The resulting impacts were manually added to FTOT's feedstock transportation impacts. Last-mile calculations were not required for the MSW feedstock, because feedstock transportation is not included due to facilities being co-located with existing landfills, where MSW is already being transported.

2.3 Conversion – ASCENT TEAs

A suite of previously published TEA models produced by the ASCENT program was used as a starting place to model the GFT and pyrolysis conversion processes in this study.[24-26] The creation of these models was funded by the US FAA with the purpose of informing SAF policy formation.[27] The systems boundaries for the fuel production phase of the ASCENT TEAs encompassed several relevant auxiliary processes, including feedstock pre-processing and separation of the fuel product into multiple distillates. The TEAs use ratio factors and regional-specific assumptions to estimate MPSP for SAF. Virginia-specific inputs for these spreadsheet models are in Table 1. Users select a distillate breakdown (for this study, SAF production was maximized) and the TEAs use feedstock-to-fuel ratios from literature; based on the quantity of feedstock input by the user, quantities of SAF, diesel, and other products are known. The quantities of fuel that are produced determine the MPSP to balance the total revenue and expenditures. There are set relationships between the value of SAF to the other products based on historical records from 1983 to 2018; when the TEA models run, the SAF price is solved to meet these constraints.

These TEAs include the ability to model a pilot facility versus an n^{th} (mature) facility using a cost growth factor.[28]

For GFT and pyrolysis of woody waste, three facility size scenarios were studied: 500,000, 1 million, and 1.5 million tonnes of feedstock per year. MSW facilities were sized based on actual amounts collected by landfills from Virginia's solid waste report.[10] These facility sizes were used to determine feedstock pre-processing costs. Total feedstock cost was then input into the GFT or pyrolysis TEA along with the facility size to report an MPSP for SAF. This value can then be input into the overall spreadsheet model to combine with FTOT results as discussed below. This process was completed for each of the pathways studied.

Table 1. *Virginia-specific input values for the ASCENT TEAs compared with default values.*

Variable	TEA Default	Virginia-specific value	Sources
Forest residues ($/t)	125	124-142	White (29) & Cheng et al. (30) adjusted for inflation; Brandt et al. (26) for feedstock pre-processing
MSW ($/t)	30	(-197)-171	Different assumptions surrounding: recyclables content and recovery; market value of recyclables; tipping fee value and recipient
Feedstock transport price ($/gal)	0	0.08-0.39	FTOT modeling
Fuel transport price ($/gal)	N/A	0.06-0.13	FTOT modeling
Electricity ($/kWh)	0.069	0.081	EIA Electric Power Monthly
Natural gas ($/MMBtu)	4.24	5.04	EIA Natural Gas Prices
Cost of land (%TCI)	1.5	Dependent on location and property value	Virginia Department of Education

For necessary energy calculations, a few input values are required depending on the pathway, such as the high heating values (HHV) of the feedstock and the upgraded SAF, the assumed density of the upgraded SAF, and bio-oil yield ratios. These values can be used to calculate SAF yield (bio-oil yield ratio multiplied by the SAF distillate fraction) and the energy density of SAF using the following equation:

$$(1)\ SAF_e = \frac{HHV_{SAF} * \rho_{SAF}}{264.17}$$

where SAF_e is the energy density of SAF in MJ/gal, HHV_{SAF} is the high heating value of upgraded SAF in MJ/kg, ρ_{SAF} is the density of upgraded SAF in kg/m^3, and 264.17 is the number of gallons per cubic meter. In this analysis, 40 MJ/kg was used for HHV_{SAF} and 750 kg/m^3 was used for ρ_{SAF} (mid value of 730-770 kg/m^3 range).[34]

Bio-oil yields were taken from the ASCENT TEAs for GFT (woody waste and MSW) and pyrolysis (woody waste), which are based on literature values. Bio-oil yield for pyrolysis of MSW was not available in the literature, so pyrolysis of different MSW components was collected from the literature. This compilation can be found in Appendix A.3.

As part of the spreadsheet model for this study, after outputs are applied, a property value is determined for the land needed to house each facility. Sizing was based on an assumed value of 0.0005 acres per tonne of feedstock input (i.e., 50 acres per 100,000 tonnes of feedstock). This assumption is based on Red Rock Biofuels in Oregon, which owns 88 acres for a facility of 166,000 dry tons (approximately 200,000 wet tonnes) capacity.[35] Land values are per county or independent city and were determined by dividing the true value of county property by the total land in said county. For Virginia, this information is found in the Department of Education's Composite Index of Local Ability to Pay documentation.[33]

For a typical chemical engineering plant, the price of land is assumed to be 1.5% of the total capital investment.[36] Property values were necessary to calculate rather than assuming they are always 1.5% of the total capital investment to get a more accurate cost of land, particularly because of the wide array of land values in Virginia. As expressed in Table 1, a specific value of land was entered in the ASCENT TEAs, which was completed in an unlocked-cell version from the authors of the TEAs.

2.4 Global Warming Potential Calculations

Because GFT of forest residue and MSW are ASTM-certified pathways for SAF and because they significantly reduce the GWP as compared with fossil jet fuel, they are considered CORSIA-eligible fuels and have ISO-compliant life cycle assessments (LCAs) produced by the International Civil Aviation Organization (ICAO).[37] These LCAs are broken down into four components: feedstock cultivation and collection, feedstock transportation, feedstock-to-fuel conversion, and fuel transportation. The results for feedstock and fuel transportation were removed so that Virginia-specific values could be substituted; these were calculated using FTOT as described in Section 2.2.

Pyrolysis of forest residue, and potentially MSW, are not yet certified but are expected to be in the future;[38] however, because they are not certified as of this study, there are no ICAO LCAs for these pathways. Instead, de Jong et al.[39] ran LCAs for different SAF pathways including pyrolysis of forestry residues; these were broken down in a very similar fashion as CORSIA (feedstock cultivation, upstream transport, conversion, hydrogen, and downstream distribution). Again, the two transportation components were removed and replaced with results from FTOT to be used in this case study.

For SAF produced from pyrolysis of MSW, no proper analyses have been performed to date in the literature. This study utilized an open-source decision model by Cheng et al.[30] Inputs for this decision model can be found in Appendix A.3. For this study, energy allocation was used to determine the GWP of SAF compared to co-products (diesel, gasoline, and bunker fuel), consistent with the CORSIA framework and previous related work from de Jong et al.[37,39]

2.5 Incentives

The ASCENT TEAs provide incentives tabs that allow for the comparison of potential federal or state-level incentives and the effects they would have on the MPSP of SAF. For the purposes of this study in Virginia, previously existing federal incentives such as $3.21/gal RINs (credits for compliance with RFS, based on the average of the first quarter in 2022),[40] $1/gal diesel blenders tax credits (BTCs), and $0.50/gal gasoline BTCs are considered along with federal capital grants. Fulcrum Bioenergy and Red Rock Biofuels both received approximately $75 million in grants from the Department of Defense, so similar grants were assumed for pilot facilities in Virginia.[27] Next, new federal incentives in the form of a BTC for SAF were considered in alignment with the recently passed Inflation Reduction Act (IRA).[41] The IRA applies to fuels that reduce lifecycle emissions by at least 50% from fossil jet fuel, starting at a base credit of $1.25/gal plus a supplementary amount of $0.01 for every percentage point above 50% emissions reduction.[41]

Subsequently, five potential state investments were considered in order to advise Virginia on which investments would yield lower SAF prices. Those incentives include a feedstock subsidy, risk reduction (reduction of the facility's interest rate), a state-funded capital grant, a tax credit, or a policy similar to California's Low Carbon Fuel Standard (LCFS). The ASCENT TEAs were analyzed to calculate even investment levels per the first four different incentive options (when each was a possibility), with the LCFS standing separately. $350 million was chosen as the total investment amount for each incentive. The total magnitude is less important than the difference between the SAF prices resulting from an equal investment; that said, $350 million was chosen as a reasonable magnitude because it is approximately 0.5% of Virginia's total budget from FY2021,[42] 11% of the total amount in credits in California's LCFS in 2020,[43] and 50% of what

IAD paid for jet fuel in 2019.[7,20] Additionally, investments of $70 million and $585 million were analyzed to compare with the $350 million investment and to confirm results, along with necessary investments to fall within the market price range of fossil jet fuel.

3.0 Results and Discussion

3.1 Feedstock Availability and Selection of Candidate Processing Sites

3.1.1 Woody Waste Feedstock

Figure 3 summarizes the availability of woody waste feedstock by county and independent city in Virginia. There is appreciable variability in feedstock access by county, ranging from 940 to 276,820 dry tonnes per year. Total woody waste availability is approximately 6,155,030 dry tonnes per year, which includes some feedstock that is likely already utilized by other industries. This could be as high as a quarter or a third of the feedstock in this analysis.

Based on the known geographic distribution of woody waste feedstock, it was hypothesized that minimizing feedstock and fuel transportation would contribute to the production of cost-competitive and low-carbon SAF. The FTOT model was therefore used to evaluate impacts arising from the transport of feedstocks and finished SAF within the state, based on hypothetical conversion facilities at various possible locations. Figure 4 shows the results of the county prioritization analysis based on randomized sets of candidate county locations, as discussed in Section 2.2. From this figure, there was wide variability in the number of FTOT runs in which a particular county was selected for implementation of a SAF production facility. County locations that were picked most often correspond to locations that minimize overall feedstock and fuel transportation costs and impacts. These locations are seemingly good candidates for the location of a SAF production facility. In contrast, county locations that were picked less often are not as appealing for the construction of a SAF production facility, based solely on transportation optimization. Summarizing from Figure 4, the top 10 highest priority counties are (in order): Buckingham, Charlotte, Fairfax, Louisa, Roanoke, Alleghany, Greensville, Pittsylvania, Amelia, and Brunswick. Each of these counties was selected for implementation of a SAF production facility no fewer than 21 out of 24 possible selections. Table 2 summarizes the number of times each of these counties was selected.

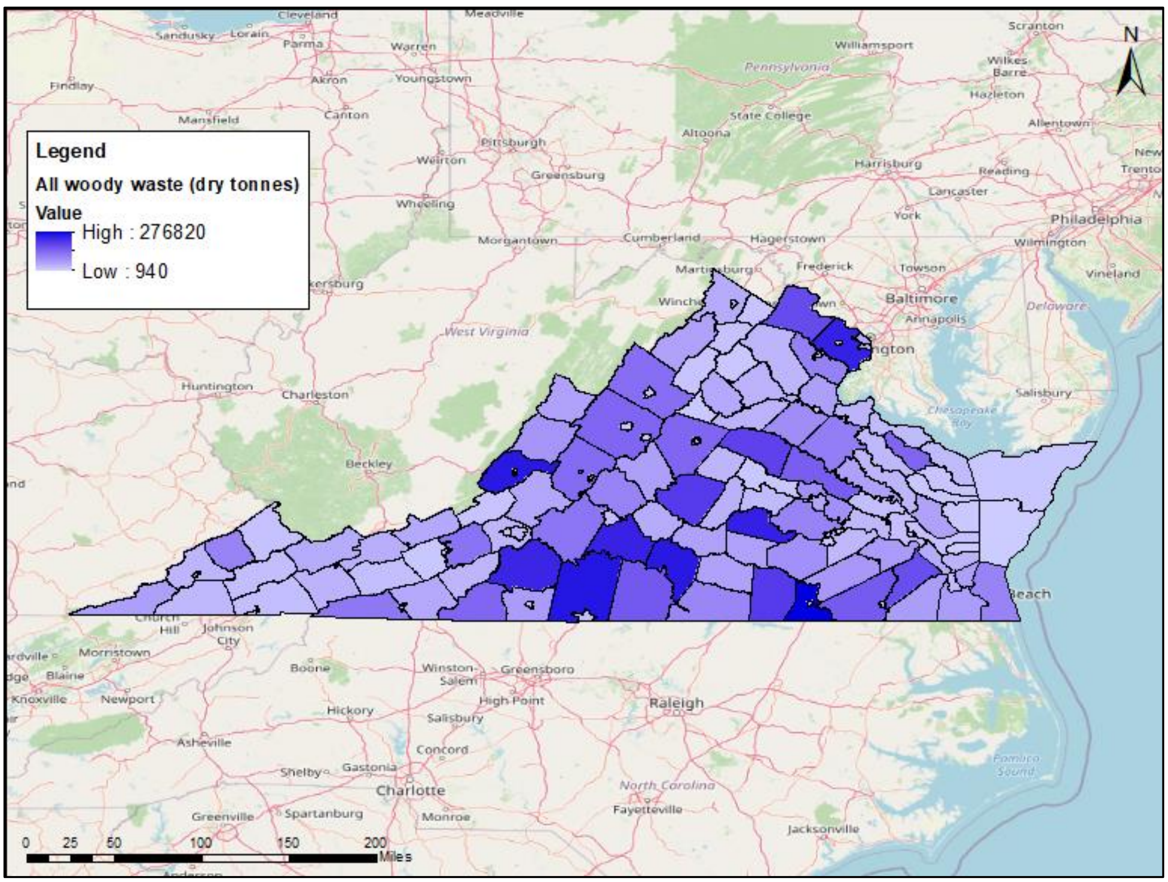

Figure 3. *Woody waste availability by county in Virginia. Units are dry tonnes per year. Data from NREL's Biofuels Atlas.*[9]

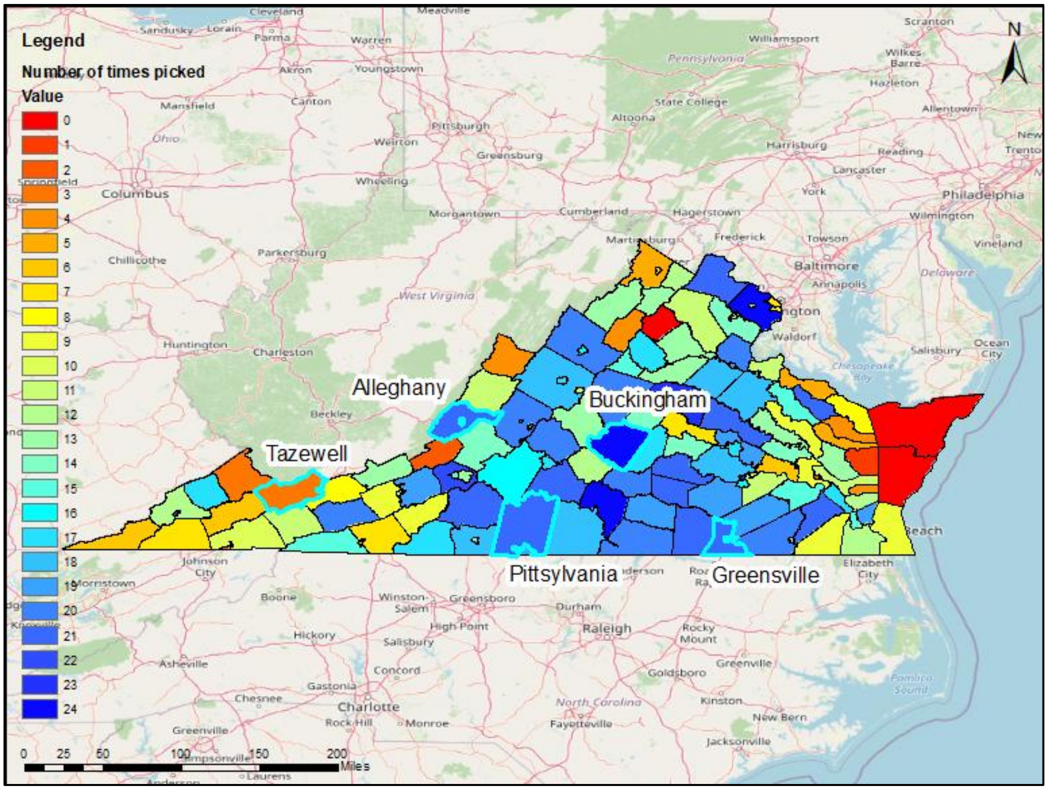

Figure 4. *County prioritization based on the frequency of selection for implementation of a SAF production facility in randomized FTOT runs. Top counties that FTOT selected out of randomized runs. List of the top ten selections can be found in Table 2. Blue outlining denotes counties selected for analysis using the ASCENT TEA modeling framework.*

Table 2. *Top ten counties that FTOT selected out of randomized runs. Note the four bolded counties selected to be analyzed for a pilot conversion facility as seen in Figure 4.*

County	FTOT facility code	# selected
Buckingham County	proc_51029	24
Charlotte County	proc_51037	24
Fairfax County	proc_51059	24
Louisa County	proc_51109	23
Roanoke County	proc_51161	22
Alleghany County	proc_51005	21
Greensville County	proc_51081	21
Pittsylvania County	proc_51143	21
Amelia County	proc_51007	21
Brunswick County	proc_51025	21

The list of 10 seemingly promising candidate counties was filtered to reflect stakeholder input, insights from previously published work, and other practical considerations. Four of the ten counties in Table 2 were selected for inclusion in subsequent modeling, including Alleghany, Buckingham, Greensville, and Pittsylvania. These were considered to be higher priorities than the other six. Alleghany County was selected because of its large quantities of woody wastes, particularly primary mill residue. It was also anticipated that feedstock could be easily imported from West Virginia, further boosting SAF production in Virginia. Additionally, a facility in this county would bring economic development to the Appalachian region, particularly in the western portion of the state. Buckingham County was selected because of its large quantities of feedstock, particularly forest residues. Additionally, it is located in the central part of the start (unlike other selected counties), and it is transected by the Colonial Pipeline. There was strong anticipation by relevant stakeholders that pipeline adjacency would be useful for keeping cost and GWP as low as possible. Greensville County was selected as a candidate because of its large quantities of woody waste, particularly primary mill residue, and because feedstock from North Carolina would be easily accessible. Pittsylvania County was selected as a candidate because it has the most woody waste of any county in the state, and it is particularly high in forest residues and primary mill residue. It also has easy access to North Carolina feedstock, and it is traversed by the Colonial Pipeline.

Finally, Tazewell County was added to the list based on strong interest from relevant stakeholders due to a previous related analysis.[22] That study highlighted its centralized location relative to the Appalachian “wood basket”, whereby feedstocks could be conveniently imported from West Virginia, Kentucky, Tennessee, and North Carolina. The UT Institute of Agriculture mentioned Tazewell as a promising biorefinery location in its 545_75 scenario, which confirms its potential to be an economically powerful option.[22] This candidate would also bring economic development to the Appalachian region, particularly in the southwestern portion of the state, which has traditionally been underserved. Lastly, from a practical perspective, the selection of Tazewell County instead of the other top 10 counties also avoided the selection of locations that are too close to each other (Charlotte and Louisa are very close to Buckingham), since it was anticipated that two side-by-side counties would not yield meaningfully different TEA modeling results. Additionally, Alleghany County was chosen instead of Roanoke County because of Roanoke's lack of available feedstock (Figure 3), and Fairfax County was not chosen because of high property values.

3.1.2 Municipal Solid Waste Feedstock

For MSW, three landfills were analyzed for potential co-location of a pilot SAF production facility, because it was assumed that co-location would avoid extra transportation costs. The selected landfills were Maplewood Recycling and Waste Disposal in Amelia County, Charles City County Landfill, and Atlantic Waste Disposal Inc. in Sussex County (Figure 5). These were selected due to their large sizes and remaining capacities (greater than 30 years left). Amelia County Landfill collected about 960,000 tonnes of MSW in 2020 and is estimated to have 126 years remaining; Charles City County Landfill collected about 650,000 tonnes of MSW in 2020 and is estimated to have 33 years remaining; Sussex County Landfill collected about 1.19 million tonnes of MSW in 2020 and is estimated to have 54 years remaining.

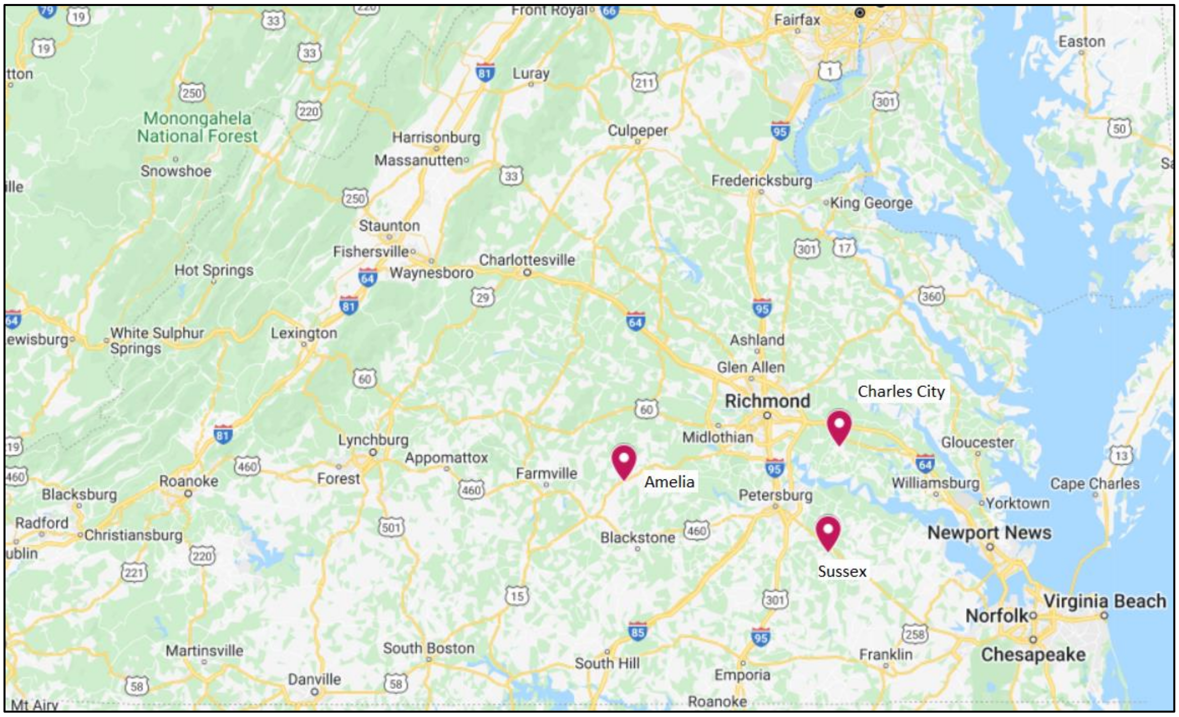

Figure 5. *Three landfills analyzed for an adjacent, pilot conversion facility.*

The selection of five hypothetical woody waste processing locations and three hypothetical locations MSW processing locations co-located with existing landfills would not fully consume all of the available feedstock in the state. However, it was of interest to evaluate a small number of seemingly promising pilot facilities, to determine which locations are best suited for earliest deployment. It was envisioned that additional facilities would then be constructed at other locations once the technology had time to mature. The locations and sizes of the latter facilities would be influenced by the size and location of the first few pilot facilities.

3.2 Gasification-Fischer Tropsch (GFT)

3.2.1 Pilot Woody Waste Facilities

Figure 6 shows SAF prices for each of the five hypothetical facilities at the three different facility sizes, including with possible pipeline access at one location. These cost estimates were for pilot facilities because there is little precedent for the operation of this technology in Virginia.

Table 3 contains these results in tabular form along with feedstock ranges and what fraction of overall demand is met by each individual facility. The difference in MPSP values computed for different facilities was due to differences in feedstock and fuel transportation by location. From Figure 6 and Table 3, there was no significant variability in SAF MPSP by location among the five selected counties. However, there was much greater variability in MPSP based on facility size, whereby larger facilities produce cheaper SAF. This illustrates appreciable economies of scale. These differences were large because conversion is the most intensive portion of this process. Finally, it was anticipated that pipeline access would reduce SAF MPSP by reducing transportation costs. However, this outcome was not observed because conversion costs were much greater than transportation costs. Regardless, the use of pipelines to transport SAF would have significant benefits that are not captured in this analysis; e.g., minimizing additional truck transport on existing roadways in Virginia.

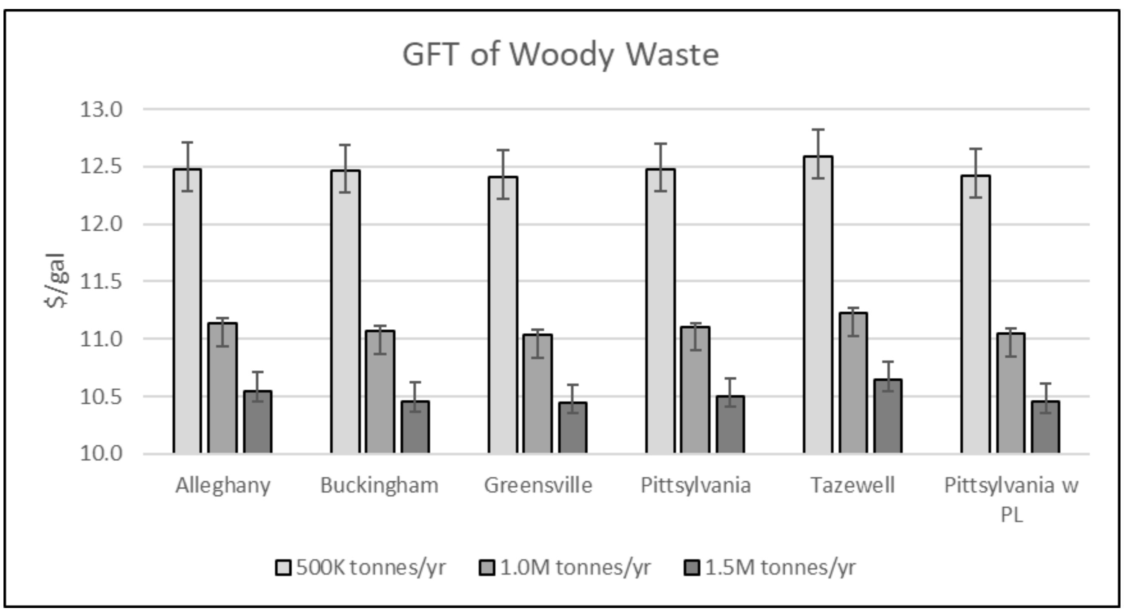

Figure 6. *SAF prices for each hypothetical pilot facility at different scales for the counties of interest, assuming truck and rail transport only. "w PL" refers to potential future pipeline access. No incentives are included in these cost estimates. Error bars account for variability in the moisture content of the feedstock.*

Table 3. *Results for single, hypothetical pilot facilities for GFT of woody waste. Demand at Dulles International Airport is based on correspondence with the airport.*[20] *Virginia 2019 consumption is from EIA.*[7]

Size	County	Pilot plant ($/gal)	Area of feedstock range (sqmi)	Exclusively VA feedstock?	Adjacency to pipeline?	% of Dulles Demand	% of VA 2019 Consumption	Average cost ($/gal)
500K tonnes/yr	Alleghany	12.48	3149.05	N	N	3.43%	1.51%	12.47
	Buckingham	12.46	2592.31	Y	Y			
	Greensville	12.41	1442.30	N	N			
	Pittsylvania	12.47	2651.00	N	Y			
	Pittsylvania w PL	12.42	2652.00	N	Y			
	Tazewell	12.59	5179.60	N	N			
1.0M tonnes/yr	Alleghany	11.14	6833.71	N	N	6.86%	3.01%	11.11
	Buckingham	11.07	3949.69	Y	Y			
	Greensville	11.04	3741.64	N	N			
	Pittsylvania	11.10	4800.53	N	Y			
	Pittsylvania w PL	11.05	4800.53	N	Y			
	Tazewell	11.23	10304.94	N	N			
1.5M tonnes/yr	Alleghany	10.55	9340.67	N	N	10.28%	4.52%	10.51
	Buckingham	10.46	6514.89	Y	Y			
	Greensville	10.44	5913.54	N	N			
	Pittsylvania	10.50	6364.46	N	Y			
	Pittsylvania w PL	10.45	6365.46	N	Y			
	Tazewell	10.64	13849.75	N	N			

For a deeper analysis, Pittsylvania County's results were broken down to understand the apportionment of the overall price per gallon among constituent steps of the SAF life cycle (Figure 7). This county was selected as a representative case because it corresponded to the median (middle) MPSP value for the set of counties shown in Figure 3. Other counties showed similar results, with some slight increase or decrease in the overall MPSP estimate. The overall MPSP was broken down into four components: feedstock pre-processing, feedstock transportation, conversion, and fuel transportation costs (Figure 7). It was also of interest to apportion overall GWP by life-cycle stage results; however, it was not possible to separate feedstock collection and pre-processing costs from conversion costs. Therefore, overall GWP was only broken down into three components: feedstock transportation, conversion, and fuel transportation (Figure 8). Conversion and fuel transportation did not change as facility size changed because CORSIA does not provide for economies of scale; however, feedstock transportation increased with increasing facility size due to the expanded distance of transport to reach a larger facility.

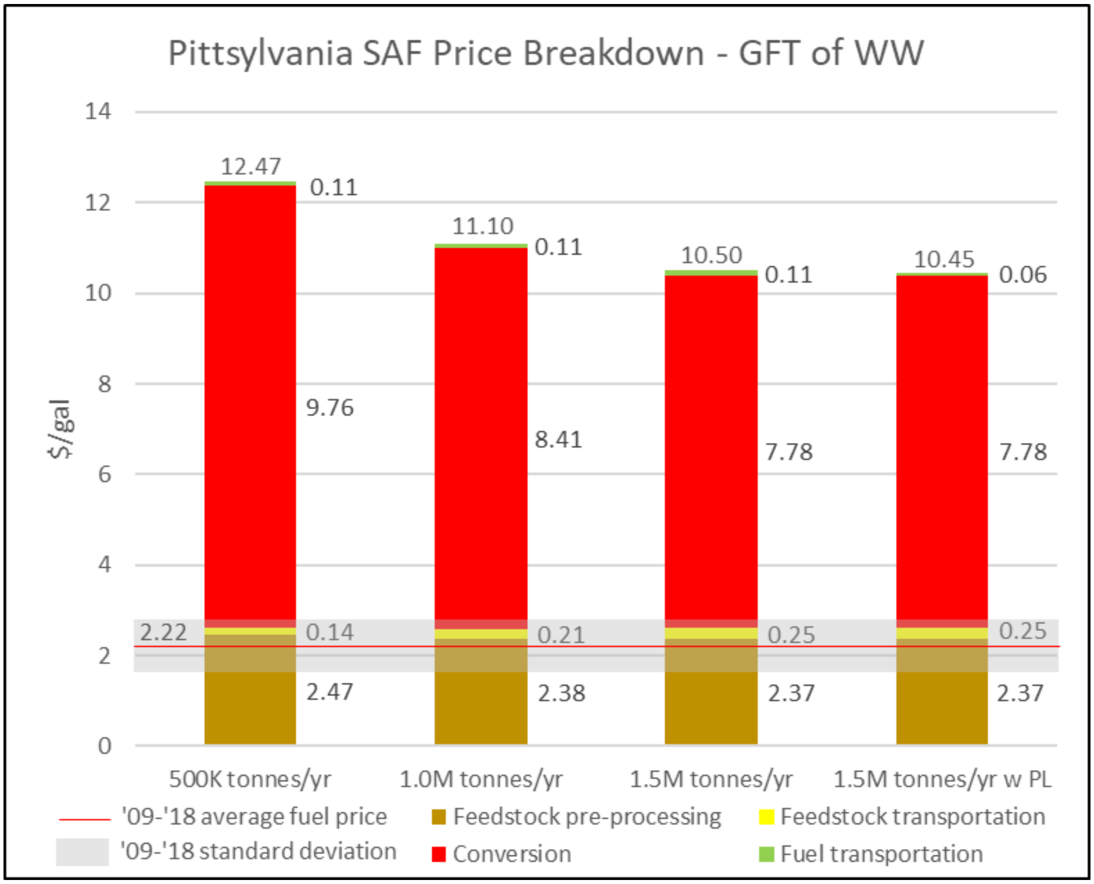

Figure 7. *Price breakdown for different facility size scenarios for pilot plants in Pittsylvania County, assuming truck and rail transport only. "w PL" refers to potential future pipeline access. This is compared to the average fossil jet fuel market price in the decade from 2009 to 2018, marked in red ($2.22 ± 0.67 /gal).*

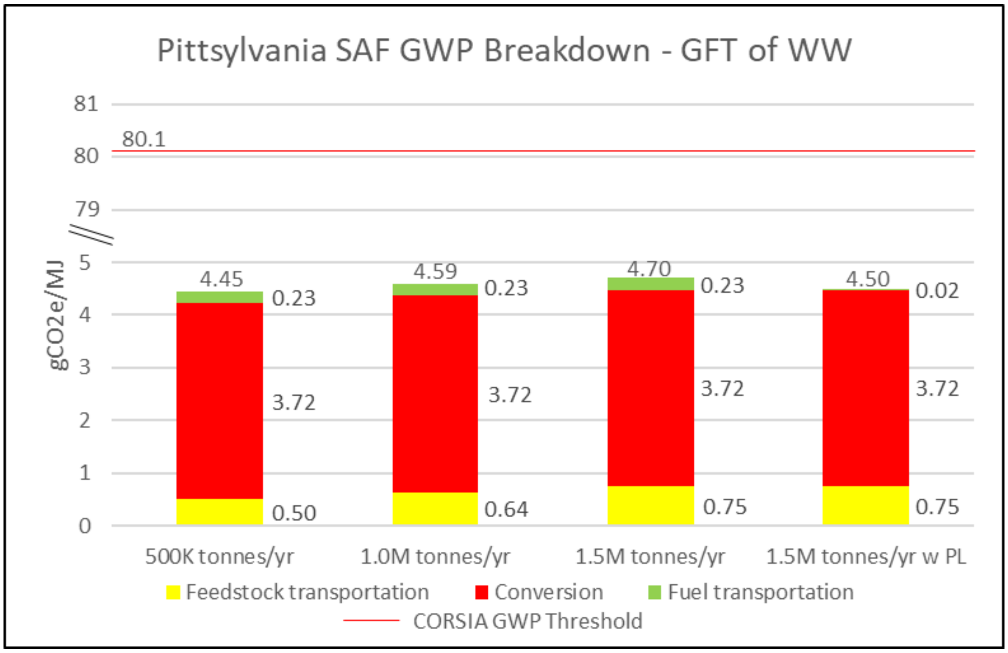

Figure 8. *GWP breakdown for different facility size scenarios for pilot plants in Pittsylvania County, assuming truck and rail transport only. "w PL" refers to potential future pipeline access. This is compared to CORSIA's fossil jet fuel baseline marked in red (80.1 gCO_2e/MJ).*[12]

From Figures 7 and 8, conversion accounted for most of the overall cost (74-78%) and GWP (79-84%) arising from SAF production via GFT of woody waste feedstocks in pilot facilities. There was virtually no influence of facility size on SAF GWP. Finally, these results show that the MPSP of SAF produced from GFT processing of woody wastes is significantly higher than the historical price of fossil jet fuel ($10.45-12.47/gal vs. $2.22 ± 0.67 /gal). However, SAF GWP is appreciably lower than the allowable CORSIA cutoff (4.5-4.7 vs. 80.1 g CO_2/MJ).[12]

3.2.2 Pilot MSW Facilities

It was also of interest to analyze GFT conversion of MSW feedstock at selected hypothetical pilot facilities co-located at existing landfill sites. This technology is currently in use by Fulcrum Bioenergy in Reno, Nevada supplying SAF for San Francisco International Airport; however, there are no such facilities currently operating in Virginia. Figure 9 shows SAF prices and breakdowns for three hypothetical facilities co-located at existing mega-landfills, including one location with possible pipeline access. Unlike the hypothetical pilot woody waste facilities, some variation arose among SAF costs exhibited by various hypothetical facilities due to differences in facility size. Feedstock transportation cost was assumed to be zero because the MSW would have to be transported to the landfill location even in the absence of a SAF production facility. Therefore, all variability in SAF cost in Figure 9 was due to differences in conversion cost based on expected facility size. The sizes were selected based on known landfill MSW intake at each location, assuming that each hypothetical SAF production facility would accept all of the MSW currently processed at each existing landfill. The largest facility (Sussex) exhibited the cheapest expected fuel cost ($6.05/gal). Even so, there was very little variability among estimated SAF costs by county computed in this analysis.

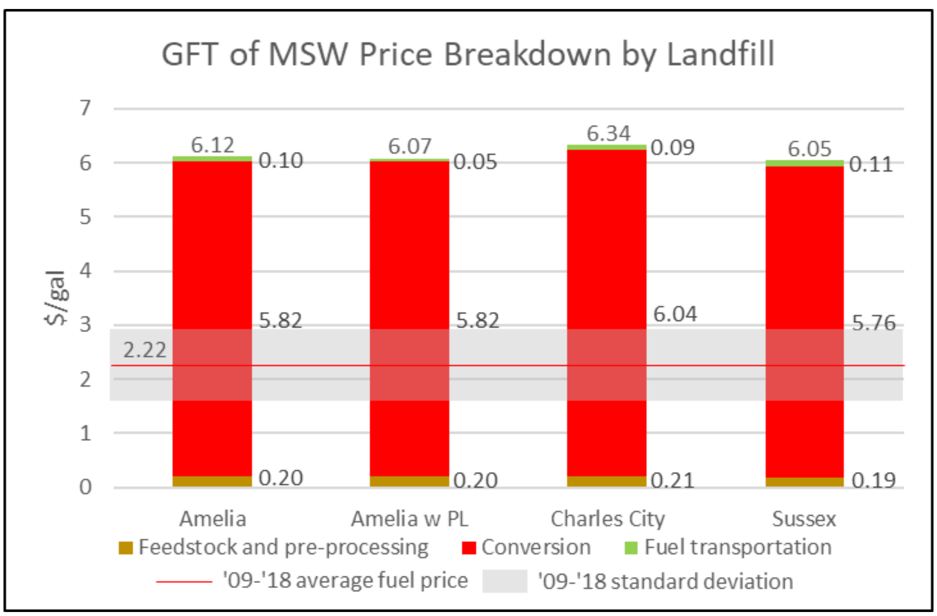

Figure 9. *Price breakdown for pilot facilities co-located with three different landfills, assuming truck and rail transport only. "w PL" refers to potential future pipeline access. This is compared to the average fossil jet fuel market price in the decade from 2009 to 2018, marked in red ($2.22 ± 0.67 /gal).*

Table 4 contains the results from Figure 9 in tabular form, along with estimates of what fraction of total SAF demand at IAD could be met by each individual hypothetical facility. In addition to average MPSP estimates, Table 4 also includes best and worst-case cost estimates. These ranges were computed to bound the wide variability in SAF cost estimates arising from significant uncertainty and/or variability in MSW feedstock cost. There was a wide range of possible MSW prices reported in existing literature, corresponding to wide variability in MSW quality (e.g., with and without pre-processing to recover valuable materials such as metals, glass, or organic materials for composting). It was difficult to interpret existing tipping fee information since it was often not evident whether these costs accounted for pre-processing to various extents. Future work should focus on refining the MSW cost estimates by locality in seemingly promising locations for deployment of pilot SAF production facilities. Table A1 in Appendix A.2 provides additional information about variability and/or uncertainty in MSW feedstock costs, and how those influence estimated ranges of SAF production cost.

Figure 10 shows the apportionment of life-cycle SAF GWP by step, accounting for conversion, fuel transportation, and combustion stages. The inclusion of combustion-phase GWP emissions is required under the CORSIA framework for MSW feedstock, but not woody waste feedstock because it is assumed that MSW contains non-biogenic carbon content at varying 5%

Table 4. *Results for single, hypothetical pilot facilities for GFT of MSW. Best case refers to lower feedstock cost and higher recoverability; worst case refers to higher feedstock cost and lower recoverability (see Table A1 in Appendix A.2). Demand at Dulles International Airport is based on correspondence with the airport.[20] Virginia 2019 consumption is from EIA.[7]*

County	Size (tonnes/yr	Pilot plant ($/gal)			Adjacency to	Middle case with pipeline	% of Dulles Demand	% of VA 2019 Consumption
		Best case	Middle case	Worst case				
Amelia	960K	3.88	6.12	7.71	Y	6.03	13.51%	5.93%
Charles City	650K	4.07	6.34	7.93	N	-	9.16%	4.02%
Sussex	1.19M	3.81	6.05	7.64	N	-	16.71%	7.34%

ranges. For this analysis, 10-15% non-biogenic carbon was assumed. In contrast, it is assumed that all woody waste carbon is biogenic such that the same CO_2 released during SAF combustion exactly cancels out the CO_2 taken up by the biomass during the growing phase. GWP emissions arising from conversion and combustion stages were the same for all evaluated landfill locations since these are expressed on a per-MJ basis. However, there was a small amount of variability in fuel transportation GWP, reflecting differences in transportation distance between each evaluated location and the assumed fuel consumption site at IAD.

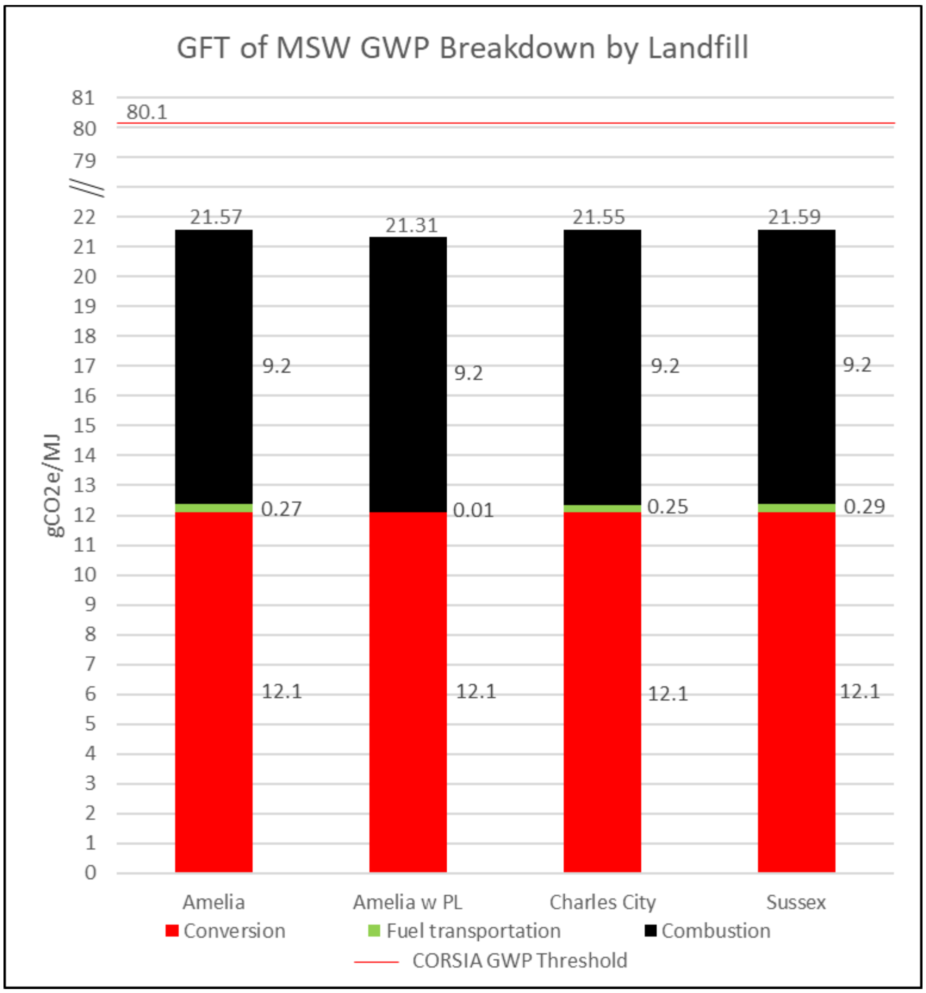

Figure 10. *GWP breakdown for pilot facilities co-located with three different landfills, assuming truck and rail transport only. "w PL" refers to potential future pipeline access. This is compared to CORSIA's fossil jet fuel baseline marked in red (80.1 gCO_2e/MJ).*[12]

From Figures 9 and 10, conversion accounted for most of the overall cost (95%) and GWP (56%) arising from SAF production via GFT of MSW feedstocks in pilot facilities. There was practically no influence of facility size on SAF GWP. Along with GFT of woody waste, these results show that the MPSP of SAF produced from GFT processing of MSW is still considerably higher than the historical price of fossil jet fuel ($6.05-6.34/gal vs. $2.22 ± 0.67 /gal). However, SAF GWP is still much lower than the allowable CORSIA cutoff (21.3-21.6 vs. 80.1 g CO_2/MJ).[12]

3.2.3 Longer-Term Projections: Networks of Mature Facilities

The ASCENT TEAs make it possible to analyze the performance of SAF production facilities in the near term, assuming a small number of "pilot" facilities, and over longer time frames for "mature" facilities. It is assumed that technology development and the establishment of robust supply chains will contribute to better performance of the system, ultimately leading to lower SAF production costs over time. After examining results for pilot GFT conversion facilities, it was therefore also of interest to examine how hypothetical networks of SAF production facilities would perform once the technology had had sufficient time to become mature. For these analyses, the FTOT feedstock and fuel transportation optimization was repeated, considering the known location of each feedstock and the desired use location at IAD, but with many possible locations for hypothetical production facilities. FTOT was offered a candidate facility location in each county, and the tool picked the number and sizes of facilities to optimize transportation and build costs. The tool was constrained to use all of the feedstock available. Figure 11 shows the network of eight 1.0 M-tonne/year SAF production facilities arising from the most relevant FTOT modeling. The selected county locations were as follows: Amelia, Campbell, Caroline, Clarke, Greensville, Isle of Wight, Rockbridge, and Wythe. Notably, five of these eight locations are closely aligned with the five counties selected in the pilot-scale analysis: Amelia and Campbell are very near to Buckingham; Campbell is adjacent to Pittsylvania; Rockbridge is adjacent to Alleghany; Wythe is very near Tazewell; Greensville was one of the selected counties. This means that all of the locations that are seemingly appealing for the construction of a pilot facility in the near-term future will still be good choices in the longer-term future, even as other facilities are added elsewhere in the network. The average MPSP over these eight facilities was \$7.21/gal, which is approximately \$3.90 cheaper than the cost calculated for the pilot facilities; however, the projected cost is still nearly \$5/gal higher than the average fossil jet fuel market price from 2009 to 2018 (\$2.22 ± 0.67 /gal).

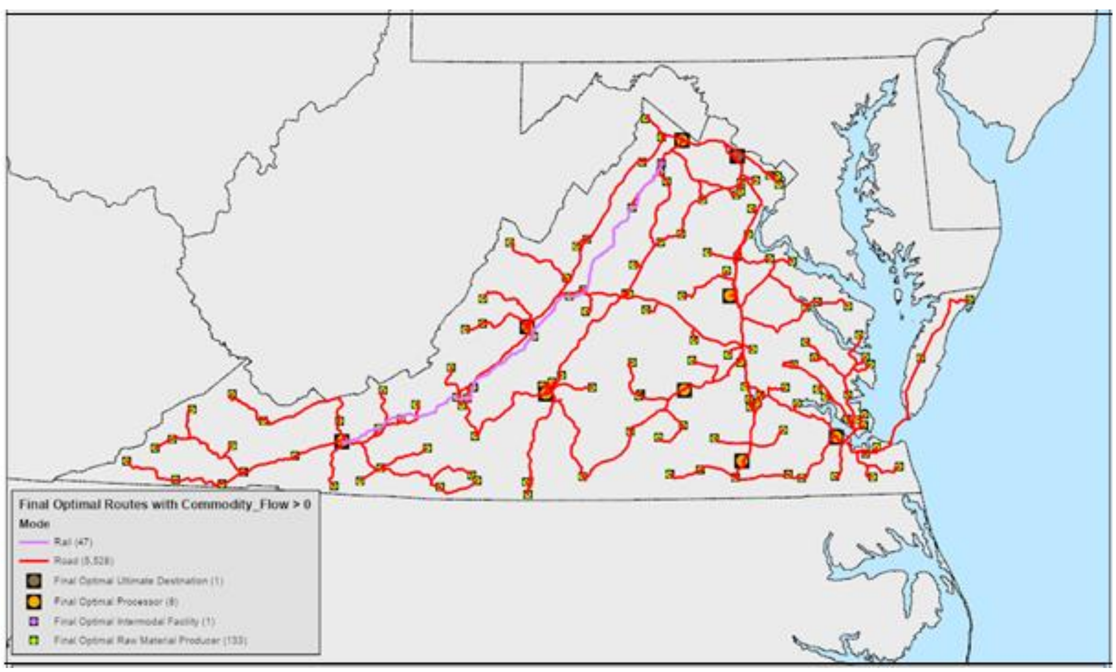

Figure 11. *The proposed network of mature SAF production facilities via GFT conversion of woody waste feedstock at 1.0M tonnes/yr. This network captures all woody waste in Virginia. Selection county locations include Amelia, Campbell, Caroline, Clarke, Greensville, Isle of Wight, Rockbridge, and Wythe Counties. Pink links correspond to railways; red links correspond to roadways (trucking).*

The total amount of SAF that could be produced per year in the proposed eight-facility network would be slightly less than 55% of IAD's recent historical fuel demand. With 50:50 blending, this amount of SAF would be enough to meet IAD's needs. However, it is notable that the creation of this much SAF would consume all available woody waste in Virginia. This is likely unrealistic, given the demand from other industries, and given feedstock prices would likely increase in response to increased demand.

The ASCENT TEAs were also used to assess the cost of SAF production via GFT of MSW feedstock under an assumed technologically "mature" scenario. It was again assumed that SAF production facilities would be co-located at landfills. A list of candidate landfill locations was compiled based on existing landfills with at least 30 years left in their service life (20-year facility lifespan plus a 10-year grace period to start and end construction) that accept at least 100,000 tonnes of MSW per year. Based on these criteria, there are 12 existing Virginia landfills where SAF production facilities could be co-located. These landfills are in Amelia, Brunswick, Charles City, Fairfax, Gloucester, King and Queen, Loudoun, Roanoke, Rockingham, Stafford, and Sussex Counties, along with the City of Hampton (Figure 12). A key assumption about this network is that the local municipalities would approve the construction of a SAF production facility at those sites and that sufficient land would be available at each location. These assumptions would need to be validated in future work.

Figure 12 shows the network of candidate landfills for the co-location of a SAF production facility. The average SAF cost over these 12 facilities was \$3.80/gal. Best- and worst-case estimates were bounded by \$1.58 and \$5.37/gal, respectively. Again, these ranges were useful for illustrating how significant uncertainty and/or variability in MSW feedstock prices contributes to significant uncertainty and/or variability in projected SAF production cost. The expected value of

SAF MPSP for the technologically mature scenario ($3.80/gal) is $2.25-2.54 cheaper than the pilot scenario; however, it is still $1.58/gal more expensive than the average fossil jet fuel price from 2009 to 2018 ($2.22 ± 0.67 /gal).

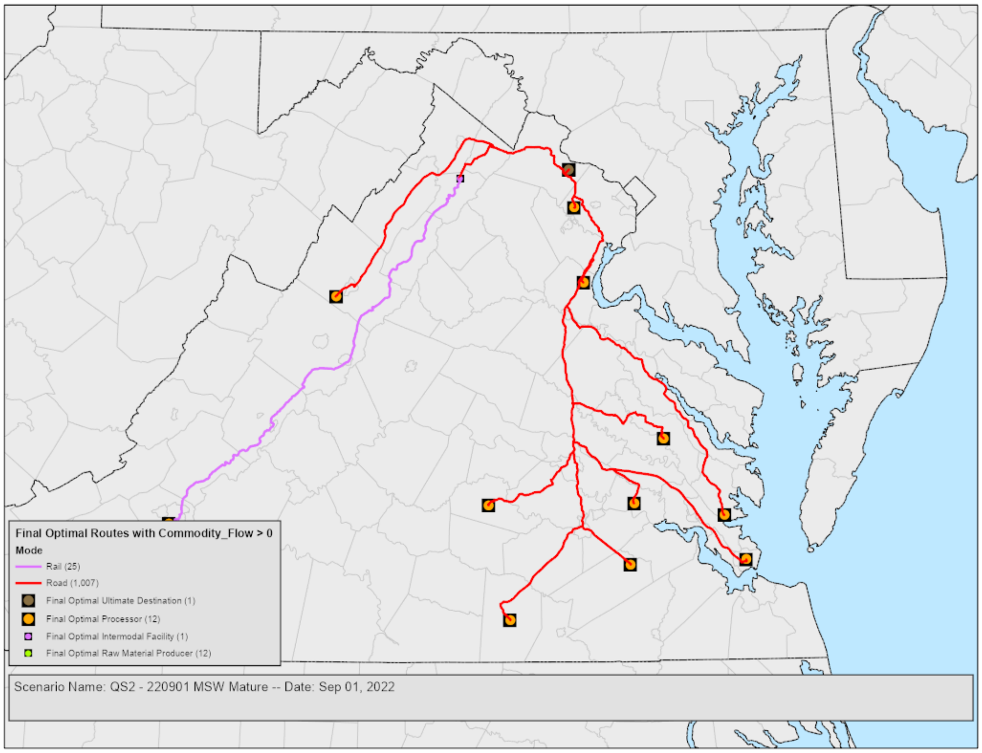

Figure 12. *The proposed network of mature SAF production facilities for GFT conversion of MSW feedstock. This network captures all MSW from twelve county/city landfills: Amelia, Brunswick, Charles City, Fairfax, Gloucester, King and Queen, Loudoun, Roanoke, Rockingham, Stafford, Sussex, and City of Hampton. Pink link corresponds to railways; red links correspond to roadways (trucking).*

The total amount of SAF that could be produced per year in this proposed twelve-facility network would be slightly less than 85% of IAD's recent historical fuel demand. Again, with 50:50 blending, this amount of SAF would be more than adequate to meet IAD's needs. This scenario would consume all of the incoming MSW at these twelve large landfills. It is unknown whether facilities at this size and scale would be realistic because it is a novel technology with few operational examples.

3.3 Pyrolysis

3.3.1 Pilot Woody Waste Facilities

Pyrolysis was also analyzed as an alternative to GFT. As discussed above, pyrolysis is not yet an ASTM-certified or CORSIA-approved pathway for SAF production; however, the ASTM certification process is underway and there are plans for Alder Energy to produce SAF at low cost soon.[44] Given that there are no operational conversion facilities currently using pyrolysis, it was assumed that the first few facilities constructed would comprise "pilot" facilities. Therefore, as with GFT, the first phase of pyrolysis modeling focused on pilot facilities consuming woody waste feedstocks.

Figure 13 shows SAF prices for each of the five hypothetical county locations of interest (Section 3.1.1), as evaluated for three different possible facility sizes and assuming that one location could make use of the existing pipeline for fuel transportation. Table A2 in Appendix A.2 presents the same results in tabular format, alongside estimates of what fraction of Virginia's total woody waste would be consumed and what fraction of total SAF demand at IAD could be met by each individual hypothetical facility. As with GFT, the slight MPSP differences between facility locations are due to the variations in feedstock and fuel transportation. Facility size once again exhibits a much stronger influence on SAF production cost than transportation logistics.

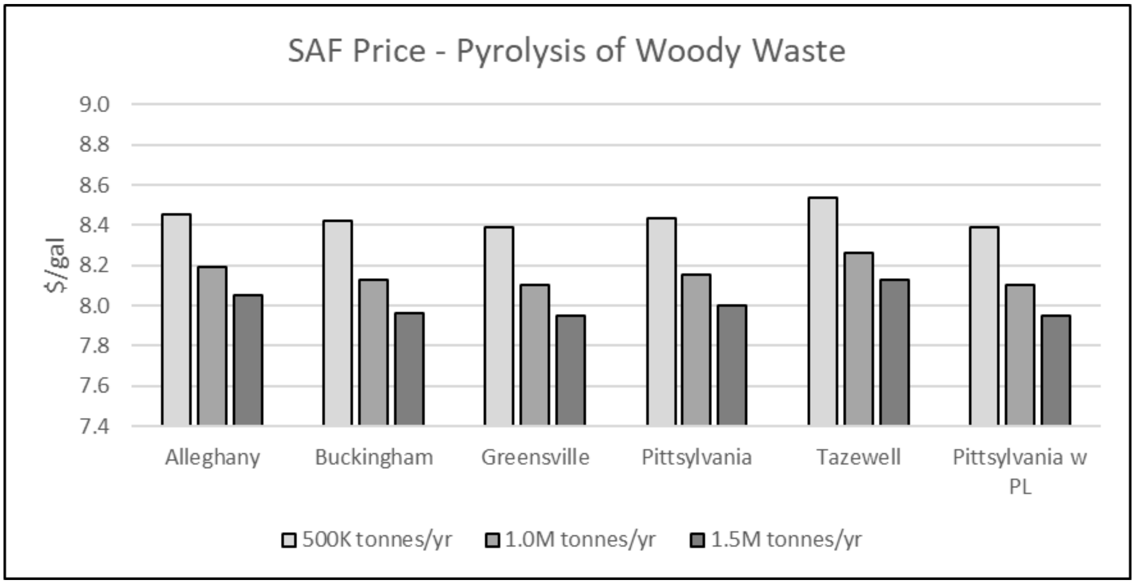

Figure 13. *SAF prices for each hypothetical pilot facility at different scales for the counties of interest, assuming truck and rail transport only. "w PL" refers to potential future pipeline access. No incentives are included in these cost estimates.*

Again, for a deeper analysis of the median case, Pittsylvania County's results were broken down to understand the apportionment of the overall price per gallon among constituent steps of the SAF life cycle (Figure 14). From these results, conversion again accounts for most of the overall cost (72-74%) arising from SAF production via pyrolysis of woody waste feedstocks in pilot facilities. These results show that the MPSP of SAF produced from pyrolysis processing of woody wastes is significantly higher than the historical price of fossil jet fuel ($7.95-8.44/gal vs. $2.22 ± 0.67 /gal).

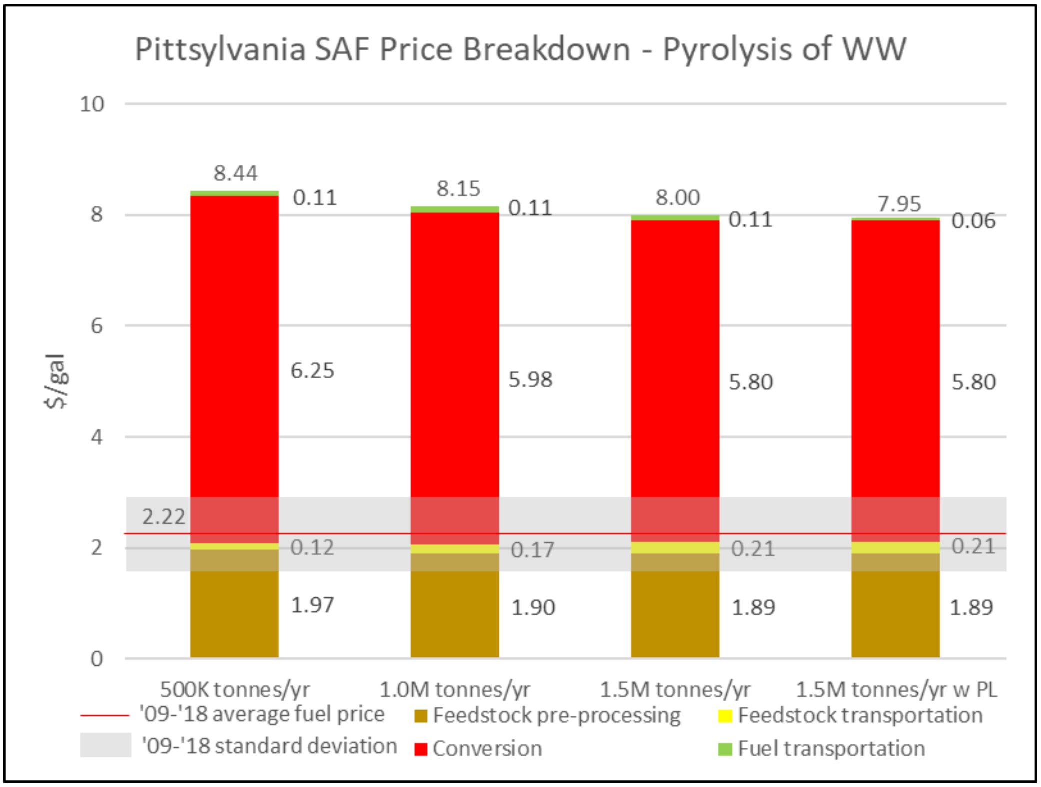

Figure 14. *Price breakdown for different facility size scenarios for pilot plants in Pittsylvania County, assuming truck and rail transport only. "w PL" refers to potential future pipeline access. This is compared to the average fossil jet fuel market price in the decade from 2009 to 2018, marked in red ($2.22 ± 0.67 /gal).*

Apportioned GWP results are summarized in Figure A1 in Appendix A.2. Taken together, the apportionment of production cost and GWP is helpful to understand how the breakdown of cost and GWP vary given differing facility sizes.

3.3.2 Pilot MSW Facilities

Compared to the other process combinations (i.e., GFT of woody waste and MSW, pyrolysis of woody waste), there was relatively little published information regarding pyrolysis of MSW. Therefore, it was first necessary to compile MSW composition information and other relevant technical parameters. The estimated SAF yield ratio was 0.0726 kg SAF per kg MSW (see Appendix, Section A.3). Because this yield is appreciably lower than for pyrolysis of woody waste, the SAF production cost for pyrolysis of MSW is significantly higher, with the middle case value for a pilot facility falling between $11.83 and $12.53/gal SAF. As with GFT of MSW, the wide uncertainty in MSW feedstock cost translates to correspondingly wide uncertainty in SAF production cost for pyrolysis of MSW facilities. Variability in location and size of the co-located landfills further contributes to the wide range of MPSPs for this pathway. The full range of MPSP estimates is as low as $5.49 and as high as $17.01/gal. Further tables and figures can be found in Appendix A.2.

The estimated GWP for a pilot pyrolysis of MSW facility was calculated to be 43.7-44.0 g CO_2e/MJ. This range corresponds to an emissions reduction of approximately 50.7% compared to fossil jet fuel. Based on this range, pyrolysis of MSW easily qualifies as a CORSIA-eligible fuel but does not necessarily qualify as SAF under the recently-passed IRA. This means that a more detailed analysis of life-cycle GWP will need to be conducted before financial incentives made available under the recent legislation could be assured for this pathway. Finally, this study did not include possible GWP offsets associated with the beneficial reuse of biochar that is co-produced with SAF. In other words, systems expansion was not performed to account for the possible GWP reduction benefits associated with the use of biochar as a soil amendment or carbon sequestration material. These adjustments would make the pathway seemingly less carbon-intensive; however, because de Jong et al.[39] did not incorporate negative emissions from char into their analysis, and because a robust market for biochar does not currently exist, these calculations were not pursued for this study. Future analysis of the pyrolysis pathway should revisit these calculations if financial incentives for carbon storage via biochar land amendment become more valuable.

3.3.3 Networks of Mature Pyrolysis Facilities

Similarly to GFT, it was assumed that the maturation of the pyrolysis technology and supply chains throughout the state would lead to lower SAF prices over time. Figure 15 shows a network of eight 1.0 M-tonne/yr SAF production facilities arising from the most relevant FTOT modeling. The selected county locations are as follows: Augusta, Caroline, Charlotte, Culpeper, Franklin, Giles, Greensville, and Prince George. Again, multiple of these eight locations are closely aligned with the five counties selected in the pilot-scale analysis: Augusta is near to both Alleghany and Buckingham; Charlotte is very near to both Buckingham and Pittsylvania; Franklin is adjacent to Pittsylvania; Giles is very near to Tazewell; Greensville was one of the selected counties; Prince George is very near to Greensville. This correspondence, which was also observed for the GFT maturity scenario, confirms that county locations that are appealing in the near term for construction of a pilot facility will still be good choices in the longer-term future as other facilities are added to the network. The average MPSP over these eight facilities was \$5.54 /gal, which is \$2.61 cheaper than what was calculated for the pilot facility in Pittsylvania County; however, this value is still \$3.32 above the average fossil jet fuel market price from 2009 to 2018 (\$2.22 ± 0.67 /gal). Notably, MPSP for pyrolysis of woody waste is expected to be \$1.67 cheaper than GFT for woody waste once both platforms reach technological maturity.

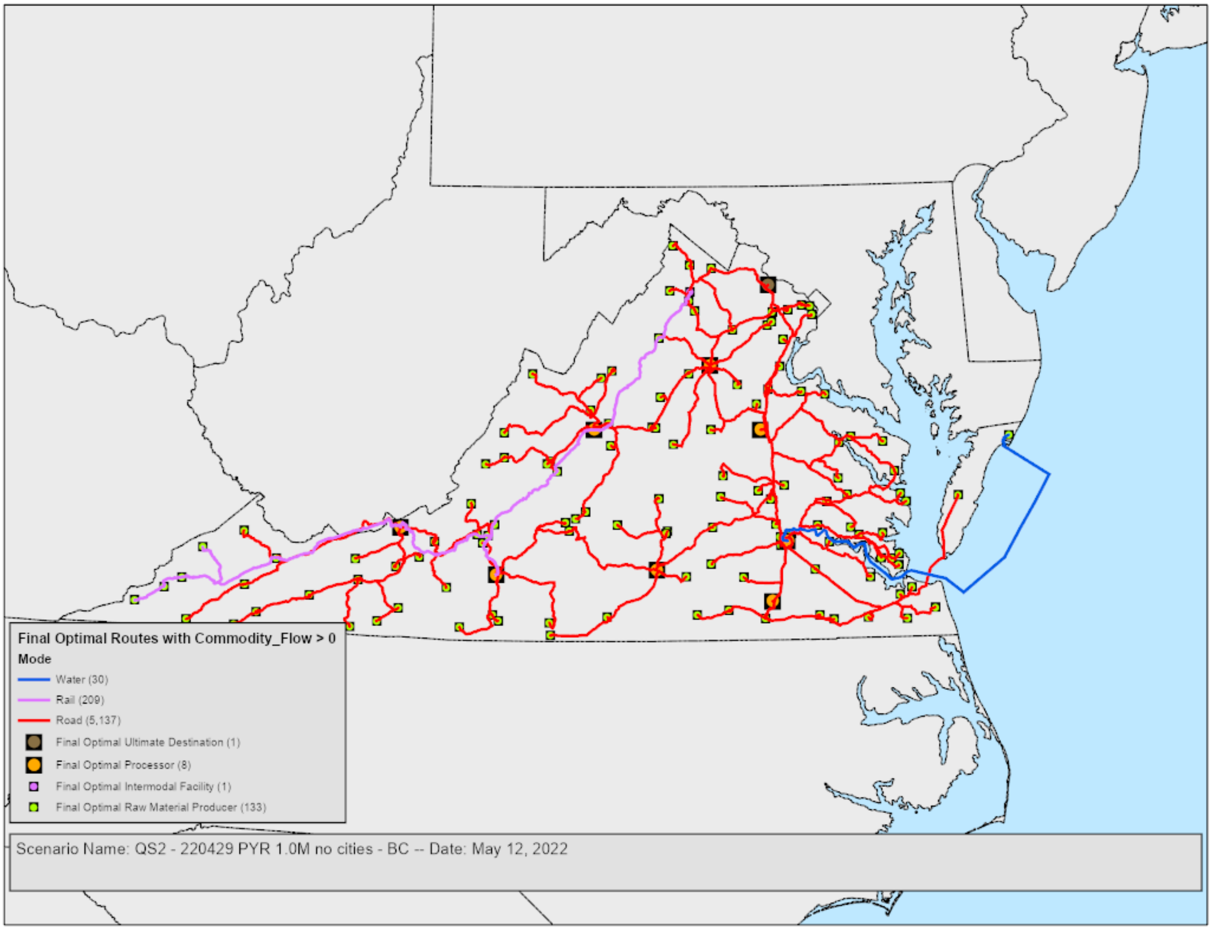

Figure 15. *The proposed network of mature SAF production facilities via pyrolysis conversion of woody waste feedstock at 1.0M tonnes/yr. This network captures all woody waste in Virginia. Selection county locations include Augusta, Caroline, Charlotte, Culpeper, Franklin, Giles, Greensville, and Prince George Counties. Pink links correspond to railways; red links correspond to roadways (trucking). The blue link corresponds to waterways (shipping); this is unique to this scenario because Prince George County was selected, which is accessible via the James River.*

Pyrolysis of MSW has the same landfill location assumptions used for GFT in Section 3.2.3. The proposed network would therefore look identical to Figure 12. The average MPSP over the twelve facilities is $7.48/gal of SAF, with possible best- and worst-case scenarios of $1.44 and $11.72/gal. This range still comes from the vast variability and uncertainty in MSW makeup and cost. The middle case of $7.48 is $4.40-5.05 cheaper per gallon than the three pilot facilities considered, but it is still $5.26 more expensive per gallon than the average fossil jet fuel market price from 2009 to 2018. Pyrolysis of MSW is significantly more cost-intensive than GFT per gallon of SAF primarily because of the lower yield rate. MSW is a messy feedstock, and pyrolysis is not the most efficient method of conversion to bio-oil due to feedstock impurities and lower quantities of cellulose and lignin.

3.4 Evaluating Existing Federal and Potential State Incentives

The results in previous sections show that neither of the analyzed pathways will be cost-competitive with fossil jet fuel in Virginia without financial incentives. It is therefore of interest to assess to what extent state incentives may be necessary beyond currently existing federal incentives. To understand how incentives from the state could affect the cost comparison between SAF and other benchmarks, different types and levels of investment were analyzed for GFT and pyrolysis of woody waste feedstock. In contrast, financial incentives were not analyzed for conversion of the MSW feedstock via either conversion platform, because the wide variability in feedstock cost gave rise to such a wide range of estimated MPSP that it was not worthwhile to analyze what amount of financial incentive would be needed to make SAF from MSW cost-competitive with other alternative platforms.

3.4.1 Financial Incentives for SAF from GFT of Woody Waste

The example 1.0 M-tonne pilot facility in Pittsylvania County was again analyzed to determine how different types of incentives would affect the MPSP of SAF. Figure 16 shows the range of MPSPs computed without financial incentives and with accumulating existing federal incentives, new federal incentives, and possible state incentives. MPSPs following state incentives range from $5.21-6.09/gal. State incentives were set to $350 million as structured in several possible ways: feedstock subsidy, interest rate reduction, or capital grant, or a Low Carbon Fuel Standard (LCFS)-style strategy. For this study, the magnitude of the hypothetical state incentive was considered less important than the difference between the SAF prices resulting from equal investments of different kinds, because the goal of this analysis was to examine whether different kinds of incentives were differently efficient in reducing MPSP even when total state investment was held constant. Finally, the LCFS-style incentive is distinct from the other proposed incentives shown on the right side of the yellow line in Figure 16, insofar as the Commonwealth would not need to put up the funds directly, but they would need to set up the necessary policy or regulatory framework.

To ensure that the selected magnitude of the hypothetical state incentive did not unduly affect the comparison between different conversion platforms and/or among different incentive structures, the analysis was repeated at two additional investment magnitudes: \$70 million and \$585 million (Figure 17). It was observed that the magnitude of the hypothetical investment did not affect the rank order of the four possible incentive structures. At all tested investment levels, the magnitude of cost reduction achieved was ranked the same as shown in Figure 16; i.e., <u>cost reduction</u> for feedstock subsidy $\lesseqqgtr$ risk reduction $\lesseqqgtr$ state capital grant. At a hypothetical state investment of \$70 million, MPSP ranged from \$5.21 - \$6.42/gal. At \$585 million, MPSP was reduced to \$5.08 - \$5.81/gal. The carbon reduction of \$150/tonne CO_2e for LCFS did not change with different assumed investment sizes because it is dependent on the market, not state investment levels. Therefore, the MPSP for this assumed incentive structure stayed constant at \$5.21.

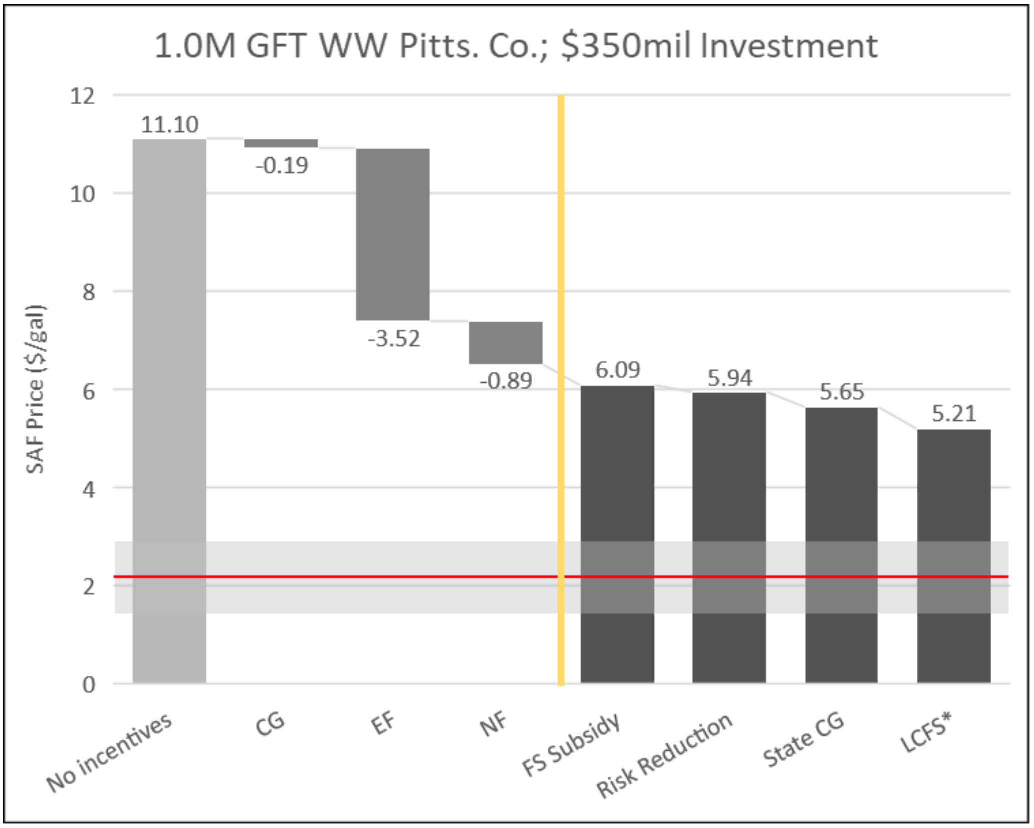

Figure 16. *Waterfall graph showing baseline ("no incentives") cost per gallon plus accumulating price reductions corresponding to three incentives: CG = assumed federal capital grant ($75M); EF = existing federal RINs at $3.21/gal for all output blends, plus blender's tax credit (BTC) at $1.00/gal diesel and $0.50/gal gasoline and naphtha (Jet B) [assumes 20-year facility service life]; NF = new federal incentives corresponding to an enhanced BTC under the IRA, at $1.70/gal SAF for GFT of woody wastes, specifically. Values on the right side of the vertical yellow line show how individual proposed incentives could further reduce the price per gallon relative to the NF bar on the left side of the yellow line. FS subsidy = feedstock subsidy ($22.75/tonne) [assumes 23 years]; risk reduction = 4.49% rate reduction [assumes 23 years]; state CG = state capital grant of $350M per facility; LCFS = market value for CO_2e reductions relative to baseline fuel ($150/tonne CO_2e), similar to California's existing Low Carbon Fuel Standard. Bars to the right of the yellow line are independent of one another, whereby each shows what price reduction would accrue from the implementation of a single, new incentive. The horizontal red line denotes the average historical price per gallon for fossil jet fuel from 2009-2018 ($2.22 ± 0.67 /gal).*

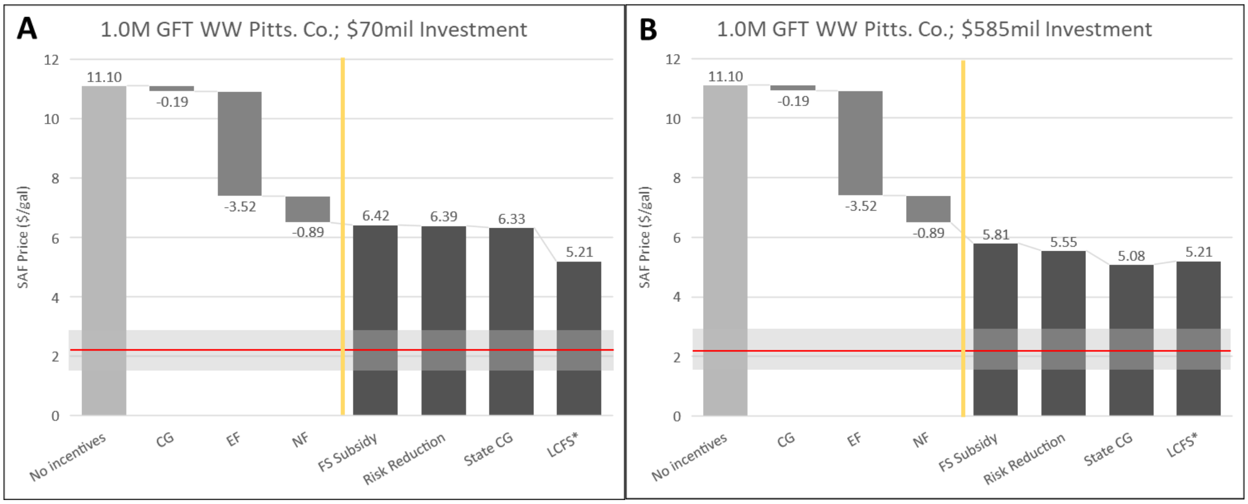

Figure 17. *Waterfall graphs showing baseline ("no incentives") cost per gallon plus accumulating price reductions corresponding to three incentives: CG = assumed federal capital grant ($75M); EF = existing federal RINs at $3.21/gal for all output blends, plus blender's tax credit (BTC) at $1.00/gal diesel and $0.50/gal gasoline and naphtha (Jet B) [assumes 20-year facility service life]; NF = new federal incentives corresponding to an enhanced BTC under the IRA, at $1.70/gal SAF for GFT of woody wastes, specifically. For each panel, values on the right side of the vertical yellow lines show how individual proposed incentives could further reduce the price per gallon relative to the NF bars on the left sides of the yellow lines. Panel A: FS subsidy = feedstock subsidy ($4.55/tonne) [assumes 23 years]; risk reduction = 0.85% rate reduction [assumes 23 years]; state CG = state capital grant of $70M per facility. Panel B: FS subsidy = feedstock subsidy ($38/tonne) [assumes 23 years]; risk reduction = 8% rate reduction [assumes 23 years]; state CG = state capital grant of $585M per facility. For each panel, LCFS = market value for CO_2e reductions relative to baseline fuel ($150/tonne CO_2e), similar to California's existing Low Carbon Fuel Standard. Bars to the right of the yellow lines are independent of one another, whereby each shows what price reduction would accrue from the implementation of a single, new incentive. The horizontal red lines denote the average historical price per gallon for fossil jet fuel from 2009-2018 ($2.22 ± 0.67 /gal).*

The state-wide maturity scenario was also analyzed to see how impactful different incentives would be. As with the pilot analysis, a uniform hypothetical investment of $350 million, as structured into four different formats, was assumed. However, it was assumed that this investment would be apportioned across the entire network of facilities; i.e., when eight facilities are constructed, each receives 1/8 of the total investment. Figure 18 summarizes the results of this analysis for a representative county. As mentioned above, transportation accounts for a relatively small fraction of the overall SAF production cost, which means that conversion cost dominates overall SAF production cost, and there is no significant variability in MPSP by county. The assumed facility size is the same (1.0 M-tonnes/yr) such that pilot and mature scale results are directly comparable to each other. Results from this analysis reveal that though SAF will not be cost-competitive with fossil jet fuel in the absence of financial incentives, the price of SAF from mature facilities can be brought within the desired price range via the implementation of the proposed incentives. MPSPs range from $1.32 - $2.62/gal. Even without state-level investments, relying only on existing federal incentives, the MPSP is in the range of fossil jet fuel at $2.67/gal.

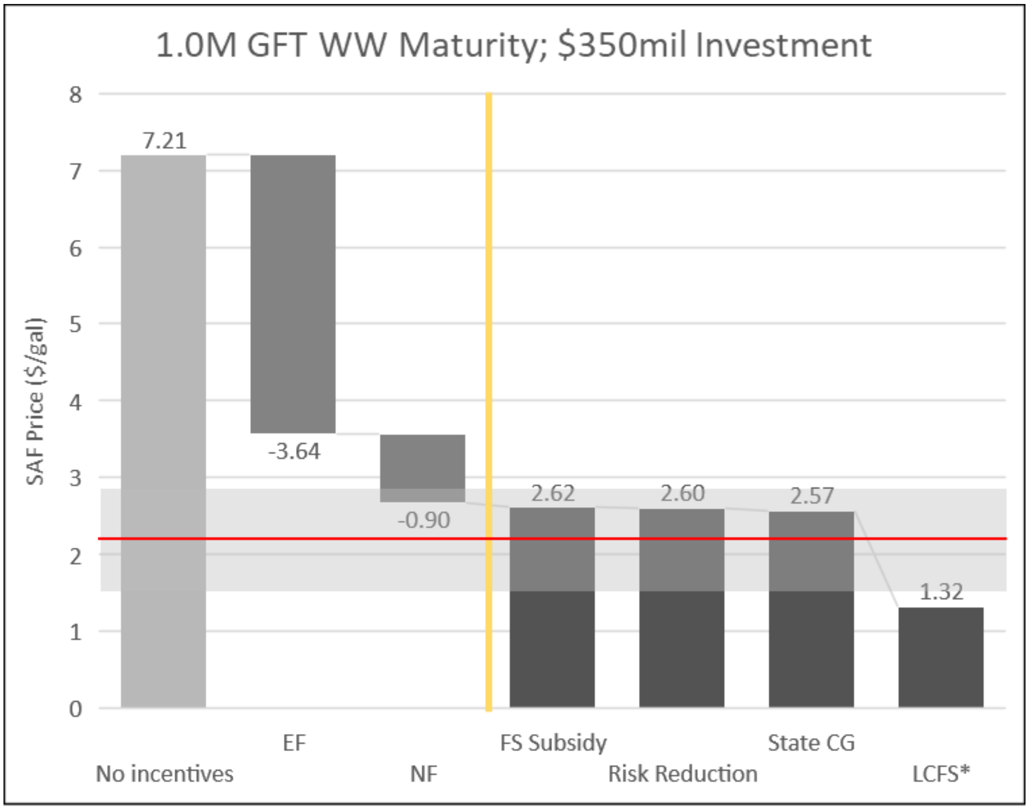

Figure 18. *Waterfall graph showing baseline ("no incentives") cost per gallon from a mature SAF production facility via GFT conversion of woody waste feedstocks; plus accumulating price reductions corresponding to existing and hypothetical incentives. Existing federal (EF) incentives comprise RINs at \$3.21/gal for all output blends and the current blender's tax credit (BTC) at \$1.00/gal diesel and \$0.50/gal gasoline and naphtha (Jet B). New federal (NF) incentives correspond to an enhanced BTC under the IRA, at \$1.70/gal SAF. Values on the right side of the vertical yellow line show how individual proposed incentives could further reduce the price per gallon relative to the NF bar on the left side of the yellow line. FS subsidy = feedstock subsidy; risk reduction = 1.06% rate reduction; state CG = state capital grant of \$43.75 per facility; LCFS = market value for CO_2e reductions relative to baseline fuel (\$150/tonne CO_2e), similar to California's existing Low Carbon Fuel Standard. Bars to the right of the yellow line are independent of one another, whereby each shows what price reduction would accrue from the implementation of a single new incentive. The horizontal red line denotes the average historical price per gallon for fossil jet fuel from 2009-2018 (\$2.22 ± 0.67 /gal).*

3.4.2 Financial Incentives for SAF from Pyrolysis of Woody Waste

The hypothetical investment analysis was similarly applied to the pyrolysis of woody waste pathway, again using a 1.0 M-tonne hypothetical pilot facility in Pittsylvania County as a case study. Figure 19 shows example MPSPs ranging from \$2.83 - \$3.29/gal after a federal capital grant, previously existing federal incentives, and new federal incentives, plus a \$350 million investment from the state in the form of either a feedstock subsidy, interest rate reduction, or capital grant, or a Low Carbon Fuel Standard (LCFS)-style strategy. The new federal incentive takes the form of a blender's tax credit (BTC), whereby the magnitude of the credit is proportional to the difference in GWP relative to a fixed baseline. The value of the new federal incentive (from the IRA) credit for pyrolysis was \$1.34/gal, which is slightly lower than the value computed for the GFT pathway (\$1.70/gal) because the GFT pathway achieves greater GWP reduction than the pyrolysis pathway. The LCFS incentive is similarly tied to extent of GWP reduction, such that the LCSF-style incentive for pyrolysis was also smaller than for GFT.

For a hypothetical state investment of \$70 million, MPSPs ranged from \$2.83 - \$3.57/gal. When this amount was increased to a higher level of \$423 million, MPSPs ranged from \$2.77 - \$3.22/gal, while the rank order of investment structures remained the same. These trends are the same as those from when incentives for GFT of woody waste were calculated.

The mature pyrolysis of woody waste platform was also analyzed to evaluate the impacts of different economic incentives. Figure 20 shows that MPSP reaches \$1.24/gal once all existing federal incentives are applied. Given these very low values, there was no analysis completed on the effects of state-level incentives.

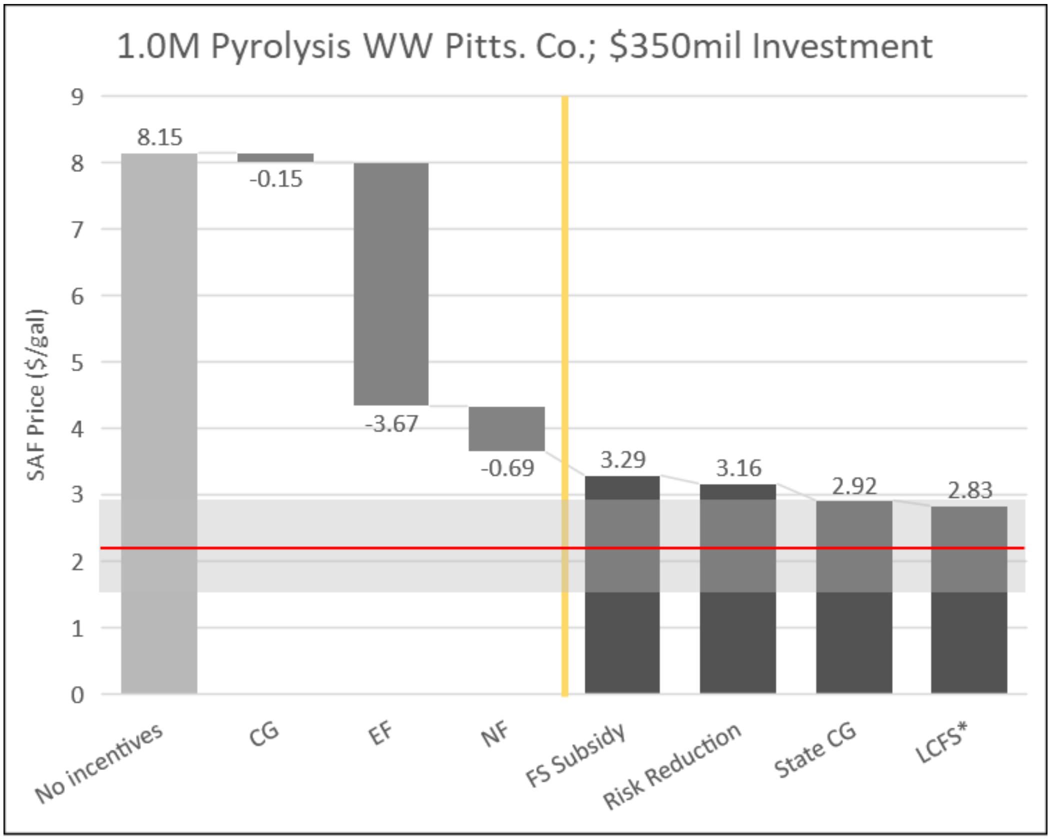

Figure 19. *Waterfall graph showing baseline ("no incentives") cost per gallon plus accumulating price reductions corresponding to three incentives: CG = assumed federal capital grant ($75M); EF = existing federal RINs at $3.21/gal for all output blends, plus blender's tax credit (BTC) at $1.00/gal diesel and $0.50/gal gasoline and naphtha (Jet B) [assumes 20-year facility service life]; NF = new federal incentives corresponding to an enhanced BTC under the IRA, at $1.34/gal SAF for pyrolysis of woody wastes, specifically. Values on the right side of the vertical yellow line show how individual proposed incentives could further reduce the price per gallon relative to the NF bar on the left side of the yellow line. FS subsidy = feedstock subsidy ($22.75/tonne) [assumes 23 years]; risk reduction = 6.46% rate reduction [assumes 23 years]; state CG = state capital grant of $350M per facility; LCFS = market value for CO_2e reductions relative to baseline fuel ($150/tonne CO_2e), similar to California's existing Low Carbon Fuel Standard. Bars to the right of the yellow line are independent of one another, whereby each shows what price reduction would accrue from the implementation of a single, new incentive. The horizontal red line denotes the average historical price per gallon for fossil jet fuel from 2009-2018 ($2.22 ± 0.67 /gal).*

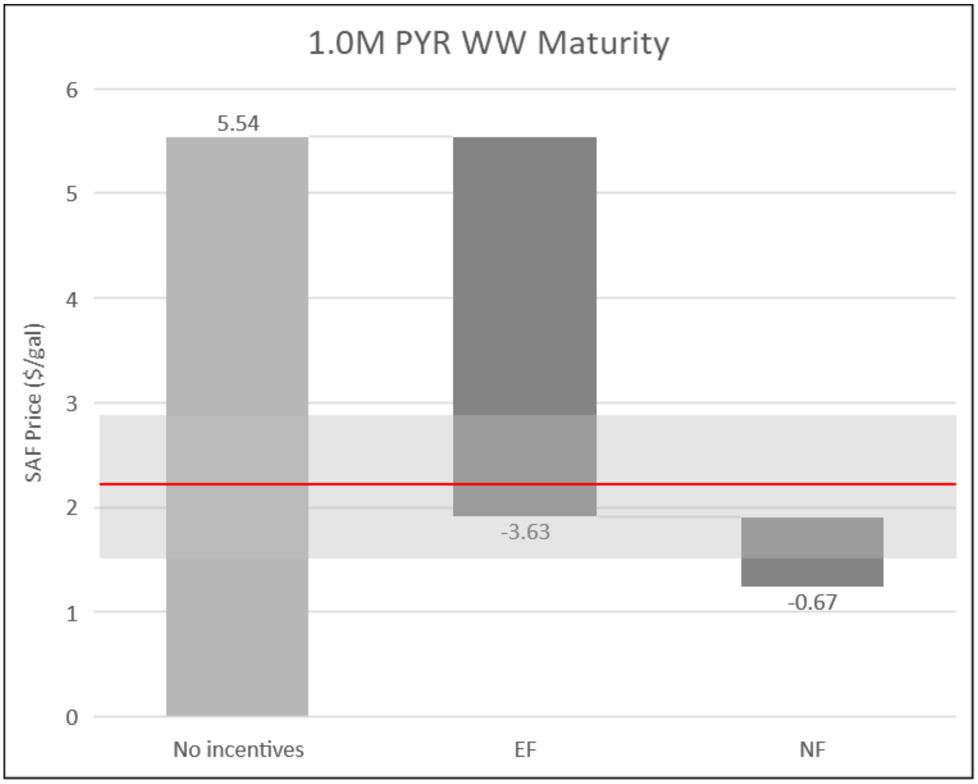

Figure 20. *Waterfall graph showing baseline ("no incentives") cost per gallon from a mature SAF production facility via pyrolysis conversion of woody waste feedstocks; plus accumulating price reductions corresponding to previously existing and new incentives. Existing federal (EF) incentives comprise RINs at $3.21/gal for all output blends and the current blender's tax credit (BTC) at $1.00/gal diesel and $0.50/gal gasoline and naphtha (Jet B). New federal (NF) incentives correspond to an enhanced BTC under the IRA, at $1.34/gal SAF. The horizontal red line denotes the average historical price per gallon for fossil jet fuel from 2009-2018 ($2.22 ± 0.67 /gal).*

3.4.3 Insights from Comparisons

Given all of these results, context must be provided to understand favorability among the different pathways. For easy comparison, Figure 21 shows the MPSP differences between GFT and pyrolysis of woody waste, including pilot vs. mature facilities and with vs. without federal incentives. This figure clearly shows that pilot facilities need additional incentives, while mature facilities do not. The difference in price between GFT and pyrolysis stems from several factors.

First, GFT has a higher total capital investment than a pyrolysis facility ($1.72 billion vs. $1.26 billion for a 1.0 M-tonne facility).[24,25] Second, GFT has higher operating costs than pyrolysis ($288.5 million vs. $278.1 million for a 1.0 M-tonne facility).[24,25] Finally, pyrolysis has higher assumed yields than GFT, leading to more SAF being produced per tonne of equal feedstock. More information and reasoning for the difference in capital investment, operating costs, and yields can be found in Section 1.0.

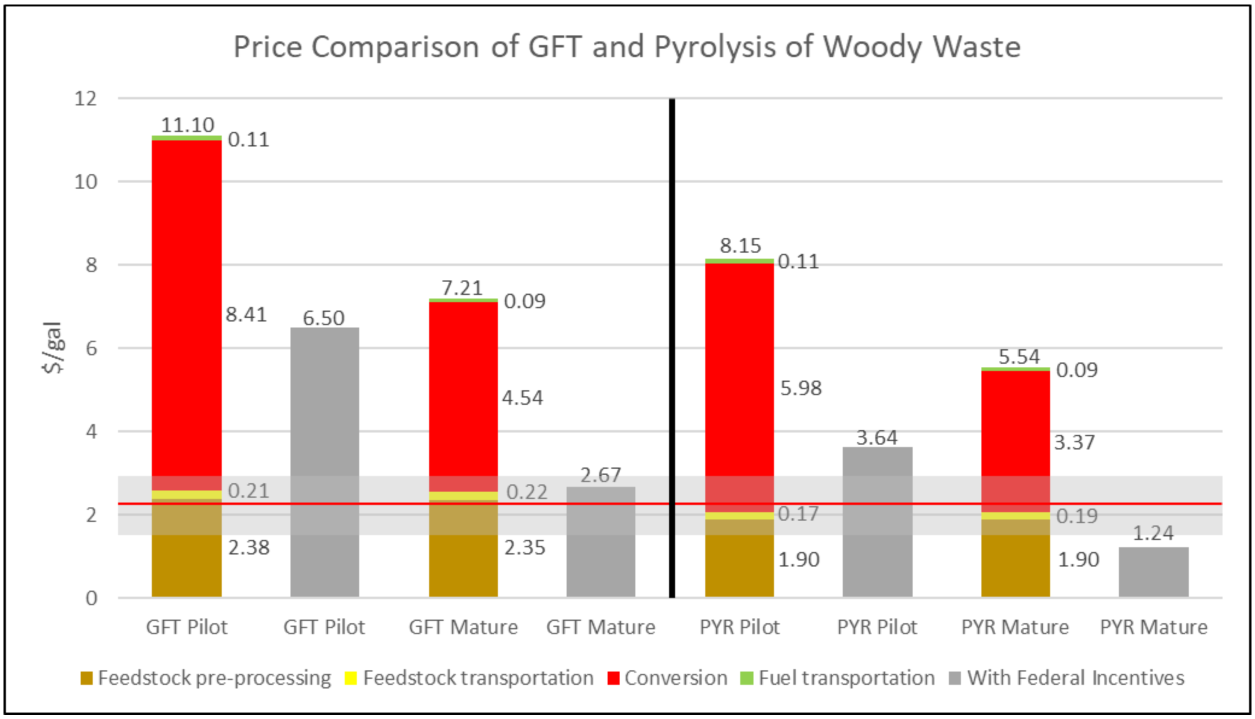

Figure 21. *Comparison between GFT and pyrolysis of woody waste. Pilot refers to a 1.0M tonne/yr scenario in Pittsylvania County, while mature refers to a 1.0M tonne/yr scenario in Virginia (average price across eight hypothetical facilities). Shown with and without federal incentives. The horizontal red line denotes the average historical price per gallon for fossil jet fuel from 2009-2018 ($2.22 ± 0.67 /gal).*

Because pyrolysis is lower in cost in this analysis, it would seem to be the obvious choice once the pathway is ASTM-certified and CORSIA-approved; however, the GWPs of the two pathways are far from equal. Comparing only woody waste, the GWP of GFT is 4.59 g CO_2e/MJ while pyrolysis is 36.47 g CO_2e/MJ (a breakdown of this can be found in Figure A4 in Appendix A.2). The existing federal incentive structure was largely set up to decrease the price per gallon alone. This included RINs and basic blender tax credits (BTCs). The recently passed IRA, however, includes a BTC based on GWP, attempting to motivate environmentally responsible investments; however, it does not lead to significant differences in incentives, even among these two pathways where the GWP varies significantly. Currently, the IRA only applies to SAF that achieves at least a 50% reduction of lifecycle emissions, starting at a base credit of $1.25/gal. There is then a supplementary amount of $0.01 for every percentage point above 50% emissions reduction, leading to a maximum of $1.75/gal for a fuel that is free of emissions.[41] This does give an advantage to pathways like GFT over pathways like pyrolysis, but the advantage is not nearly enough to close the price gap. The passage of the IRA was a very important step in SAF production, offering the first really purposeful incentive structure for SAF specifically. This was greatly needed for SAF industries and stakeholders.[45] But as discussed above, a more aggressive alignment of environmental and economic priorities and impact is needed.

If the Commonwealth (or the federal government) is serious about promoting pathways with lower GWP, a stronger system to differentiate the two should be in place, such as California's LCFS. At a minimum, the IRA should have a larger supplementary amount, or new federal or state legislation should enact higher supplementary amounts (currently only $0.01 for every percentage point above 50% emissions reduction). Using the ASCENT TEAs from many different conversion processes and feedstock combinations, it appears that there is no significant trendline between price and GWP reduction, but if only GFT and pyrolysis are considered, a supplementary amount would need to be $0.18 for every percentage point above 50% emissions reduction for GFT to match the lower price of pyrolysis. This is significantly more than the existing $0.01

supplementary amount, and it would lead to a BTC of $8.70/gal for GFT and $3.12/gal for pyrolysis (hypothetical, median case pilot woody waste facility). This would be enough to close the price gap between the two pathways, but it is clearly too high for governments to invest. This dilemma of investing enough to make GFT preferable for businesses for both environmental and economic reasons but not over-investing as a government entity will be difficult to parse out once pyrolysis is certified. Under current economic conditions, pyrolysis would be more desirable to invest in from a business perspective; from an environmental perspective, however, pyrolysis leaves much to be desired when comparing the emissions reductions.

4.0 Conclusions

The results from this study are not meant to be prognoses but are instead scenarios that can help Virginia and other states envision potential outcomes. Ultimately, pyrolysis of MSW was the most expensive pathway, with pilot facilities having MPSPs of $11.88-12.53/gal SAF, while mature facilities would lead to about $7.48/gal SAF. GFT of woody waste was the next most expensive, with pilot MPSPs of about $11.10/gal SAF, while mature MPSPs are estimated to be about $7.21/gal SAF. Next, pyrolysis of woody waste pilot facilities would lead to $8.15/gal SAF, with mature facilities producing SAF at $5.54/gal. Finally, the least expensive pathway was found to be GFT of MSW at $6.05-6.34/gal SAF for pilot facilities, and about $3.80/gal SAF for mature facilities. With those laid out, a single pilot facility could produce between 4-16% of IAD's current fuel demand, depending on the pathway; a network of mature facilities for a single pathway, however, could produce between 53-85%. Also, it is important to note that the pathway with the highest reduction of GWP is GFT of woody waste, followed by GFT of MSW, pyrolysis of woody waste, and pyrolysis of MSW. Therefore, according to this analysis, if the lowest price or GWP is sought, GFT of woody waste or MSW will be superior to the pyrolysis pathways. If the highest quantity of SAF is sought, GFT of MSW has the most potential. At the time of this study, GFT is still an emerging technology but could be a go-to choice for the SAF industry in the future. Another important result from this study is that transportation costs are relatively low compared to conversion costs, emphasizing the importance of building fewer, larger facilities. Finally, after comparing incentives for the two platforms, this study illustrates a misalignment of environmental and economic impacts under current federal incentives. To better align the two, federal and/or state governments will have to consider stronger incentives that more heavily target GWP reductions. Of the state-level investment options that were analyzed, one-time capital grants are the best route to incentivize pilot facilities. Pilot facilities will especially need incentives to get off the ground and start producing fuel at reasonable prices.

The aviation industry significantly contributes to global CO_2 emissions, which is why the U.S. government has issued a national roadmap to 100% SAF by 2050.[4] National support is critical to the successful implementation of this goal; ultimately, individual regions need to determine their own paths to success. Certain states will find more success using conversion processes and feedstocks that would not work for others. In this report, Virginia was analyzed as a case study because of the support from stakeholders across the state along with an invested Department of Transportation (DOT). VDOT is considered one of the most forward-looking DOTs in the country because of its research arm; national leaders on the issue, like the Commercial Aviation Alternative Fuels Initiative, consider Virginia a hotbed for support and interest on the issue of SAF, rivaling any other state in the country.[46] These reasons make Virginia a good example to study and try to emulate moving forward.

Future research should incorporate a deeper dive into feedstock availability and pricing. More detailed spatial analysis (U.S. Forest Service Timber Product Output datasets) could be used to get a more accurate distribution of woody biomass in Virginia. A similar approach to Martinkus et al. and Latta et al. could be taken, whereby future feedstock supply was calculated using empirical and economic optimization models.[47,48] In addition, further analysis into the current and future uses of biomass around the state could be undertaken. Better data on MSW composition is needed to understand the potential for recoverability of recyclables; having a better understanding of the characteristics of this feedstock would greatly narrow the variability in input costs. Future research should include adjusting the ASCENT TEAs to be better equipped as a financial model rather than an economic model. Finally, carbon emissions could be analyzed in more detail as well: less reliance on CORSIA could lead to more granular GWP results.

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Appendix

A.1 FTOT Inputs

Inputs for a generic FTOT run include a personalized scenario.xml file and four CSV files (one for the commodity types allowed on each transportation network (commodity_modes.csv); one for the destination (dest.csv); one for the processing facility candidates (proc.csv); one for the raw material producers (rmp.csv)).

For the commodity_mode.csv, all networks were specified as usable except the crude pipelines and the product pipelines for feedstock. For the dest.csv, Dulles International Airport was specified as the only destination and the demand value was set to meet the total amount supplied to avoid any unmet demand penalties. For the proc.csv, in the case of a single pilot facility, one county was provided. In the case of the state-wide maturity scenario, every county in Virginia was provided as a candidate with the same maximum processor input (500,000, 1 million, or 1.5 million). In both cases, the conversion ratio in kgal SAF per 100 tonnes is used (this is calculated using the bio-oil and SAF yields referenced in Section 2.3) and the total amount of SAF from a single, hypothetical facility was calculated. In the maturity scenario, a build cost was calculated by adding the facility capital investment (from the ASCENT TEAs) to the total land value. The build cost helps to optimize the number, size, and location of facilities to both the cost to build and the cost to transport feedstock and fuel. For the rmp.csv, every county and city was provided along with the quantity of woody waste.

For the scenario.xml file, the proper file structure and input files are called out appropriately. Edits made to the default scenario.xml file include updating the intermodal network file to include pipeline access (when applicable), changing all modes to be permitted, turning NDR on, and raising the unmet demand penalty to make sure that scenarios run properly. Other minor changes were made to python files for troubleshooting as suggested by Volpe staff. Volpe staff were very responsive to questions regarding FTOT and even incorporated suggestions into new releases.

A.2 Additional Tables and Figures

Table A1. *Variables within MSW price that cause uncertainty, with best case extremes, worst case extremes, and most likely cases. Virginia does not have information on the quantity of steel, aluminum, and glass recovery in its MSW; additionally, the cost of the raw material varies significantly. There is also the possibility that these recovered recyclables would not be marketable. Includes MSW price after pre-processing. MPSP values for GFT of MSW are highlighted and correspond to Table 4.*

Variable	Best case extreme	Most likely case	Worst case extreme
MSW Price ($/tonne)	$ (53.48)	$ -	$ 26.74
Recovered Steel Price ($/tonne)	$ 650.00	$ 342.00	$ -
Recovered Aluminum Price ($/tonne)	$ 3,500.00	$ 1,858.00	$ -
Recovered Glass Price ($/tonne)	$ 72.00	$ 22.00	$ -
Steel Recovery (% of total MSW)	6.50%	5.91%	5.32%
Aluminum Recovery (% of total MSW)	1.80%	1.64%	1.47%
Glass Recovery (% of total MSW)	5.12%	4.65%	4.19%
MSW Price ($/tonne) after pre-processing	**Best case**	**Middle case**	**Worst case**
Amelia County MSW price ($/tonne)	$ (195.00)	$ 19.52	$ 170.05
Charles City County MSW price ($/tonne)	$ (194.37)	$ 20.15	$ 170.69
Sussex County MSW price ($/tonne)	$ (196.66)	$ 17.86	$ 168.39
Final MPSP	**Best case**	**Middle case**	**Worst case**
Amelia County SAF final price ($/gal)	$ 3.88	$ 6.12	$ 7.71
Charles City County SAF final price ($/gal)	$ 4.07	$ 6.34	$ 7.93
Sussex County SAF final price ($/gal)	$ 3.81	$ 6.05	$ 7.64

Table A2. *Results for single, hypothetical pilot facilities for pyrolysis of woody waste. Demand at Dulles International Airport is based on correspondence with the airport. Virginia 2019 consumption is from EIA.*

	County	Pioneer plant ($/gal)	Area of feedstock range (sqmi)	Exclusively VA feedstock?	Adjacency to pipeline?	% of Dulles Demand	% of VA 2019 Consumption	Average cost ($/gal)
500K tonnes/yr	Alleghany	8.45	3149.05	N	N	4.06%	1.78%	8.44
	Buckingham	8.42	2592.31	Y	Y			
	Greensville	8.39	1442.3	N	N			
	Pittsylvania	8.44	2651	N	Y			
	Pittsylvania w PL	8.39	2651	N	Y			
	Tazewell	8.54	5179.6	N	N			
1.0M tonnes/yr	Alleghany	8.19	6833.71	N	N	8.13%	3.57%	8.16
	Buckingham	8.13	3949.69	Y	Y			
	Greensville	8.10	3741.64	N	N			
	Pittsylvania	8.15	4800.53	N	Y			
	Pittsylvania w PL	8.10	4800.53	N	Y			
	Tazewell	8.26	10304.94	N	N			
1.5M tonnes/yr	Alleghany	8.05	9340.67	N	N	12.19%	5.35%	8.01
	Buckingham	7.96	6514.89	Y	Y			
	Greensville	7.95	5913.54	N	N			
	Pittsylvania	8.00	6364.46	N	Y			
	Pittsylvania w PL	7.95	6364.46	N	Y			
	Tazewell	8.12	13849.75	N	N			

Table A3. *Results for single, hypothetical pilot facilities for pyrolysis of MSW. Best case refers to lower feedstock cost and higher recoverability; worst case refers to higher feedstock cost and lower recoverability (see Table A4). Demand at Dulles International Airport is based on correspondence with the airport. Virginia 2019 consumption is from EIA.*

County	Size (tonnes/yr	Pilot plant ($/gal)			Adjacency to	Middle case with pipeline	% of Dulles Demand	% of VA 2019 Consumption
		Best case	Middle case	Worst case				
Amelia	960K	5.49	11.88	16.35	Y	11.83	6.13%	2.69%
Charles City	650K	6.15	12.53	17.01	N	-	4.15%	1.82%
Sussex	1.19M	5.51	11.89	16.37	N	-	7.58%	3.33%

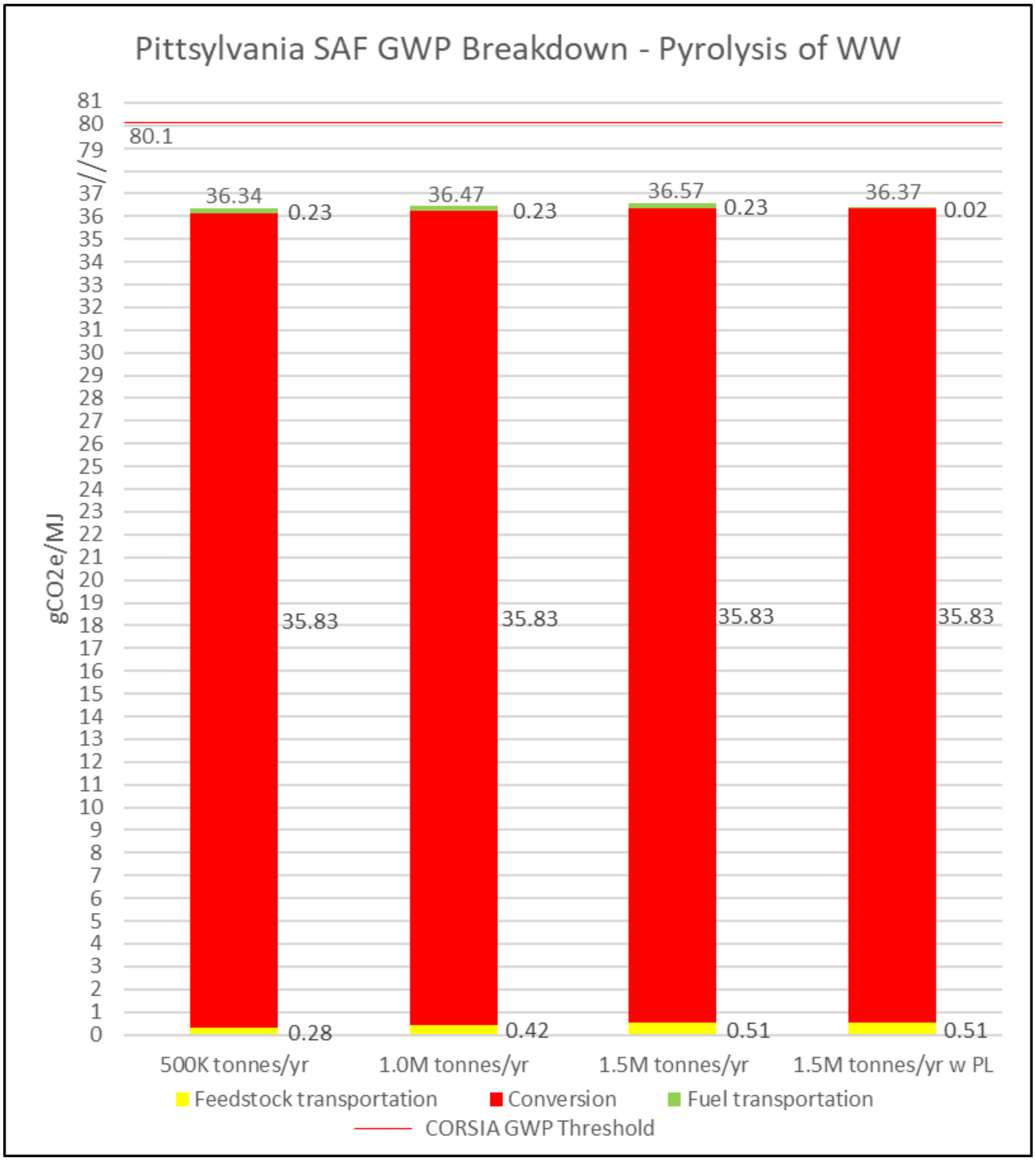

Figure A1. *GWP breakdown for different facility size scenarios for pilot plants in Pittsylvania County, assuming truck and rail transport only. "w PL" refers to potential future pipeline access. This is compared to CORSIA's fossil jet fuel baseline marked in red (80.1 gCO_2e/MJ).*

Table A4. *Variables within MSW price that cause uncertainty, with best case extremes, worst case extremes, and most likely cases. Virginia does not have information on the quantity of steel, aluminum, and glass recovery in its MSW; additionally, the cost of the raw material varies significantly. There is also the possibility that these recovered recyclables would not be marketable. Includes MSW price after pre-processing. MPSP values for pyrolysis of MSW are highlighted and correspond to Table A3.*

Variable	Best case extreme	Most likely case	Worst case extreme
MSW Price ($/tonne)	$ (53.48)	$ -	$ 26.74
Recovered Steel Price ($/tonne)	$ 650.00	$ 342.00	$ -
Recovered Aluminum Price ($/tonne)	$3,500.00	$ 1,858.00	$ -
Recovered Glass Price ($/tonne)	$ 72.00	$ 22.00	$ -
Steel Recovery (% of total MSW)	6.50%	5.91%	5.32%
Aluminum Recovery (% of total MSW)	1.80%	1.64%	1.47%
Glass Recovery (% of total MSW)	5.12%	4.65%	4.19%
MSW Price ($/tonne) after pre-processing	**Best case**	**Middle case**	**Worst case**
Amelia County MSW price ($/tonne)	$ (195.00)	$ 19.52	$ 170.05
Charles City County MSW price ($/tonne)	$ (194.37)	$ 20.15	$ 170.69
Sussex County MSW price ($/tonne)	$ (196.66)	$ 17.86	$ 168.39
Final MPSP	**Best case**	**Middle case**	**Worst case**
Amelia County SAF final price ($/gal)	$ 5.49	$ 11.88	$ 16.35
Charles City County SAF final price ($/gal)	$ 6.15	$ 12.53	$ 17.01
Sussex County SAF final price ($/gal)	$ 5.51	$ 11.89	$ 16.37

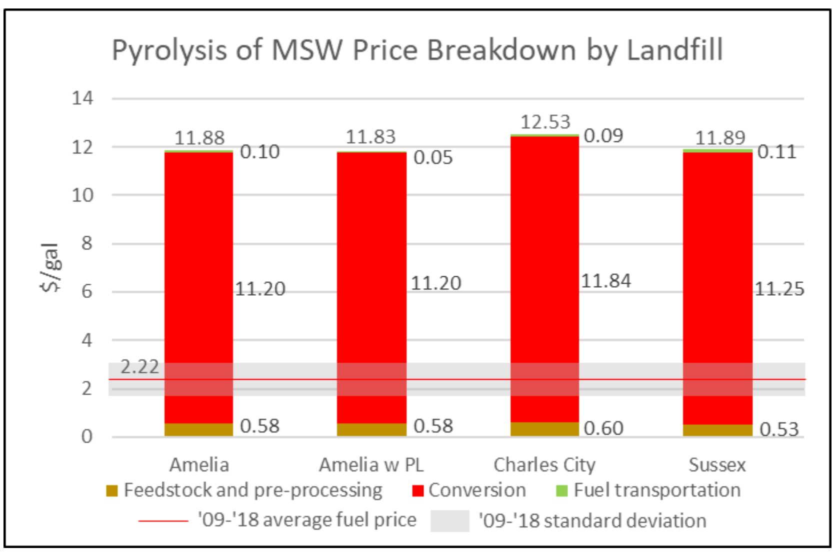

Figure A2. *Price breakdown for pilot facilities co-located with three different landfills, assuming truck and rail transport only. "w PL" refers to potential future pipeline access. This is compared to the average fossil jet fuel market price in the decade from 2009 to 2018, marked in red ($2.22 ± 0.67 /gal).*

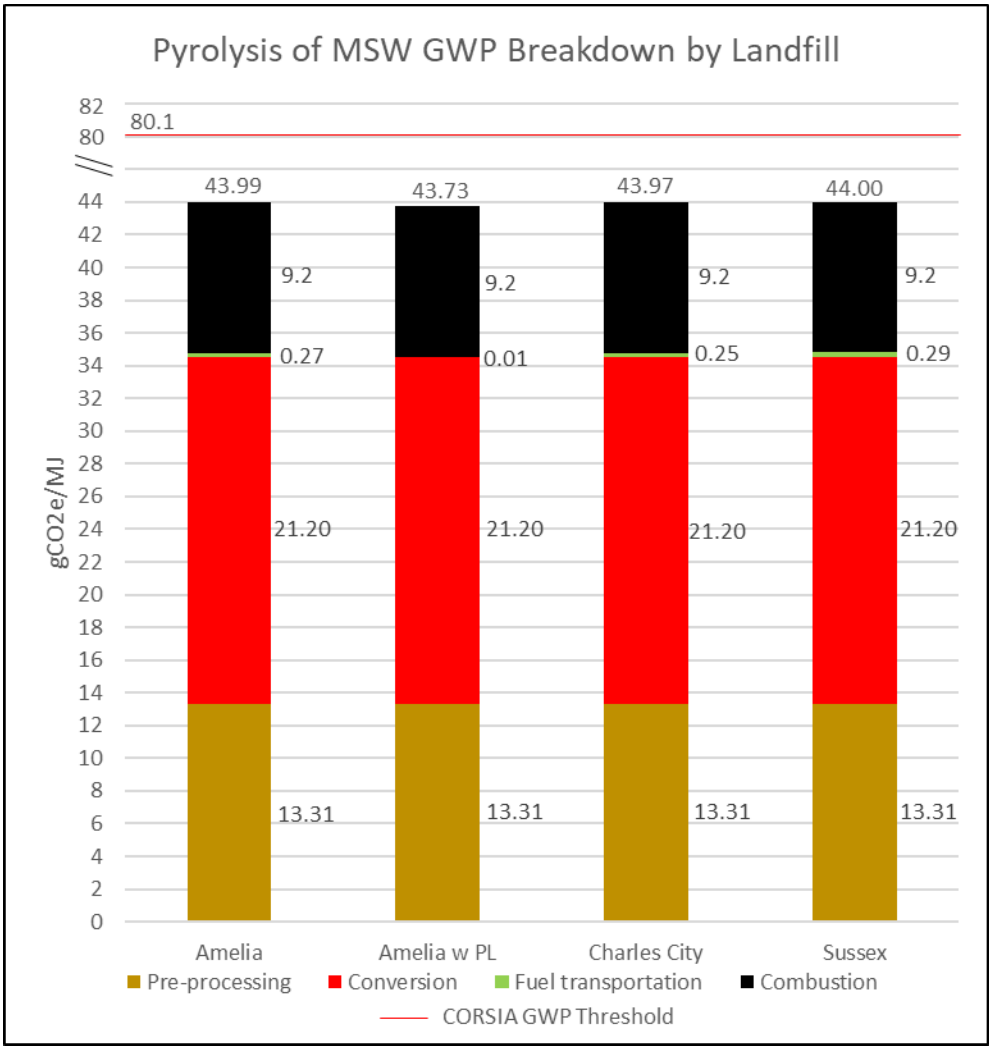

Figure A3. *GWP breakdown for pilot facilities co-located with three different landfills, assuming truck and rail transport only. "w PL" refers to potential future pipeline access. This is compared to CORSIA's fossil jet fuel baseline marked in red (80.1 gCO_2e/MJ).*

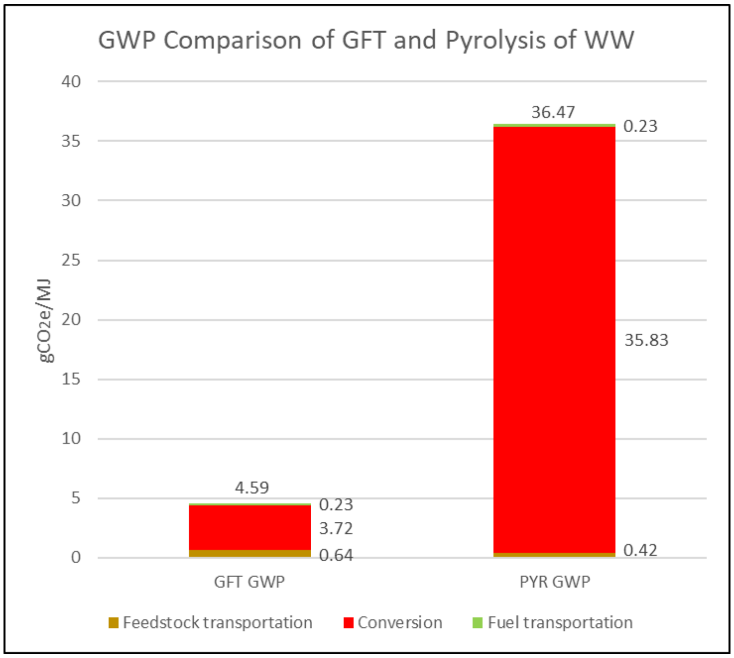

Figure A4. *GWP comparison between GFT and pyrolysis of woody waste. 1.0M tonne/yr scenario in Pittsylvania County. The fossil jet fuel baseline is 89 gCO_2e/MJ (note that this is not visible on the y-axis); GFT is a 95% reduction and pyrolysis is a 59% reduction.*

A.3 Decision Model Inputs

Table A5. *Inputs for decision model from Cheng et al. In papers where aqueous portion is not separated out, 30% of biocrude is assumed to be bio-oil. PTBO is the end result, kg CO_2e per tonne bio-oil.*

Feedstock	C	H	N	O	HHV (MJ/kg)	Moisture	Ash	Temp °C	t (min)	HR (°/min)	biocrude	bio-oil	char	aqueous	gas	PTBO	Ref
HDPE	67.57	4.13	0.51	0.79	28.64	0.2	11.16	700	60	25	79.7	23.91	0	0	18	443.1	
HDPE	78	13	0.06	4	49.4	0	1.4	450	8	0	84	25.2	3	0	13	419.9	
HDPE	78	13	0.06	4	49.4	0	1.4	550	5	0	84.7	25.41	0	0	16.3	416.5	
HDPE	78	13	0.06	4	46.95	0	0	500	1	30	82.66	24.798	0.56	0	16.78	426.7	
LDPE	69.67	10.12	0.09	18.55	34.8	0	1.57	700	60	25	84.3	25.29	0	0	15.1	418.4	
LDPE	75.69	11.25	0.001	11.06	44.24	0.05	1.05	550	5	0	93.11	27.933	0	0	14.6	379.0	1
LDPE	75.69	11.25	0.001	11.06	47.12	0	0	500	1	30	82.68	24.804	0.44	0	16.88	426.6	
PP	77.54	14.22	0.1	7.46	45.36	0	0.67	700	60	25	84.4	25.32	0.2	0	15.3	417.9	
PS	83.1	7.82	0.21	8.88	37.76	0	0	700	60	25	83.8	25.14	3.5	0	3.4	420.9	
PVC	38.85	4.7	0.03	32.11	14.12	0	24.3	700	60	25	31.7	31.7	13.8	52.9	2.5	1112.7	
PET	43.28	3.56	0.04	22.38	15.72	0	30.74	700	60	25	41.3	12.39	15.6	0	38.7	854.1	
pine wood	48.2	5.9	0.1	45.7	20.30	7	0.8	300	120	5	10.6	10.6	53.8	21	14.6	3781.5	
pine wood	48.2	5.9	0.1	45.7	20.30	7	0.8	420	120	5	12.4	12.4	29.7	35.9	21.5	3232.6	
pine wood	48.2	5.9	0.1	45.7	20.30	7	0.8	600	120	5	12.4	12.4	24.4	36.6	26.4	3232.6	
pine wood	48.2	5.9	0.1	45.7	20.30	7	0.8	720	120	5	13	13	23.2	37	26.8	3083.4	
pine wood	48.2	5.9	0.1	45.7	20.30	7	0.8	300	120	20	10.1	10.1	55.6	20.5	14	3968.7	
pine wood	48.2	5.9	0.1	45.7	20.30	7	0.8	420	120	20	12.2	12.2	27.2	37.4	23	3285.6	
pine wood	48.2	5.9	0.1	45.7	20.30	7	0.8	600	120	20	12.8	12.8	22.6	37.6	27	3131.6	
pine wood	48.2	5.9	0.1	45.7	20.30	7	0.8	720	120	20	14.1	14.1	19.6	37.5	28.8	2842.9	
pine wood	48.2	5.9	0.1	45.7	20.30	7	0.8	300	120	40	6.7	6.7	58	21.7	13.6	5982.7	2
pine wood	48.2	5.9	0.1	45.7	20.30	7	0.8	420	120	40	11.8	11.8	26.4	34.2	27.6	3397.0	
pine wood	48.2	5.9	0.1	45.7	20.30	7	0.8	600	120	40	13.2	13.2	20.4	37.6	28.8	3036.7	
pine wood	48.2	5.9	0.1	45.7	20.30	7	0.8	720	120	40	14.3	14.3	18.4	37.7	29.6	2803.1	
pine wood	48.2	5.9	0.1	45.7	20.30	7	0.8	300	120	80	6.4	6.4	60.8	21.6	11.2	6263.2	
pine wood	48.2	5.9	0.1	45.7	20.30	7	0.8	420	120	80	11.9	11.9	25.2	36.9	26	3368.4	
pine wood	48.2	5.9	0.1	45.7	20.30	7	0.8	600	120	80	14.6	14.6	18.7	37.8	29.1	2745.5	
pine wood	48.2	5.9	0.1	45.7	20.30	7	0.8	720	120	80	15.9	15.9	16.2	37.7	30.2	2521.0	

Paulowina Wo	44.73	6.12	0.82	48.28	20.7	6.5	1.06	350	30	10	24	7.2	34.5	0	25.3	1665.4	
Paulowina Wo	44.73	6.12	0.82	48.28	20.7	6.5	1.06	400	30	10	23.8	7.14	29.8	0	27.5	1679.4	
Paulowina Wo	44.73	6.12	0.82	48.28	20.7	6.5	1.06	450	30	10	24.5	7.35	28	0	26.5	1631.4	
Paulowina Wo	44.73	6.12	0.82	48.28	20.7	6.5	1.06	500	30	10	25	7.5	27	0	27	1598.8	
Paulowina Wo	44.73	6.12	0.82	48.28	20.7	6.5	1.06	550	30	10	24.8	7.44	26.2	0	27.5	1611.6	
Paulowina Wo	44.73	6.12	0.82	48.28	20.7	6.5	1.06	600	30	10	24.5	7.35	25.4	0	29.2	1631.4	
Paulowina Wo	44.73	6.12	0.82	48.28	20.7	6.5	1.06	350	30	50	27	8.1	29.5	0	22.4	1480.3	
Paulowina Wo	44.73	6.12	0.82	48.28	20.7	6.5	1.06	400	30	50	27.2	8.16	29	0	23	1469.4	3
Paulowina Wo	44.73	6.12	0.82	48.28	20.7	6.5	1.06	450	30	50	28.5	8.55	27.5	0	22.5	1402.4	
Paulowina Wo	44.73	6.12	0.82	48.28	20.7	6.5	1.06	500	30	50	29.3	8.79	26	0	22.5	1364.1	
Paulowina Wo	44.73	6.12	0.82	48.28	20.7	6.5	1.06	550	30	50	27.5	8.25	24.6	0	24.8	1453.4	
Paulowina Wo	44.73	6.12	0.82	48.28	20.7	6.5	1.06	600	30	50	26	7.8	24	0	27.1	1537.3	
Paulowina Wo	44.73	6.12	0.82	48.28	20.7	6.5	1.06	500	30	50	29	8.7	27	0	22	1378.2	
Paulowina Wo	44.73	6.12	0.82	48.28	20.7	6.5	1.06	500	30	50	29.2	8.76	25	0	25	1368.8	
Paulowina Wo	44.73	6.12	0.82	48.28	20.7	6.5	1.06	500	30	50	29.1	8.73	25.5	0	24	1373.5	
Wood	49.5	4.1	0.5	45.2	16	7.9	0.7	500	0.16	600	25	7.5	55	0	10	1611.8	
Wood	49.5	4.1	0.5	45.2	16	7.9	0.7	600	0.16	600	55	16.5	32	0	17	732.6	
Wood	49.5	4.1	0.5	45.2	16	7.9	0.7	700	0.16	600	64	19.2	21	0	28	629.6	
Wood	49.5	4.1	0.5	45.2	16	7.9	0.7	800	0.16	600	70	21	17	0	36	575.6	
Wood	49.5	4.1	0.5	45.2	16	7.9	0.7	900	0.16	600	75	22.5	15	0	40	537.3	
Wood	49.5	4.1	0.5	45.2	16	7.9	0.7	1000	0.16	600	75	22.5	14	0	41	537.3	
Reed	50	4.2	0.5	45.6	10.8	8.8	19.4	500	0.16	600	35	10.5	43	0	18	1157.4	4
Reed	50	4.2	0.5	45.6	10.8	8.8	19.4	600	0.16	600	46	13.8	34	0	24	880.7	
Reed	50	4.2	0.5	45.6	10.8	8.8	19.4	700	0.16	600	51	15.3	32	0	30	794.3	
Reed	50	4.2	0.5	45.6	10.8	8.8	19.4	800	0.16	600	52	15.6	32	0	32	779.0	
Reed	50	4.2	0.5	45.6	10.8	8.8	19.4	900	0.16	600	54	16.2	31	0	33	750.2	
Reed	50	4.2	0.5	45.6	10.8	8.8	19.4	1000	0.16	600	56	16.8	30	0	36	723.4	
Napier grass	48.6	6.01	0.99	44.1	18.1	75.3	1.75	450	15	30	27.7	8.31	45.5	0	26.8	3976.6	
Napier grass	48.6	6.01	0.99	44.1	18.1	75.3	1.75	550	15	30	31	9.3	34.69	0	34	3553.3	
Napier grass	48.6	6.01	0.99	44.1	18.1	75.3	1.75	600	15	30	32.26	9.678	29.67	0	36.3	3414.5	5
Napier grass	48.6	6.01	0.99	44.1	18.1	75.3	1.75	650	15	30	31.97	9.591	26.56	0	41.47	3445.4	
Perennial Gras	42	6.2	1.5	36.3	17.14	8.5	5.3	350	30	10	16.67	5.001	45.77	0	28.74	3050.3	
Perennial Gras	42	6.2	1.5	36.3	17.14	8.5	5.3	400	30	10	18.26	5.478	43.87	0	30.61	2784.7	
Perennial Gras	42	6.2	1.5	36.3	17.14	8.5	5.3	450	30	10	20.13	6.039	42.91	0	32.97	2526.0	
Perennial Gras	42	6.2	1.5	36.3	17.14	8.5	5.3	500	30	10	21.54	6.462	40.51	0	34.58	2360.6	
Perennial Gras	42	6.2	1.5	36.3	17.14	8.5	5.3	550	30	10	19.51	5.853	35.24	0	41.03	2606.2	
Perennial Gras	42	6.2	1.5	36.3	17.14	8.5	5.3	600	30	10	17.59	5.277	33.11	0	44.59	2890.7	
Perennial Gras	42	6.2	1.5	36.3	17.14	8.5	5.3	650	30	10	16.65	4.995	32.98	0	45.16	3053.9	
Perennial Gras	42	6.2	1.5	36.3	17.14	8.5	5.3	350	30	40	18.64	5.592	42.38	0	29.96	2727.9	6
Perennial Gras	42	6.2	1.5	36.3	17.14	8.5	5.3	400	30	40	22.49	6.747	38.04	0	31.54	2260.9	
Perennial Gras	42	6.2	1.5	36.3	17.14	8.5	5.3	450	30	40	25.91	7.773	33.72	0	33.75	1962.5	
Perennial Gras	42	6.2	1.5	36.3	17.14	8.5	5.3	500	30	40	26.18	7.854	33.5	0	36.29	1942.2	
Perennial Gras	42	6.2	1.5	36.3	17.14	8.5	5.3	550	30	40	23.82	7.146	32.15	0	38.11	2134.7	
Perennial Gras	42	6.2	1.5	36.3	17.14	8.5	5.3	600	30	40	21.79	6.537	30.18	0	40.12	2333.5	
Perennial Gras	42	6.2	1.5	36.3	17.14	8.5	5.3	650	30	40	21.02	6.306	29.98	0	41.23	2419.0	
Maple Fruit	45.32	6.22	3.05	45.41	19.92	8.72	6.27	400	30	200	41.1	12.33	34.8	0	24	1238.5	
Maple Fruit	45.32	6.22	3.05	45.41	19.92	8.72	6.27	500	30	200	45.3	13.59	27	0	26.8	1123.6	
Maple Fruit	45.32	6.22	3.05	45.41	19.92	8.72	6.27	600	30	200	50.2	15.06	25.8	0	24	1014.0	
Maple Fruit	45.32	6.22	3.05	45.41	19.92	8.72	6.27	700	30	200	45.4	13.62	24.4	0	29	1121.2	7
Maple Fruit	45.32	6.22	3.05	45.41	19.92	8.72	6.27	600	30	200	49.5	14.85	28	0	22	1028.3	
Maple Fruit	45.32	6.22	3.05	45.41	19.92	8.72	6.27	600	30	200	48.5	14.55	27.5	0	27.5	1049.5	
Maple Fruit	45.32	6.22	3.05	45.41	19.92	8.72	6.27	600	30	200	49.2	14.76	27	0	27.5	1034.6	
Tea Factory W	49.6	5.1	2.7	42.6	17.1	30	3.4	502	0	120	28.9	8.67	33.5	0	37.6	1992.5	
Tea Factory W	49.6	5.1	2.7	42.6	17.1	30	3.4	652	0	120	25.4	7.62	32.8	0	41.8	2267.0	8
Tea Factory W	49.6	5.1	2.7	42.6	17.1	30	3.4	702	0	120	24.5	7.35	32	0	43.5	2350.3	
Tea Factory W	49.6	5.1	2.7	42.6	17.1	30	3.4	752	0	120	23.2	6.96	31.1	0	45.7	2482.0	
Bagasse	48.58	5.97	0.2	38.94	19.2	4	1.26	300	60	50	18.66	5.598	77	0	4.34	2669.9	
Bagasse	48.58	5.97	0.2	38.94	19.2	4	1.26	350	60	50	51.32	15.396	43.8	0	4.87	970.8	
Bagasse	48.58	5.97	0.2	38.94	19.2	4	1.26	400	60	50	60.66	18.198	31.93	0	7.41	821.3	
Bagasse	48.58	5.97	0.2	38.94	19.2	4	1.26	450	60	50	65.47	19.641	26.26	0	8.27	761.0	9
Bagasse	48.58	5.97	0.2	38.94	19.2	4	1.26	500	60	50	66.13	19.839	24.86	0	9.01	753.4	
Bagasse	48.58	5.97	0.2	38.94	19.2	4	1.26	550	60	50	60.63	18.189	24.66	0	14.71	821.7	
Bagasse	48.58	5.97	0.2	38.94	19.2	4	1.26	600	60	50	59.52	17.856	22.86	0	17.82	837.0	
Waste Paper	41.27	5.8	0	51.89	0	11.19	1.05	300		10	42.18	12.654	45.16	0	12.66	974.4	
Waste Paper	41.27	5.8	0	51.89	0	11.19	1.05	330		10	42.97	12.891	43.57	0	13.56	956.5	
Waste Paper	41.27	5.8	0	51.89	0	11.19	1.05	360		10	44.04	13.212	41.08	0	13.88	933.3	
Waste Paper	41.27	5.8	0	51.89	0	11.19	1.05	390		10	45.57	13.671	39.11	0	15.32	902.0	
Waste Paper	41.27	5.8	0	51.89	0	11.19	1.05	420		10	46.86	14.058	36.97	0	16.17	877.1	
Waste Paper	41.27	5.8	0	51.89	0	11.19	1.05	450		10	47.03	14.109	35.23	0	17.74	874.0	
Waste Paper	41.27	5.8	0	51.89	0	11.19	1.05	300		30	46.06	13.818	40.63	0	13.31	892.4	10
Waste Paper	41.27	5.8	0	51.89	0	11.19	1.05	330		30	47.21	14.163	38.93	0	13.86	870.6	
Waste Paper	41.27	5.8	0	51.89	0	11.19	1.05	360		30	47.86	14.358	38.02	0	14.12	858.8	
Waste Paper	41.27	5.8	0	51.89	0	11.19	1.05	390		30	48.46	14.538	36.16	0	15.38	848.2	
Waste Paper	41.27	5.8	0	51.89	0	11.19	1.05	420		30	49.13	14.739	34.41	0	16.46	836.6	
Waste Paper	41.27	5.8	0	51.89	0	11.19	1.05	450		30	48.34	14.502	33.43	0	18.23	850.3	

The bio-oil fraction was averaged from the inputs in Table A5 above, along with MSW compositional breakdown from the EPA.[11] From Table A5, HDPE, LDPE, PP, PS, PVC, and PET are plastics (composition in MSW found in Bodzay et al.);[12] reed, Napier grass, and perennial grass are considered types of yard trimmings; and maple fruit, tea factory waste, and bagasse are considered food waste. Bio-oil fraction is 14.5% after the averaging; with a 50% distillate fraction becoming SAF, the yield ratio is 7.26%.

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