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Geospatially explicit technoeconomic assessment of sustainable aviation fuel production: A regional case study in Virginia

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ABSTRACT

There is strong interest in sustainable aviation fuels (SAF) to decarbonize aviation; however, local decision-makers will need to consider what additional incentives could stimulate SAF commercialization within their own jurisdictions. This study analyzed SAF production in Virginia, evaluating two biomass-to-energy platforms (gasification Fischer Tropsch [GFT] and pyrolysis) and two regionally abundant feedstocks (woody wastes and municipal solid wastes). A suite of open-access modeling tools were applied to possible SAF supply chains encompassing feedstock collection and transportation, conversion, and fuel upgrading and transport. Key modeling outputs were minimum product selling price (MPSP) ($/gallon) and life-cycle global warming potential (GWP) (g CO_2eq/MJ). Results suggest that early SAF production via GFT will require local incentives of approximately $3.61 per gallon compared to $0.75 per gallon for pilot-scale pyrolysis. Location of production facility (by county) influences economic and environmental metrics but is not nearly as important as facility size (tonnes/year). Different formats of financial incentives (i.e., tax credits, loan forgiveness, etc.) offer markedly different reductions in SAF MPSP. Finally, under current federal incentives in the US, it is still more economically efficient to use pyrolysis (with higher GWP) than GFT (with lower GWP). Therefore, regional stakeholders will need to navigate the tradeoff between economic and environmental performances of these platforms. Though Virginia was used as a case study, the methodology is replicable for other jurisdictions, insofar it can be adapted for use in other locations without decision-makers having to completely build their own TEA models.

1. Introduction

Federal agencies, regional governments, and commercial airlines are urgently interested in commercialization of sustainable aviation fuels (SAFs), a class of drop-in fuels designed to power existing aircraft without modification at blend ratios of up to 50 % with fossil jet fuel [1]. Low-carbon SAFs produced from domestically sourced biomass and/or waste feedstocks are critical for ensuring sustainable commercial and military aviation, which are vital to economic prosperity and homeland security [2]. Multiple federal agencies released the *SAF Grand Challenge Roadmap* in 2022, which explored methods for the U.S. government to help de-risk SAF production technologies and supply chains, prioritize engagement with stakeholders, and generally reduce barriers to SAF production and scaling [2]. Against this backdrop, state and local governments and other stakeholders seek information about what the costs and benefits of SAF production could be within their own jurisdictions. Therefore, it is valuable for evaluation of SAF production pathways using life cycle assessment (LCA) and/or technoeconomic assessment (TEA) to account for the biophysical and socio-technical features of the regional context in which they will be deployed. In the terminology of LCA and TEA, systems modeling to support local decision-making about SAF commercialization should be geospatially explicit [3–7].

The Virginia Department of Transportation (VDOT) has engaged in exploratory research pertaining to possible SAF production pathways in Virginia over the last ten years, initially commissioning a broad-based economic and environmental analysis of SAF feedstock availability [8]. The results of that work formed the basis for the current study, which was launched in 2020 at the behest of the Virginia Transportation Research Council (VTRC) [9]. Virginia ranks among the top ten states for jet fuel consumption per year, but it is not currently producing or

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consuming SAF [10,11]. 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 as SAF feedstocks [12,13]. For these reasons, Virginia serves as a good case study for understanding the logistical and incentive readiness for scaling SAF within a particular jurisdiction.

There are currently seven ASTM D7566-qualified pathways for converting biomass feedstocks into SAF [14,15]. These seven pathways are also certified under the *Carbon Offsetting and Reduction Scheme for International Aviation* (CORSIA) as CORSIA-eligible fuels (CEFs). CORSIA is an international framework that requires airlines to offset emissions from international travel beyond 2019 levels, and CEFs are a method for achieving compliance [15]. 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 when "well to wake" system boundaries are applied (Fig. 1) [15]. Based on outcomes from VDOT's preliminary exploratory work [8] and conversations with stakeholders, it was decided that the gasification with Fischer Tropsch (GFT) and pyrolysis pathways would be most appropriate for commercialization in Virginia. There was also strong interest in woody wastes and MSW as SAF feedstocks, since both are locally abundant. Accordingly, modeling efforts were focused on four pathways arising from combination of the two selected pathways and the two selected feedstocks. All four scenarios were evaluated assuming near-term production in "pilot" facilities and over longer time horizons ("mature" technologies). Additional details about the selected pathways are provided in the following sections.

GFT. GFT converts carbon-rich feedstocks into syngas which is then reformed into liquid hydrocarbons. Biomass is first chipped or chopped to produce smaller particle sizes and then dried, before being gasified in an updraft or downdraft gasifier [16]. The resulting "bio-syngas" comprises a mixture of CO, H_2, CO_2, N_2, and CH_4. It is conditioned via a cleaning process that removes organic (tars, benzene, etc.), inorganic (O_2, NH_3, etc.), or physical (dust, soot, etc.) impurities [16]. Cleaned bio-syngas then undergoes the Fischer-Tropsch process which converts gaseous carbon compounds into a mixture of hydrocarbon liquids and water [16].

GFT is currently in use to produce SAF at a pilot-scale facility in Nevada operated by Fulcrum Bioenergy. This facility converts MSW feedstock into SAF which is then transported to California airports for blending and use [17]. Virginia 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 [18]. It is therefore appealing to imagine that Virginia's MSW could be transformed into a valuable resource for producing SAF, whereby the drawbacks of community landfills (e.g., odor, noise, possible groundwater contamination, etc.) could be offset via economic benefits arising from production of energy from waste. Though GFT is widely expected to be the most desirable SAF production platform over the long-term future, it is well-known how difficult its road to commercialization may be. The facility operated by Fulcrum Bioenergy experienced long production delays before it was up and running. These delays and other difficulties signify the serious technical challenges associated with the GFT platform [17].

Pyrolysis. Pyrolysis is an alternative method of converting carbon-rich feedstocks into liquid fuels. Biomass is heated in a non-reactive atmosphere under conditions of high heat and pressure, such that the biomass is decomposed into gases, liquids (tars and oils), and solid char [19]. Variation in temperature, pressure, residence time, and heating rate leads to different physical and chemical compositions of the process outputs [19]. Slow pyrolysis has higher residence times but shorter heating rates and lower temperatures than fast pyrolysis, producing more gas and char products. In contrast, fast pyrolysis generally produces more bio-oil, which is the desired fraction for refining into SAF and other liquid fuels [19]. There are currently no operational pyrolysis-based SAF production facilities. Also, unlike GFT, pyrolysis is not yet CORSIA-certified. However, several pyrolytic pathways are under active evaluation, and the process is widely anticipated to be certified soon [20]. A significant benefit of the pyrolysis pathway is that it can produce not only SAF but other valuable liquid fuels. For the Virginia context, it was posited that the establishment of pilot pyrolysis facilities in the near-term future could help grow feedstock supply chains, create robust markets for other distillates (i.e., gasoline, diesel), and give time for SAF certification and/or technological maturation of GFT. Therefore, both pyrolysis and GFT were evaluated in this study.

Finally, it was anticipated at the outset of the study that SAF produced in Virginia would not be cost-competitive with fossil jet fuel despite recent increases to federal incentives [21,22]. Therefore, the analysis commissioned by VDOT was specifically meant to assess how much SAF could be produced in Virginia (via which platforms using which feedstocks, and in what locations); and to estimate what state-level incentives would be required to spur local SAF commercialization. Geospatially explicit techno-economic assessment (TEA) was applied to four pathways of interest in order answer these questions for the Virginia context and deliverable generalizable methodologies and conclusions that are relevant to other jurisdictions.

2. Methods

Supply chain and transportation logistics analyses for SAF

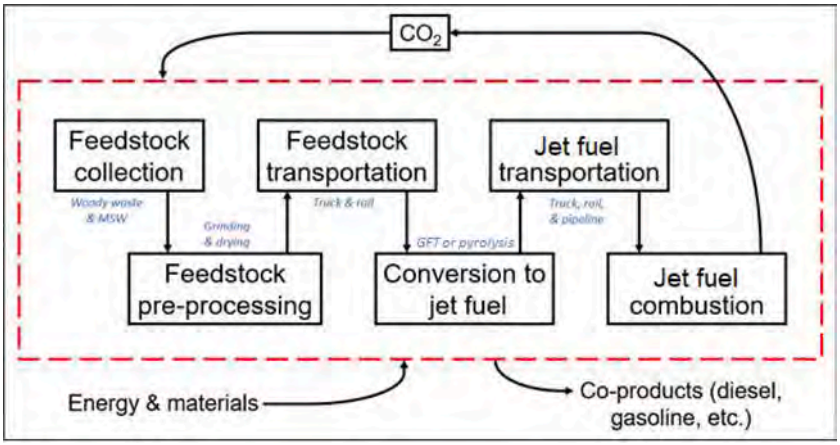

Fig. 1. System boundaries for LCA of SAF in this study, as adapted from CORSIA core LCA [15]. MSW = municipal solid waste. GFT = gasification with Fischer-Tropsch.

production were performed via adaptation of two previously validated, open-access modeling tools promulgated 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 TEA models for SAF production from the *Aviation Sustainability Center* (ASCENT) (funded by the U.S. Federal Aviation Administration [FAA]). These tools 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 a TEA framework implemented via spreadsheet in Microsoft Excel. Systems boundaries included all of the sub-processes shown in Fig. 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 sections 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 Fig. 1.

2.1. Feedstock availability

NREL's Biofuels Atlas was used to get county-by-county data for woody waste feedstock availability per year [12]. 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." [12].

These quantities were compiled into a 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. [23], GREET uses water contents of 50 % at the time of harvest, but it is assumed that natural drying reduces the water content of forest residue to 20 % before transport. This same moisture content was also assigned for primary mill residue and urban wood, but a lower range (15–20 %) was assigned for secondary mill residue [24]. These water contents were later increased and decreased by 5 % in sensitivity analyses, to analyze how changes in assumed water content influenced overall system performance.

MSW availability changes from year to year, so Virginia's most recent solid waste report at the time of modeling was used [13]. This report includes the total amount of MSW collected from within the state and imported from other states, 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 2.1) to candidate conversion facility sites; as well as for fuel transport, from candidate conversion facilities to the desired consumption location at Dulles International Airport (IAD). For simplicity, feedstock and candidate conversion sites were mapped to the GIS coordinates of the population centroid of each county. 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 which 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 (~1 million gallons per day, based on communication with officials from the airport's fuel supplier) [25]. FTOT also reported total GWP impacts for feedstock and fuel transportation within the optimized network from each run. The analysis of various possible county combinations was repeated at three different sizes of hypothetical conversion facilities (300 K, 500 K, and 750 K 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) in an individual FTOT run was recorded for all 24 sets of possible county combinations, to determine which counties were picked by FTOT most frequently. Finally, the county prioritization results arising from the randomized FTOT assessment were filtered based on input from relevant stakeholders (e.g., Commercial Aviation Alternative Fuels Initiative, UT Institute of Agriculture) [26,27] and insights from previously published work [8]. More information about how to use FTOT is available in Section S.1 of Supporting Information (SI) and FTOT's public GitHub page [28].

Because FTOT modeling assumed that all relevant operations were conducted at the county population centroids, it was also necessary to account for the transport distances between each county centroid and the actual feedstock locations. Therefore, "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 it was assumed that SAF production facilities would be co-located with existing landfills, such that existing MSW transport operations would remain unchanged.

2.3. Conversion – ascent TEAs

A suite of open-access TEA models published by the federally-funded ASCENT program was used as a starting place to model the GFT and pyrolysis conversion processes [29–31]. The systems boundaries for the fuel production phase modeled within 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 SAF production cost at each location of interest. Virginia-specific inputs for these spreadsheet models are in Table 1. Users select a distillate breakdown, and the TEAs use feedstock-to-fuel ratios from literature. For this study, inputs were selected to maximize SAF production relative to other distillates. Based on the quantity of feedstock entered by the user, corresponding quantities of SAF, diesel, and other products are computed. These fuel quantities determine the minimum product selling price (MPSP) ($/gallon) that is required to balance total revenue and expenditures. ASCENT's assignment of SAF prices relative to other distillates was based on historical records from 1983 to 2018. When the TEA models were run, the SAF price was solved to meet these constraints. The TEAs were used in two different modes; first modeling model pilot facilities (representing near-term future conditions), then modeling an n^{th} (mature) facility (representing longer-term future conditions). The relation between pilot and nth facility costs is estimated within ASCENT using an empirical cost growth factor [32].

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 of materials collected by landfills, as taken from Virginia's solid waste report [13].

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

Variable	TEA Default	Virginia-specific value	Sources
Forest residues ($/t)	125	124–142	White [33] and Cheng et al. [34] adjusted for inflation; Brandt et al. [29] for feedstock pre-processing
Municipal solid waste ($/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; with conversion from units of $/t feedstock assuming known conversion efficiency.
Fuel transport price ($/gal)	N/A	0.06–0.13	FTOT modeling
Electricity price ($/kWh)	0.069	0.081	EIA Electric Power Monthly [35]
Natural gas price ($/MMBtu)	4.24	5.04	EIA Natural Gas Prices [36]
Cost of land (% of total cost)	1.5	Dependent on location and property value	Virginia Department of Education [37]

These facility sizes were used to determine feedstock pre-processing costs. Total feedstock cost was then input into the GFT or pyrolysis TEA model along with the facility size to compute MPSP for SAF. Resulting values were then fed into the overarching spreadsheet model as discussed below. This process was completed for each of the pathways studied.

To compute ASCENT's input data, it was necessary to pre-calculate several parameters. These calculations were done in a separate regionally contextualized spreadsheet analysis that integrated relevant model inputs with FTOT and ASCENT TEA modeling. For energy density, a few input values are required depending on the SAF production pathway; e.g., 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, as shown in Eq. (1):

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

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) [38].

Bio-oil yields were taken from the ASCENT TEAs for GFT conversion of woody waste or MSW and pyrolysis conversion of woody waste. Bio-oil yield for pyrolysis of MSW was not available via the ASCENT TEAs or in relevant literature, so pyrolysis yields for different MSW components were collected from literature and assembled into a weighted average. This compilation can be found in SI Section S.2.

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 the Red Rock Biofuels production facility in Oregon, which owns 88 acres for a facility of 166,000 dry tons (approximately 200,000 wet tonnes) capacity [39]. 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 [37]. This approach was used instead of the chemical engineering approach, whereby the price of land is assumed to be 1.5 % of the total capital investment [40]. This choice was made to include as much county-specific information as possible into the estimates of SAF production costs, and land values vary dramatically by county in Virginia. As expressed in Table 1, specific land values were entered into the ASCENT TEAs by county. This required overwriting of data that was already in ASCENT, which made it necessary to ask the authors of the ASCENT TEAs to provide an unlocked version of the spreadsheet tool.

2.4. Global warming potential calculations

Because GFT of forest residue and MSW are ASTM-certified pathways for SAF production and because they significantly reduce GWP relative to fossil jet fuel, they qualify as CORSIA-eligible fuels and have ISO-compliant life cycle assessments (LCAs) produced by the International Civil Aviation Organization (ICAO) [41]. These LCAs are broken down into four stages: 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 either forest residue or MSW, is not yet certified as a SAF production pathway under the CORSIA framework but this is expected to change in the future [42]. Nevertheless, there were no published ICAO LCAs for these pathways at the time of this study. Therefore, GWP estimates for SAF produced via these pathways were computed via adaptation of LCA results from de Jong et al. [43]. That study used system boundaries that were very similar to CORSIA's (i.e., feedstock cultivation, upstream transport, conversion, hydrogen, and downstream distribution). Similar to the GFT pathway modeling, generalized GWP estimates for the two transportation stages were removed and replaced with results from FTOT for use in this study.

Pyrolysis of MSW to produce SAF is not well documented in scientific literature. Therefore, this study utilized an open-source decision model by Cheng et al. [34] to estimate GWP for this pathway. Inputs for this decision model can be found in SI Section S.2. Energy allocation was used to apportion the GWP of the overall production process across the multiple distillates including SAF (also, diesel, gasoline, and bunker fuel), consistent with the CORSIA framework and previous related work from de Jong et al. [41,43].

Finally, a landfill emissions credit was computed to account for the GWP savings that is achieved when MSW is diverted or removed ("mined") from a landfill and is instead used as SAF feedstock. From Zhao [44], US landfill methane emissions were 0.032 t CH4 / t MSW, which is equivalent to a GWP value of 0.90 t CO2e / t MSW per year. Applying energy allocation over the four distillates, the resulting GWP credit for SAF was 38 g CO_2e avoided / MJ SAF production.

2.5. Incentives

The ASCENT TEAs include built-in tabs to evaluate and compare several kinds of possible incentives at the federal or state level, making it possible to estimate what impact they would have on SAF production cost. For this study, previously existing federal incentives were evaluated, including: *Renewable Identification Numbers (RINs)*, which are credits for compliance with the *Renewable Fuel Standard* (RFS), at $3.21/gal (corresponding to the average value in the first quarter of 2022); $1/gal blenders tax credits (BTCs) for diesel; $0.50/gal BTCs for gasoline; as well as 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 [22]. New federal incentives in the form of a BTC for SAF, which was created via the *Inflation Reduction Act (IRA) of 2022*, were also included [45]. The IRA applies to fuels that reduce lifecycle emissions by at least

50 % relative to fossil jet fuel, starting at a base credit of $1.25/gal plus a supplementary amount of $0.01 for every 1 % emissions reduction above the 50 % threshold [45].

Subsequently, five hypothetical (not yet existing) kinds of state investments were also evaluated: feedstock subsidy, risk reduction (i.e., reduction of the facility's interest rate), capital grant, tax credit, or a policy similar to California's *Low Carbon Fuel Standard* (LCFS). The LCFS is a program that reduces the overall carbon intensity of the transportation sector, allowing producers and other entities to trade credits based on pre-determined sector reduction goals [46]. The amount of hypothetical state investment was held constant at a fixed value ($350 million) for input into the ASCENT TEAs for four of the five investment types (i.e., all but tax credits). This amount was selected arbitrarily without any special significance, as a way to assess differences in how differently structured investments would influence overall SAF production cost. The selected investment magnitude corresponds to approximately 0.5 % of Virginia's total budget from FY2021 [47], 11 % of the total value of credits in California's LCFS in 2020 [48], and 50 % of what IAD paid for jet fuel in 2019 [10,25]. The analysis was repeated at alternative investment values of $70 million and $585 million, to determine whether modeling results were robust for different assumed investment magnitudes. The larger hypothetical state investment was often required to yield estimates of SAF MPSP that were comparable to the historical cost of fossil jet fuel.

2.6. Integration with carbon capture and storage (CCS)

Over time, state stakeholders became increasingly interested in possible integration of SAF production with carbon capture and sequestration (CCS). Data from a recent analysis by Michaga et al. [49] was used to evaluate how adoption of CCS at a hypothetical woody waste facility (Pittsylvania County) would influence SAF GWP and cost. The Michaga study assumed woody forest residues are used as feedstock for GFT production of SAF and that CO_2 is captured at 90 % efficiency from upgraded syngas via chemical absorption. Their analysis also assumed that CO_2 is compressed and transported for permanent geologic storage; however, it did not make use of geospatially explicit transportation distances, and it assumed pipelines were the only method of CO2 transport [49]. Regarding SAF GWP, CO_2 captured from the syngas stream constitutes about 30.5 % of the carbon comprising the original woody waste feedstock [49]. Therefore, the mass of CO_2 that could be permanently stored is 137.83 g CO_2 per MJ SAF produced [49].

Regarding SAF production cost, Michaga et al. [49] estimated that including CCS adds a cost of £13.38 - £36.38 per tonne of sequestered CO_2. This cost accounted for annualized capital expenses of the carbon capture infrastructure, as well as operating costs for CO_2 compression, transportation, and storage. The transport and storage portion was assumed to be £8 - £31/tCO_2; the remainder was, therefore, £5.31/tCO_2 for all other processes. Assuming a currency conversion rate of £1.00 to $1.30, the cost of CCS infrastructure and CO_2 compression is about $7/t$CO_2$. Because the cost of CCS varies by location, values for transport and storage were calculated specifically for this study assuming the Virginia context. The nearest low-cost geological storage formation is the Waste Gate Formation, which lies over the Delmarva Peninsula [3,50]. Storage cost in that formation is approximately $4/t$CO_2$. Transport distances corresponding to candidate SAF production facility location arising from this study range from 260 to 590 miles, thereby giving rise to a range of CO_2 transport costs [3]. The overall range of combined transport and storage costs is $6.25 - $9.35/t$CO_2$, with an average value of $7.80/t$CO_2$. The IRA increased existing 45Q tax credits from $50 to $85 per tonne of CO_2 for CO2 storage in saline geologic formations [51].

3. Results and discussion

3.1. Feedstock availability and selection of candidate processing sites

3.1.1. Woody waste feedstock

Woody waste availability varies by region within Virginia, but the overall distribution is widespread with appreciable quantities available in many locations (Fig. S1). Total availability for the entire state is approximately 6155,030 dry tonnes per year, which includes some feedstock that is likely already being utilized by other industries. Not accounting for other competing uses, feedstock availability for individual counties ranges from 940 to 276,820 dry tonnes per year.

Based on the known geographic distribution of woody waste feedstock, whereby most of the feedstock is available in counties farthest away from the SAF demand node in northeastern Virginia (Dulles Airport), it was hypothesized that minimizing feedstock and fuel transportation distances would contribute to the production of cost-competitive and low-carbon SAF. The FTOT model was therefore used to evaluate impacts arising from transport of feedstocks and finished SAF. Fig. 2 shows the results of the FTOT county prioritization analysis based on randomized sets of candidate county locations. 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 (out of 24 total trials) correspond to locations that minimize overall transportation costs and impacts. In contrast, county locations that were picked less often by FTOT are evidently not as attractive for construction of a SAF production facility based on transportation logistics. Summarizing from Fig. 2, the top 10 highest priority counties are (in order): Buckingham, Charlotte, Fairfax, Louisa, Roanoke, Alleghany, Greensville, Pittsylvania, Amelia, and Brunswick. Each of these was selected for implementation of a SAF production facility in no fewer than 21 out of 24 possible FTOT runs.

The list of ten counties picked most frequently by FTOT was filtered to reflect stakeholder input, insights from previously published work, and other practical considerations. Four of the top ten were selected for inclusion in subsequent modeling, including Alleghany, Buckingham, Greensville, and Pittsylvania. 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 though this was not explicitly accounted for in the current study. Additionally, a facility in Allegheny 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 SAF cost and GWP as low as possible. Greensville County was selected because of its large quantities of woody waste, particularly primary mill residue, and because feedstock from North Carolina would be easily accessible (though, again, biomass import was excluded from this study). 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 selected based on strong interest from relevant stakeholders and promising results from a previous analysis led by the University of Tennessee (UT) [27]. The previous study highlighted Tazewell's central location relative to the Appalachian "wood basket", whereby feedstocks could be conveniently imported from West Virginia, Kentucky, Tennessee, and North Carolina. The UT study specifically mentioned Tazewell as a promising biorefinery location [27]. This location would also bring economic development to the Appalachian region, which has traditionally been underserved. From a practical perspective, the selection of Tazewell County instead of the other top 10

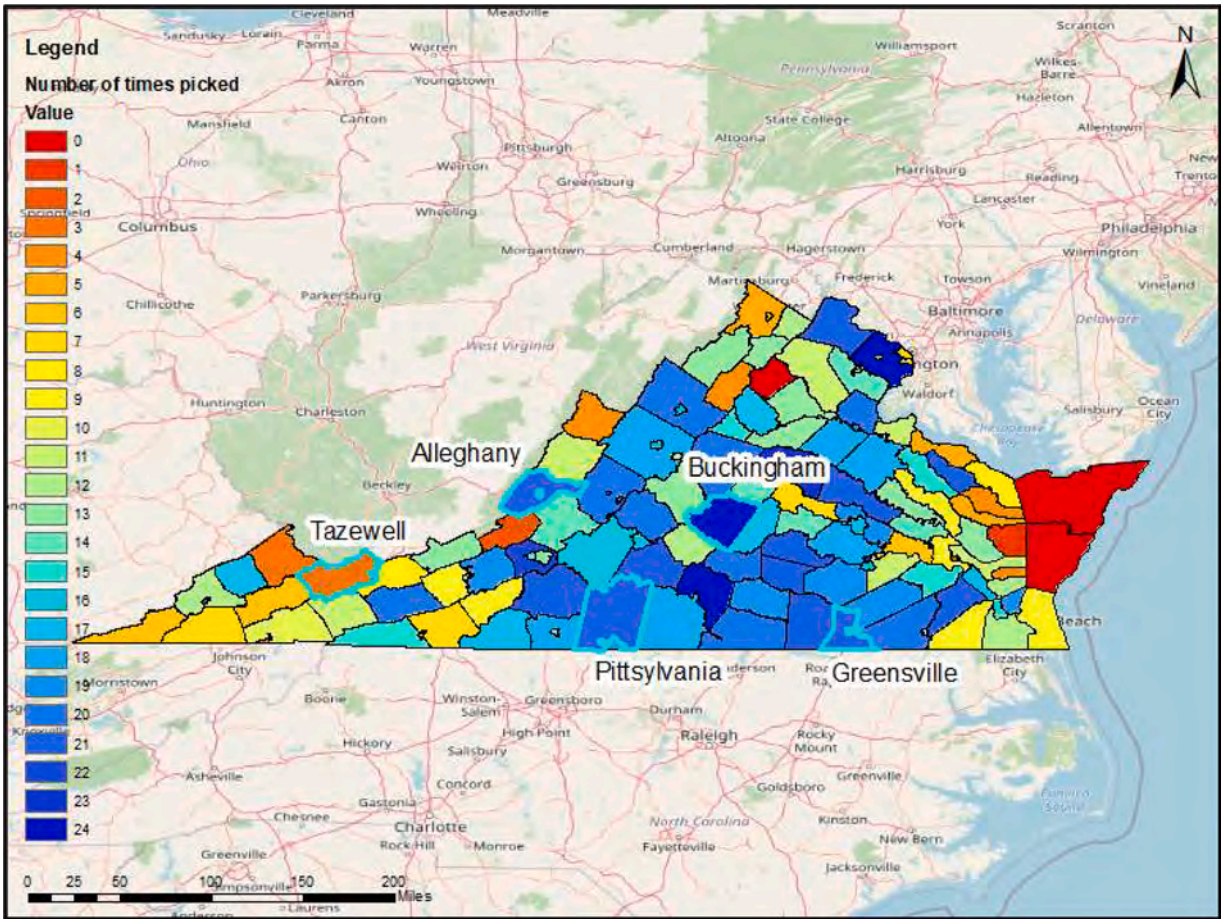

Fig. 2. County prioritization based on the frequency of selection for implementation of a SAF production facility in randomized FTOT runs. Blue outlining denotes counties selected for subsequent ASCENT modeling.

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. Finally, Alleghany County was chosen instead of Roanoke County because of Roanoke's lack of available feedstock, and Fairfax County was not chosen because of high property values.

3.1.2. Municipal solid waste feedstock

Three landfills were analyzed for potential co-location of a pilot SAF production facility consuming MSW feedstock, because it was assumed that siting SAF production facilities at currently existing landfills 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 (Fig. S2). These facilities were selected due to their large sizes and appreciable 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.

3.1.3. Pilot vs. mature facility locations

The selection of five hypothetical processing locations for woody waste (one each in Alleghany, Buckingham, Greensville, Pittsylvania, and Tazewell counties) and three for MSW (at the three selected landfill locations) would not fully consume all available feedstock of either type. 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. It was anticipated that 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

Table 2 summarizes anticipated SAF prices for each of the five hypothetical, pilot-scale GFT facilities consuming woody waste feedstock, assuming three different facility sizes and accounting for possible pipeline ("PL") access at one location. These initial cost estimates corresponded to pilot facilities because SAF production has not yet been commercialized in Virginia. Table 2 also provides information about what geographic area provides feedstock and what fraction of overall statewide fuel demand could be met by each individual facility. Although it was initially anticipated that different county locations would give rise to different MPSP values, corresponding to differences in feedstock and fuel transportation costs, there was no dramatic variability in SAF production cost among the five selected counties. There was much greater variability in MPSP based on facility size, whereby larger facilities exhibited lower SAF production costs. This outcome illustrates appreciable economies of scale and reveals that conversion cost, rather than transportation, most strongly drives variability in SAF production cost. This result may be unique to Virginia, insofar as biomass availability is relatively well distributed over the study area. Finally, it was anticipated that pipeline access would reduce SAF MPSP

Table 2
Estimated SAF production costs for individual hypothetical pilot-scale facilities making use of GFT and woody waste feedstock.

Size	County	Pilot plant ($/gal)	Area of feedstock range (sq. mi.)	% of Dulles demand [1]	% of Virginia 2019 consumption [2]	Average cost ($/gal)
500 K tonnes/yr	Alleghany	12.48	3149	3.4 %	1.5 %	12.47
	Buckingham	12.46	2592			
	Greensville	12.41	1442			
	Pittsylvania	12.47	2651			
	Pittsylvania w PL	12.42	2652			
	Tazewell	12.59	5180			
1.0 M tonnes/yr	Alleghany	11.14	6834	6.9 %	3.0 %	11.11
	Buckingham	11.07	3950			
	Greensville	11.04	3742			
	Pittsylvania	11.10	4801			
	Pittsylvania w PL	11.05	4801			
	Tazewell	11.23	10,305			
1.5 M tonnes/yr	Alleghany	10.55	9341	10.3 %	4.5 %	10.51
	Buckingham	10.46	6515			
	Greensville	10.44	5914			
	Pittsylvania	10.50	6364			
	Pittsylvania w PL	10.45	6365			
	Tazewell	10.64	13,850			

[1] Demand at Dulles International Airport (IAD) is based on correspondence with the airport [25].
[2] Virginia 2019 consumption is from EIA [10].

by reducing transportation costs. However, no appreciable difference in SAF MPSP was observed between the cases with and without pipeline transport for Pittsylvania County. This outcome is attributed to the relatively small fraction of overall cost arising from transportation rather than conversion. Even so, the use of pipelines to transport SAF from production facilities to the demand node at Dulles Airport would have significant benefits that are not captured in this analysis; e.g., minimizing additional truck transport on existing roadways in Virginia. These benefits were of significant interest to VDOT and other stakeholders engaged in this work [52].

Pittsylvania County's results were further analyzed to understand apportionment of the overall price per gallon among constituent steps of the SAF life cycle. This county was selected as a representative case because it corresponded to the median (middle) SAF production cost from Table 2. Three different hypothetical facility sizes were evaluated (500 K, 1 M, and 1.5 M tonnes per year). Total production cost was broken down into four components: feedstock pre-processing, feedstock transportation, conversion, and fuel transportation costs (with and without assumption of fuel transport via pipeline [PL]) (Fig. 3A). It was also of interest to apportion overall GWP by life-cycle stage; 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 (Fig. 3B). Conversion and fuel transportation did not change as facility size changed because CORSIA does not provide this information; however, feedstock transportation costs increased with increasing facility size due to the expanded distance of transport required to collect feedstock from a larger radius surrounding each facility.

From Fig. 3, conversion accounted for most of the production cost (74–78 %) and GWP (79–84 %) for GFT conversion of woody waste feedstocks in pilot facilities. There was an appreciable impact of facility size on production cost, whereby increased size was associated with decreased cost, but virtually no influence on GWP. Finally, the estimated SAF production cost for this platform ($10.45–12.47/gal) is significantly higher than the historical price of fossil jet fuel ($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) [15].

3.2.2. *Pilot MSW facilities*

It was also of interest to analyze GFT conversion of MSW. Table 3 summarizes SAF production cost for three hypothetical GFT facilities co-located at existing mega-landfills, including one location with possible pipeline access (Amelia County). Feedstock transportation cost was assumed to be zero because the MSW would be transported to the landfill even in the absence of SAF production. Therefore, variability in SAF production cost by county in Table 3 is entirely due to differences in conversion cost arising from differences in facility size (i.e., different waste availability at each location gives rise to different SAF production capacity). The largest facility (Sussex) exhibited the lowest expected fuel cost ($6.05/gal). Even so, there was very little variability among estimated SAF costs by county computed in this analysis.

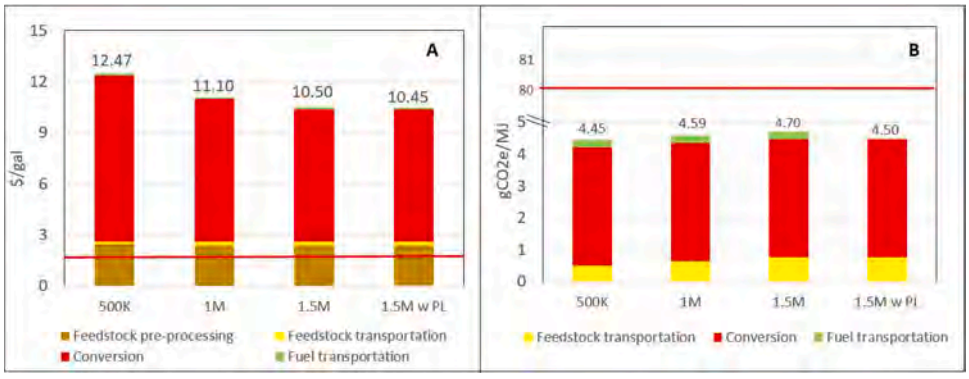

Fig. 3. Production cost **(panel A, left)** and GWP **(panel B, right)** for three different sizes of pilot-scale GFT facilities consuming woody waste feedstock, as broken down by life cycle stage.

Table 3
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 S1 in SI).

County	Size (t/yr)	Pilot plant ($/gal)			Middle case with pipeline ($/gal)	% of Dulles demand	% of Virginia 2019 consumption
		Best case	Middle case	Worst case			
Amelia	960K	3.88	6.12	7.71	6.03	13.5 %	5.9 %
Charles City	650K	4.07	6.34	7.93	NA	9.2 %	4.0 %
Sussex	1.19M	3.81	6.05	7.64	NA	16.7 %	7.3 %

Table 3 also includes best-, middle-, and worst-case SAF production cost estimates for individual production facility locations. These values bound the wide variability in SAF costs arising from wide variability in MSW feedstock cost. There was a wide range of MSW feedstock prices reported in existing literature, corresponding to variability in quality (e.g., with and without pre-processing to recover valuable materials). It was difficult to interpret existing tipping fee information since it was often not evident whether the costs accounted for various kinds of pre-processing that could strongly influence conversion into SAF (e.g., it was unclear whether compostable materials had been already removed at each target landfill location). Table S1 provides additional information about MSW feedstock costs and how they influence overall SAF production cost estimates. Future work should refine MSW cost estimates by locality, potentially via survey of landfill operators, since such information will strongly influence the location of SAF production facilities. Finally, Table 3 presents contextualizing information for each hypothetical SAF production facility, including what fraction of demand at Dulles Airport or across the state could be met by each individual hypothetical facility. Fig. 4A shows apportionment of SAF production cost by life-cycle stage for GFT conversion of MSW feedstock for each hypothetical landfill SAF production facility, including one candidate location with pipeline access. Fig. 4B shows corresponding apportionment of GWP. The inclusion of combustion-phase GWP emissions is required under the CORSIA framework for MSW because it is assumed that MSW contains non-biogenic carbon content. For this analysis, 10–15 % non-biogenic carbon was assumed. In contrast, it was 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 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 node. Results in Fig. 4 do not account for avoidance of landfill emissions. Accounting for this possible benefit would decrease GWP values in Fig. 4B by approximately 38 g CO_2e/MJ, thereby yielding total life-cycle GWP of approximately −16.4 CO_2e/MJ. These credits were not included in the current study because there is not currently a mechanism for obtaining landfill gas credits in Virginia unless bioelectricity is produced [53]. From Fig. 4, 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 GWP.

Comparing results in Table 2 vs. Table 3 and Fig. 3 vs. Fig. 4, it is evident that GFT produces lower-cost SAF for MSW relative to woody waste, but neither feedstock results in SAF that is cost-competitive with fossil jet fuel. This trend is reversed for GWP, whereby GFT of MSW yields higher-GWP SAF relative to woody waste. Thus, there is a tradeoff between cost and GWP when comparing GFT processing of these two feedstocks. Even so, is notable that both GFT feedstocks produce SAF with GWP lower than the CORSIA cutoff, even without accounting for landfill emission avoidance credits [15].

3.2.3. *Longer-term projections: networks of mature facilities*

The ASCENT TEAs can also estimate SAF production costs over longer time horizons by accounting for maturation of supply chains and conversion technologies, which will ultimately lead to lower SAF production costs over time. After examining results for pilot GFT conversion facilities, it was also of interest to examine how hypothetical networks of SAF production facilities would perform once the technology had become mature. For these analyses, feedstock and fuel transportation optimization was repeated in FTOT, again considering the known location of each feedstock and the desired demand node at Dulles Airport, but with many possible locations for production facilities (up to one per county). For these model runs, the tool was constrained to use all available feedstock of each type.

Fig. 5A shows the network of eight 1.0 M-tonne/year SAF production facilities arising from FTOT modeling for the woody waste feedstock. 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; and Greensville was selected in both analyses (pilot and mature). This close correspondence means that all of the locations that are 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

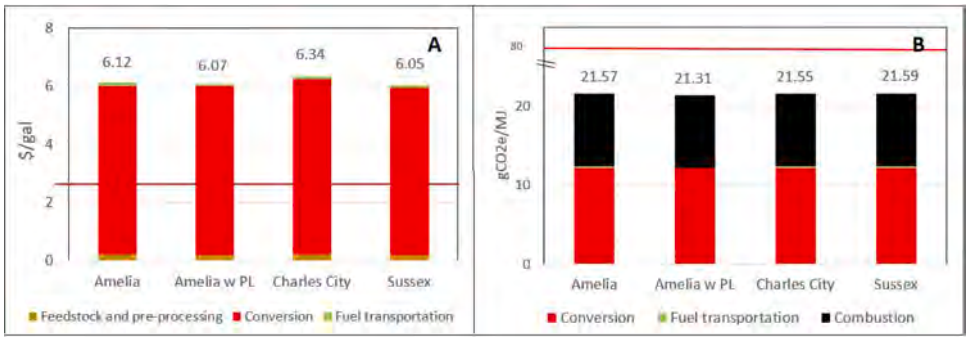

Fig. 4. Production cost **(panel A, left)** and GWP (**panel B, right**) for three different pilot-scale GFT facilities operating at various landfill locations and consuming MWS feedstock. Results are broken down by life cycle stage.

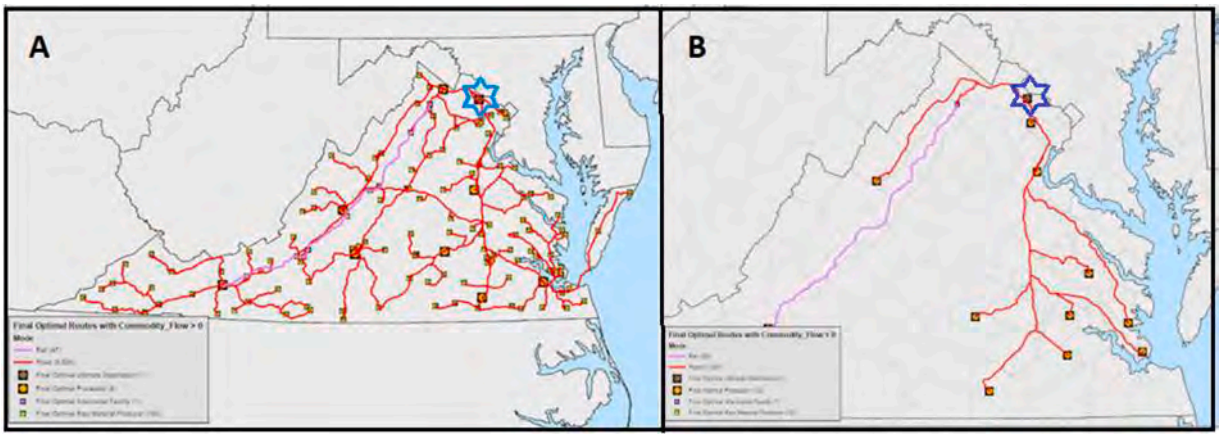

Fig. 5. (Panel A, left) The proposed network of mature SAF production facilities via GFT conversion of woody waste feedstock at 1.0 M tonnes/yr. (Panel B, right) The proposed network of mature SAF production facilities for GFT conversion of MSW feedstock. In both panels: blue star denotes SAF demand node at IAD; pink links correspond to railways, and red links correspond to roadways (trucking).

calculated for the pilot facilities; however, the projected cost is still nearly $5/gal higher than the historical average cost for fossil jet fuel.

The total amount of SAF that could be produced per year in the proposed eight-facility network would account for slightly less than 55 % of IAD's recent historical fuel demand. With 50:50 blending, this amount of SAF would be adequate 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 assumption is likely unrealistic, given the demand from other industries and that 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 conversion of MSW feedstock for the technologically "mature" scenario. It was again assumed that SAF production facilities would be co-located at landfills. A list of candidate 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), accepting at least 100,000 tonnes of MSW per year. Based on these criteria, there are 12 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 (Fig. 5B). FTOT modeling was constrained to require that all available MSW feedstock from these locations be consumed to produce SAF.

Best- and worst-case estimates for SAF production cost were $1.58 and $5.37/gal, respectively. These ranges reflect significant uncertainty and/or variability in MSW feedstock prices, contributing to high variability in projected SAF production costs. The averaged SAF production cost for this network ($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 over the period 2009 to 2018 ($2.22 ± 0.67 /gal). Notably, the modeling performed in this study assumed that landfill operators and/or local municipalities would approve the construction of a SAF production facility at the candidate sits and that sufficient land would be available at each location. These assumptions should be validated in future work.

The total amount of SAF that could be produced per year in the proposed twelve-facility network would correspond to 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 it is realistic to imagine that all MSW could be diverted to SAF production.

3.3. Pyrolysis

3.3.1. Pilot woody waste facilities

Pyrolysis was also analyzed as a possible SAF production pathway. This process is not yet an ASTM-certified or CORSIA-approved pathway for SAF production; however, the ASTM certification process is underway [54]. 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.

Table 4 summarizes estimated SAF production costs for five hypothetical county locations of interest assuming three possible facility sizes. It is also assumed that one county location could make use of an existing pipeline to transport the SAF to the IAD demand node. As with GFT, slight variability in production cost was observed for different county locations, reflecting differences in feedstock and fuel transportation costs. However, the variability arising from location was once again much smaller than the variability induced by facility size.

Results of the median case, again Pittsylvania County, were broken down by life cycle stage to understand the apportionment of the overall price per gallon (Fig. 6A). From these results, conversion again accounts for most of the overall cost (72–74 %). These results also show that the MPSP of SAF produced from pyrolysis of woody wastes ($7.95–8.44/gal) is significantly higher than the historical price of fossil jet fuel. GWP results were similarly apportioned by life cycle stage (Fig. 6B). Taken together, the apportionment of production cost and GWP is helpful to understand how the breakdown of economic and environmental impact by production stage and across production facilities of varying 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. Table 5 summarizes results of the analysis for pilot-scale pyrolysis of MSW. Because this yield is appreciably lower than for pyrolysis of woody waste, the SAF production cost for pyrolysis of MSW is significantly higher. As with GFT of MSW, the wide uncertainty in MSW feedstock cost translates to correspondingly wide uncertainty in SAF production cost. Variability in location and size of the co-located landfills further contributes to the wide range of MPSP estimates for this pathway. The full range of MPSP estimates is as low as $5.49 and as high as $17.01/gal. Additional information about GFT of MSW

Table 4
Estimated SAF production costs for individual hypothetical pilot-scale facilities making use of pyrolysis and woody waste feedstock.

Size	County	Pilot plant ($/gal)	Area of feedstock range (sqmi)	% of Dulles demand [1]	% of Virginia 2019 consumption [2]	Average cost ($/gal)
500 K tonnes/yr	Alleghany	8.45	3149	4.06 %	1.78 %	8.44 %
	Buckingham	8.42	2592			
	Greensville	8.39	1442			
	Pittsylvania	8.44	2651			
	Pittsylvania w PL	8.39	2651			
	Tazewell	8.54	5180			
1.0 M tonnes/yr	Alleghany	8.19	6834	8.13 %	3.57 %	8.16 %
	Buckingham	8.13	3950			
	Greensville	8.10	3742			
	Pittsylvania	8.15	4801			
	Pittsylvania w PL	8.10	4801			
	Tazewell	8.26	10,305			
1.5 M tonnes/yr	Alleghany	8.05	9341	12.19 %	5.35 %	8.01 %
	Buckingham	7.96	6515			
	Greensville	7.95	5914			
	Pittsylvania	8.00	6364			
	Pittsylvania w PL	7.95	6364			
	Tazewell	8.12	13,850			

[1] Demand at Dulles International Airport (IAD) is based on correspondence with the airport [25].
[2] Virginia 2019 consumption is from EIA [10].

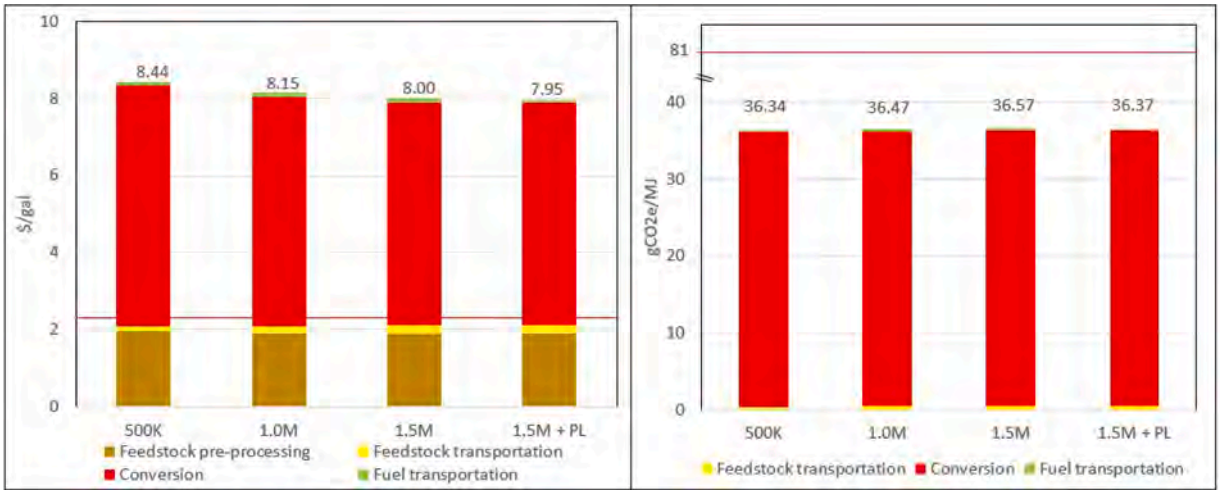

Fig. 6. Production cost **(panel A, left)** and GWP (**panel B, right**) for three different sizes of pilot-scale pyrolysis facilities consuming woody waste feedstock, as broken down by life cycle stage.

Table 5
Estimated SAF production costs for individual hypothetical pilot-scale facilities making use of pyrolysis and MSW feedstock Best case refers to lower feedstock cost and higher recoverability; worst case refers to higher feedstock cost and lower recoverability.

County	Size (t/yr)	Pilot plant ($/gal)			Close to pipeline (Y/N)	Middle case with pipeline ($/gal)	% of Dulles demand	% of Virginia 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 %

calculations can be found in SI Section S.2.

The estimated GWP for a pilot MSW pyrolysis facility was approximately 44.0 g CO_2e/MJ, without accounting for landfill emissions avoidance credits (see SI Fig. S3). This estimate corresponds to an emissions reduction of approximately 51 % compared to fossil jet fuel, which suggests that pyrolysis of MSW should easily qualify as a CORSIA-eligible fuel but would not necessarily qualify as SAF under the IRA. Including the 38 g CO_2e/MJ landfill emissions credit calculated in this study would decrease the GWP to approximately 6 g CO_2e/MJ, which would qualify as SAF under the IRA. Finally, this study did not include possible GWP offsets associated with the beneficial reuse of biochar that is co-produced with SAF during pyrolysis of organic materials. 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 even less carbon-intensive; however, because a robust market for biochar does not currently exist in Virginia, and recent related work has not accounted for sale of carbon offsets for biochar [43], char credits were not included in 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 maturation of the pyrolysis technology and its local feedstock supply chains would lead to lower SAF prices over time. Fig. S4 shows a network of eight 1.0 M-tonne/yr SAF production facilities arising from FTOT modeling under a mature technology scenario. The selected county locations are as follows: Augusta, Caroline, Charlotte, Culpeper, Franklin, Giles, Greensville, and Prince George. Again, several of these eight locations are closely aligned with the five counties selected during 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; and Prince George is very near to Greensville. This correspondence, which was also observed for the GFT pilot and maturity scenarios, 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 median-case pilot facility; however, this value is still $3.32 above the fossil jet fuel benchmark. 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.

The modeling of pyrolysis of MSW feedstock used the same landfill location assumptions as for GFT. The proposed network therefore looks identical to Fig. 5B. The average MPSP over the twelve facilities is $7.48/gal, with best- and worst-case estimates of $1.44 and $11.72/gal, respectively. As with GFT, this wide range arises from significant variability in MSW feedstock quality and cost. The median case ($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 fossil jet fuel benchmark. Pyrolysis of MSW is significantly more costly than GFT per gallon of SAF produced primarily because of the lower yield rate. MSW is a heterogenous feedstock, and pyrolysis can only convert specific feedstock constituents (principally cellulose and lignin) into bio-oil.

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 additional financial incentives. It was therefore of interest to assess how differently structured state incentives could influence that cost comparison. This analysis was performed for GFT and pyrolysis of woody waste feedstock, excluding the MSW feedstock due to its wide variability in composition and cost. It was anticipated that variability in MPSP arising from variability in MSW feedstock assumptions would obscure meaningful interpretation of results from the incentive analysis.

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 used as a case study to analyze how differently structured state incentives could affect the MPSP of SAF. Fig. 7A shows the range of MPSPs computed for several scenarios: without financial incentives, with accumulating existing federal incentives, and with several kinds of hypothetical state incentives. MPSP values for scenarios incorporating each of these incentive structures ranged from $5.21–6.09/gal. The total value of the hypothetical state incentive was fixed at $350 million, but several possible structures were evaluated; i.e., feedstock subsidy, interest rate reduction, capital grant, or a Low Carbon Fuel Standard (LCFS)-style strategy. Among these, the LCFS-style incentive (right side of the yellow line in Fig. 7A) is unique, insofar as the state 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 (Fig. S7). 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 ranking of cost reduction magnitudes was the same as shown in Fig. 7A; i.e., feedstock subsidy $\lessapprox$ risk reduction $\lessapprox$ state capital grant. At a hypothetical state investment of $70 million, MPSP ranged from $5.21 - $6.42/gal (Fig. S7). At $585 million, MPSP was reduced to $5.08 - $5.81/gal (Fig. S7). 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.

The investment analysis was also applied to a state-wide mature pyrolysis technology scenario to see how impactful different incentives would be in the longer-term future. As with the pilot analysis, a uniform hypothetical investment of $350 million was applied, as structured into four different formats. However, it was assumed that this investment would be apportioned across the entire network of facilities; i.e., when

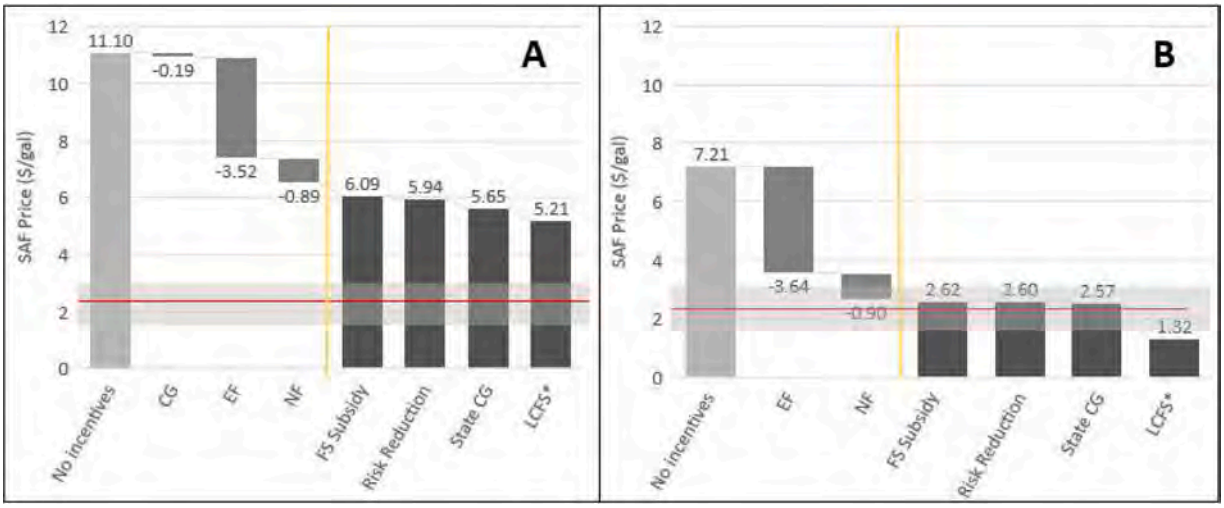

Fig. 7. Waterfall graph showing baseline cost per gallon plus accumulating price reductions corresponding to existing federal incentives (GC, EF, NF) and hypothetical state incentives (right side of yellow vertical line): **Panel A (left)** shows results for pilot-scale GFT of woody waste. **Panel B (right)** shows results for mature-scale GFT of woody waste. Light gray shading shows historical average price per gallon fossil jet fuel ± 1 standard deviation. For full caption details, see Fig. S5 in SI.

eight facilities are constructed, each receives 1/8 of the total investment. Fig. 7B 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.

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. Fig. 8A shows example MPSPs ranging from $2.83 - $3.29/gal after accounting for a federal capital grant, previously existing federal incentives, 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 the 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. Fig. 8B 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.

3.4.3. Insights from comparisons

For easy summary and comparison of key production cost results, Fig. 9 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 will require additional incentives, while mature facilities will 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) [30,31]. Second, GFT has higher operating costs than pyrolysis ($288.5 million vs. $278.1 million for a 1.0 M-tonne facility) [30,31]. Finally, pyrolysis has higher assumed yields than GFT, leading to more SAF per tonne of feedstock.

Because pyrolysis was found to produce lower-cost SAF in this analysis, it would seem to be the preferred 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. The existing federal incentives, most notably RINs and basic blender tax credits (BTCs), focus primarily on decreasing SAF price per gallon without meaningful emphasis on aligning economic and environmental performance. The IRA, however, includes a BTC based on GWP reduction relative to a fixed baseline. Even so, results from this study reveal that the new IRA incentives do not influence the financial comparison of GFT versus pyrolysis to any practical degree. 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 1 % reduction beyond 50 %, leading to a maximum of $1.75/gal for an emissions-free fuel [45]. This framing is meant to motivate lower-carbon pathways, (e.g., GFT conversion of woody waste over pyrolysis), but $0.01 per 1 % is not nearly enough to close the price gap observed in this study. 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 by SAF industries and stakeholders [55], but more aggressive alignment of environmental and economic priorities is still needed.

If the state and/or federal government is serious about promoting

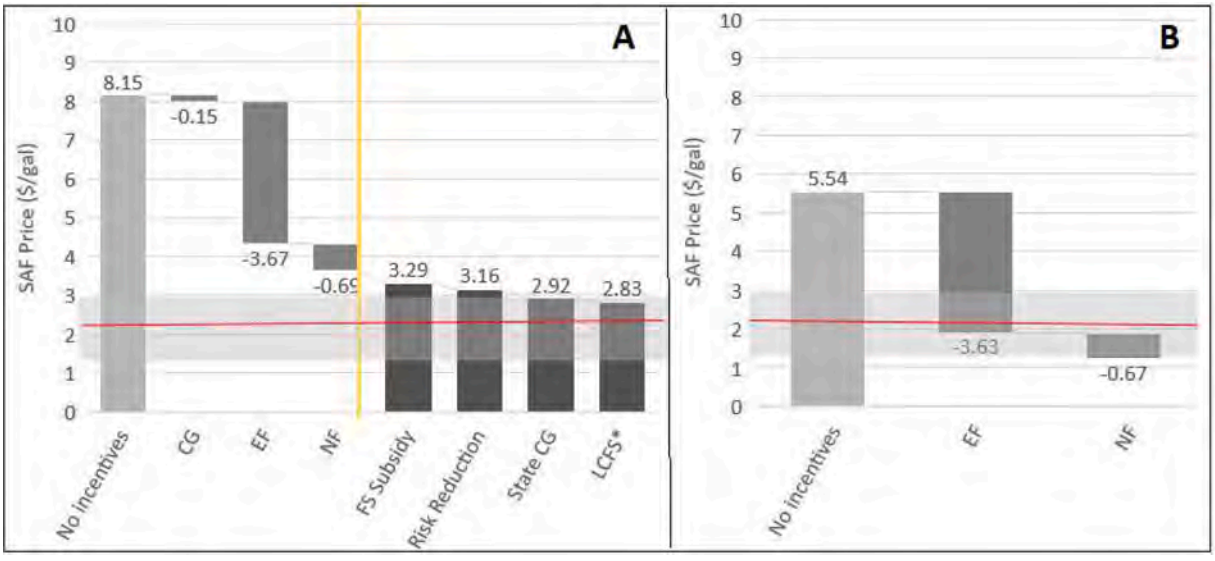

Fig. 8. Waterfall graph showing baseline cost per gallon plus accumulating price reductions corresponding to existing federal incentives (GC, EF, NF) and hypothetical state incentives (right side of yellow vertical line): **Panel A (left)** shows results for pilot-scale pyrolysis of woody waste. **Panel B (right)** shows results for mature-scale pyrolysis of woody waste. Light gray shading shows historical average price per gallon fossil jet fuel ± 1 standard deviation. For full caption details, see Fig. S6 in SI.

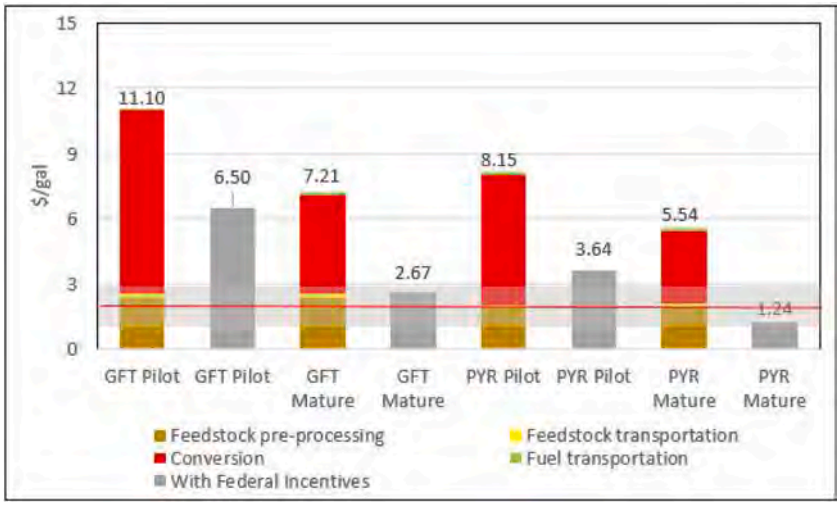

Fig. 9. Comparison between GFT and pyrolysis of woody waste feedstock; whereby, pilot results correspond to a 1.0M-tonne/yr pilot facility in Pittsylvanio County, and mature results represent average cost of output from eight hypothetical 1.0M-tonne/yr facilities.

pathways with lower GWP, a stronger system is needed; e.g., California's LCFS. At a minimum, future policies should have a larger supplementary amount than what is currently available under the IRA. Based on observed results for GFT and pyrolysis, it is estimated that the incremental incentive need to be a least $0.18 for every 1 % reductions beyond 50 % in order for GFT and pyrolysis to breakeven on cost basis (see Fig. S7). This amount is significantly more than the existing incremental incentive, and it would lead to a BTC of $8.70/gal for GFT and $3.12/gal for pyrolysis. Absent these changes to existing policy, pyrolysis is economically but not environmentally preferred over GFT.

3.5. Carbon capture and storage potential

It is also of interest to analyze what role carbon capture and storage (CCS) could play in improving the environmental and/or economic performance of SAF production facilities. Passage of the IRA also changed the landscape for decarbonization incentives including CCS [51]. Therefore, the modeling approach from a recent study of SAF production plus CCS [49] was adapted to assess how adoption of CCS would change the estimated SAF GWP and production cost for a representative case evaluated in this study. In particular, the CCS scenario was applied to a mature hypothetical woody waste GFT facility in Pittsylvania County. Accounting for CCS reduces life-cycle GWP for this case to −133.24 g CO_2e/MJ, making SAF production appreciably net carbon-negative. The corresponding cost increase is $14.50 per tonne CO2 sequestered. Per Michaga et al. [49], 1 tonne of CO_2 is sequestered per approximately 60 gallons of SAF produced, such that the value of CO_2 sequestration credits expressed on a per-gallon basis is about $1.17/gal SAF. Using this value, the estimated MPSP for the woody waste GFT case decreases to a value of $1.50/gallon. This price is for the mature scenario and accounts for existing federal incentives but no additional state-level incentives. Thus, addition of CCS is a potentially appealing option to reduce the production cost and CO2 intensity of SAF.

4. Conclusions and future work

The results from this study are not meant to be specific predictions of what *should* happen concerning future SAF production in Virginia, but rather to illustrate what environmental and economic performances *could* be achieved if different technologies are implemented at different scales in different locations. The overarching outcome is that state incentives will be necessary to make SAF cost-competitive with fossil jet fuel in the near-term future while technologies are operating at pilot scale. Another key finding is that transportation costs do not vary to any appreciable degree across candidate production sites within Virginia and that transportation accounts for a relatively small fraction of the overall SAF production cost for all four evaluated pathways included in this study. The amount of state subsidy required to make SAF cost-competitive with fossil jet fuel is therefore nearly uniform across all candidate production sites. In contrast, required incentives are larger for GFT compared to pyrolysis. A third key finding is a tradeoff between production cost and life-cycle greenhouse gas emissions, whereby pyrolysis exhibits lower MPSP but higher GWP than GFT. This tradeoff is not meaningfully mitigated by existing federal incentives including recent IRA provisions. State policymakers should therefore also consider how new incentives could offer better alignment of economic and environmental priorities by offering greater incentives to pursue aggressive emissions reductions. Finally, although this study focused on Virginia as a case study, the methodological approach is generalizable and applicable to other jurisdictions, leveraging open-access modeling tools and datasets that could be easily replicated for decision support.

CRediT authorship contribution statement

Curtis D. Davis: Writing – original draft, Methodology. **Shravan Sreekumar:** Methodology. **Richard Altman:** Supervision, Conceptualization. **Andres F. Clarens:** Writing – review & editing, Supervision, Conceptualization. **James H. Lambert:** Writing – review & editing, Supervision, Conceptualization. **Lisa M. Colosi:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Lisa M. Colosi reports financial support was provided by Virginia Transportation Research Council. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jfueco.2024.100114.

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