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Research Article

Techno-Economic Feasibility and Spatial Analysis of Thermochemical Conversion Pathways for Regional Poultry Waste Valorization

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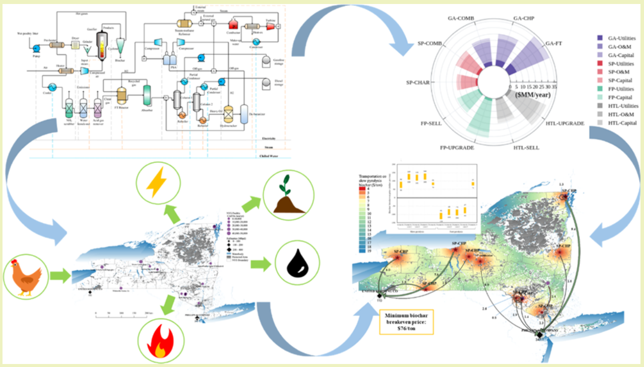

ABSTRACT: This study examines prominent thermochemical conversion technologies, such as slow pyrolysis, fast pyrolysis, gasification, and hydrothermal liquefaction, for treating poultry litter in New York State (NYS). Nine cases involving combinations of the four technologies and different downstream processing options such as bio-oil upgrading and Fischer−Tropsch conversion are chosen based on the product distribution. High-fidelity process simulations are performed to derive the mass and energy balance. Economic performance for the nine cases varied widely with largely overlapping net present values, ranging from \$10MM to \$170MM (slow pyrolysis), \$89MM to \$314.5MM (fast pyrolysis), \$28MM to \$196MM (hydrothermal liquefaction), and \$25MM to \$234MM (gasification). Both pyrolysis technologies had 18% to 56% lower greenhouse gas (GHG) emissions than the other technologies. GHG balances showed trade-offs with economic performance. Sensitivity analysis identified carbon credits, products' market price, and plant capacity as the most influential factors. Building one centralized biorefinery in NYS especially for fast pyrolysis was more economically feasible than building multiple smaller biorefineries (biochar breakeven price of −\$128 to −\$91/ton vs \$74 to \$93/ton). The trend for slow pyrolysis was similar but with comparatively little difference (biochar breakeven price of \$59 to \$96/ton for one biorefinery vs \$76 to \$91/ton for multiple biorefineries).

KEYWORDS: *spatial analysis, poultry litter, pyrolysis, gasification, hydrothermal liquefaction, New York State*

INTRODUCTION

With the exponential rise in human population over the past few decades, there has been a corresponding surge in the consumption of resources and generation of waste streams around the world.[1,2] Some of the major waste streams include wastewater sludge, municipal solid waste, dairy manure, and poultry manure, among others.[3−6] Most solid waste streams are either landfilled or incinerated with an associated transportation and disposal cost, in addition to environmental concerns, such as air pollution, leaching of toxic elements, soil fertility reduction, and nutrient losses.[7−11] Alternatively, organic fecal wastes with high nutrient contents [nitrogen (N), phosphorus (P), and potassium (K)] are often directly applied to croplands owing to their potential benefits in terms of soil fertility.[12,13] However, recent studies have shown that this method of disposal does not fare better than the other conventional methods, with over-application of wastes such as dairy manure and poultry litter leading to eutrophication of water bodies, and the risk of biomagnification of antibiotics or other harmful chemicals in the food chain.[14−16] Thus, there is an urgent need to find a more sustainable option for disposing organic wastes like poultry litter and minimizing public health risks through possible pathogens in the wastes, while ensuring maximum recovery of valuable products simultaneously.

Thermochemical technologies such as pyrolysis, hydrothermal liquefaction (HTL), and gasification (GA) are now being considered as alternatives to conventional biological and thermal methods for treating organic waste streams owing to their potential to do so with minimum environmental impact.[17−24] Additionally, they have proven to be conducive to nutrient recycling and energy generation as a result of their valuable products.[17] Despite the various options available and the multiple products produced, the conditions under which

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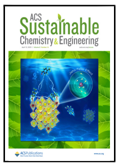

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Table 1. Different Cases Analyzed in This Study Based on Choices for Downstream Processing Options

no.	abbreviation[a]	output from main reactor	gas phase	bio-oil phase	aqueous phase	solid phase	main sources of revenue
1	GA-FT	syngas, biochar	conversion to fuels	N/A	N/A	land application of biochar	fuels
2	GA-CHP	syngas, biochar	generation of heat and electricity	N/A	N/A	land application of biochar	heat, electricity
3	GA-COMB	syngas, biochar	generation of heat	N/A	N/A	land application of biochar	heat
4	SP-COMB	off gas, bio-oil, biochar	generation of heat	sold to existing refinery	N/A	combustion of biochar	biochar, electricity
5	SP-CHAR	off gas, bio-oil, biochar	generation of heat	sold to existing refinery	N/A	land application of biochar	heat, biochar
6	FP-SELL	off gas, bio-oil, biochar	generation of heat	sold to existing refinery	N/A	land application of biochar	bio-oil, biochar, heat, electricity
7	FP-UPGRADE	off gas, bio-oil, biochar	generation of heat	upgraded to fuels	N/A	land application of biochar	bio-oil, biochar, heat
8	HTL-SELL	off gas, bio-oil, aqueous, biochar	generation of heat	sold to existing refinery	AD	land application of hydrochar	bio-oil, hydrochar
9	HTL-UPGRADE	off gas, bio-oil, aqueous, biochar	generation of heat	upgraded to fuels	AD	land application of hydrochar	fuels, hydrochar

[a] GA stands for gasification, SP for slow pyrolysis, FP for fast pyrolysis, HTL for hydrothermal liquefaction, FT for Fischer Tropsch processing, CHP for combined heat and power generation, COMB for combustion, CHAR for biochar, SELL for selling bio-oil to existing crude refineries, UPGRADE for bio-oil upgrading plant and AD for anaerobic digestion.

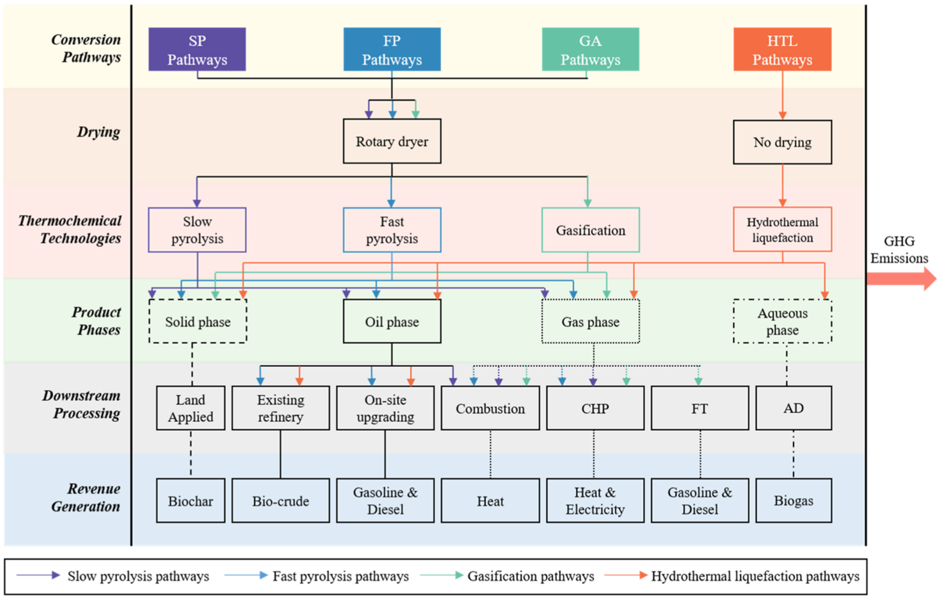


Figure 1. System boundaries for all the conversion pathways based on SP, FP, GA, and HTL technologies. Different colors represent specific technologies as shown in the legend and different line patterns represent the various product phases (as portrayed in the boxes surrounding the "poduct phases" row). Only direct GHG emissions arising from within the processes or their products are considered.

thermochemical technologies would be capable of providing clean, energy-efficient, and reliable alternatives to current biomass-to-energy conversion processes are yet to be determined.[25−33]

In the United States, 50 million tonnes of poultry litter is produced annually, with most of it being either land applied or landfilled.[14] Some states have identified thermochemical technologies to treat a part of their wastes, and they are actively investigating the large-scale application of these technologies.[34] New York State (NYS) is a prime example with a number of policies being deliberated upon currently to tackle organic wastes and produce sustainable energy.[35−37] Because the spatial data for the large poultry farms and the crop fields is also available for NYS, it provides a great opportunity to carry out a spatial analysis for the region to investigate the feasibility of implementing thermochemical technologies, along with the determination of optimal plant capacities. Furthermore, most techno-economic studies assessing thermochemical technologies are found to choose a predetermined downstream processing option for each technology without investigating the impacts for other downstream processing options or locations.[38−41]

Hence, in this study, high-fidelity process simulations for nine different cases based on different downstream processing options for the four prominent thermochemical conversion technologies to treat poultry litter (slow pyrolysis (SP), fast pyrolysis (FP), HTL, gasification) are performed.[42,43] This is followed by a thorough economic analysis with the primary objective to compare the performance of the different technologies. Ultimately, by utilizing results and parameter values from the initial analysis, a spatial analysis with a secondary objective to investigate how pyrolysis technologies would perform if implemented at different scales for NYS is conducted. Novel contributions of this study include the simulation of thermochemical technologies with flexible downstream processing options and detailed spatial analysis case studies presenting the optimal plant locations and capacities for both pyrolysis technologies in NYS.

■ MATERIALS AND METHODS

The simulations for the studied thermochemical conversion technologies—SP, FP, gasification, and HTL—along with their respective cases based on the downstream processing choices are carried out using the Aspen Plus software version 9.[43] More than one case is associated with each of the technologies depending on the proven feasibility and compatibility of a particular processing option with the main products from the individual technologies (Table 1). For instance, the cases for both HTL and FP are based on the best possible pathways for the bio-oil that is produced. Similarly, the cases for SP and GA revolve around the processing of biochar and syngas, respectively. Based on this approach, nine valid cases are identified from these four technologies. The simulations as well as the analysis of each of these cases in terms of economic performance, GHG emissions, variability, and spatial distribution involves numerous parameters and assumptions, as not all data are available at the commercial scale for these technologies. Some of these values are derived through the simulations, whereas others are based on technical government reports and additional literature (more details about the simulations are provided in Section 1 of the Supporting Information and Figure S1 contains select schematic process diagrams).[44,45]

System Boundaries and Assumptions. Because the primary objective of this study is to simulate and analyze different thermochemical processing schemes, the considered systems only involve the processes themselves along with the associated products (Figure 1). Thus, steps involving the rearing of poultry and the production and collection of poultry litter or the photosynthesis capturing the CO_2 through plant growth of the feed are not applicable to this study. Additionally, indirect and embedded environmental impacts of these processes are not analyzed, and only the GHG emissions for each system are compiled, as they could be attributed to a form of revenue or an economic burden either now or in the future (such as carbon credit/tax).

Consideration of Different Operating Scales. The plant capacities and the input feed flowrates for the simulations are based on the available poultry litter data for NYS. The data are either available in the form of a county-level distribution or based on the concentrated animal feeding operations (CAFOs), (which are defined as large farms with more than 1000 animal units or 125 thousand broiler chickens)[46] for poultry litter in NYS (Table S19 provided in the Supporting Information). The latter is selected for this study as the 14 CAFOs are found to produce approximately 175 kilotons of poultry litter per year, which accounts for roughly 63% of the total production in the state. Additionally, they are found to be hotspots in terms of poultry litter density distribution, thus providing ideal locations to build a plant, as against the county centers which would not always have the highest densities owing to much smaller, distributed farms.

Economic Parameters. The estimation of capital cost and operating and maintenance (O&M) cost is carried out based on the process economics analysis results from the Aspen economic analyzer,[47] as well as literature and government reports. Various assumptions are made to accurately calculate these values and other associated costs by allocating certain percentages of the capital costs to land cost, installation cost, start-up cost, and other operating costs. Utility costs are determined based on the simulation results and the current industrial market pricing (Table S9 in the Supporting Information). Similarly, the market values of the various products involved are derived from the literature and updated websites to calculate the revenue generation, and some of these parameters are mentioned in the following Spatial Analysis section.[48−52] Finally, in order to analyze the overall economic performance of the cases, the method of the net present value (NPV) is selected with an assumed plant life of 20 years and an annual discount rate of 5% (which has some uncertainty associated with it and has been included later in the sensitivity analysis).[39] It is also important to note here that there are different levels of uncertainties in terms of the capital, startup, and O&M costs for the various technologies considered. For instance, given the immaturity and the lack of full-scale commercial plants for HTL relative to gasification and fast and SP, the estimated costs for HTL are obviously much more uncertain, and this should be considered while interpreting the results.

Spatial Analysis. To illustrate the economics of both centralized and distributed design of the pyrolysis biorefineries, a case study for CAFOs in NYS is presented. Only slow and FP technologies are considered in this spatial analysis study because HTL has not been able to reach industrial scale production yet and there is still some uncertainty associated with its simulations and economic data. Additionally, it is more suitable for wetter feedstocks as compared to the relatively dry poultry litter (less than 25% moisture content). Furthermore, both HTL and gasification with their higher capital costs would require plants of a larger scale as compared to the distributed systems considered in this analysis.[53] The following sections provide details about the technical and economic parameters and constraints used in this study, as well as the selection of different scenarios and cases for NYS.

Associated Parameters and Constraints. The poultry CAFO data are collected from the NYS Organic Resource Locator[54] and presented in Figure S3 in the Supporting Information. It is assumed that the pyrolysis biorefineries can only be built on the CAFOs themselves to minimize transportation of the poultry litter as explained in an earlier section. Additionally, all of the poultry litter feedstock generated by the 14 poultry CAFOs is utilized in the case study. The minimum capacity of a SP biorefinery and a FP biorefinery is assumed to be 4.38 and 8.76 kton/year, respectively, which corresponds to an input feed rate of 0.5 and 1 ton/h, respectively. Any biorefinery smaller than these minimum capacities for this study would prove to be economically infeasible. Along similar lines, the minimum capacity of a CHP unit in a SP biorefinery and a FP biorefinery is assumed as 4.60 and 3.68 kton/year, respectively, and these correspond to production of 0.5 and 0.25 MW of electricity in that order.[55] Based on these constraints, it is found that all FP biorefineries in our system can process the pyrolysis gas through CHP, to generate heat to offset part of the O&M cost and to produce electricity to generate additional revenue. The bio-oil can either be upgraded on-site or sent to an existing crude refinery (Table S22 in the Supporting Information), and the biochar is to be applied on corn cropland (Table 1, Section 2 in the Supporting Information).

Choice of Scenarios and Cases for the Spatial Analysis. In this case study, three scenarios for both slow and FP technologies are chosen (Table S3 in the Supporting Information). Scenario 1 involves building only one pyrolysis biorefinery for the entire NYS. According to the CAFO data,[54] the overall estimated poultry manure generated through NYS's CAFOs is 175.3 kton/year, and thus, that is chosen as the capacity for the pyrolysis biorefinery in Scenario 1. This scenario takes advantage of the economy of scale that helps to reduce the unit production costs, but the transportation costs of both feedstock and products is expectedly higher. In scenario 2, the construction of two biorefineries for both slow and FP is considered. This scenario is chosen to highlight the trade-offs between centralized and distributed systems,[56] with impacts on the transportation costs as well as investment costs. In order to further investigate the economic performance of scenario 2, three different combinations of capacity levels for the two biorefineries are assigned (150, 120, and 90 kton/year for the first biorefinery, and 25.3, 55.3, and 85.3 kton/year for the second biorefinery, respectively). Scenario 3 is designed to minimize the transportation of poultry litter. Based on the previously defined cutoffs for building a pyrolysis biorefinery, the scales of some CAFOs are found to be too small to build a biorefinery, and hence, it is still

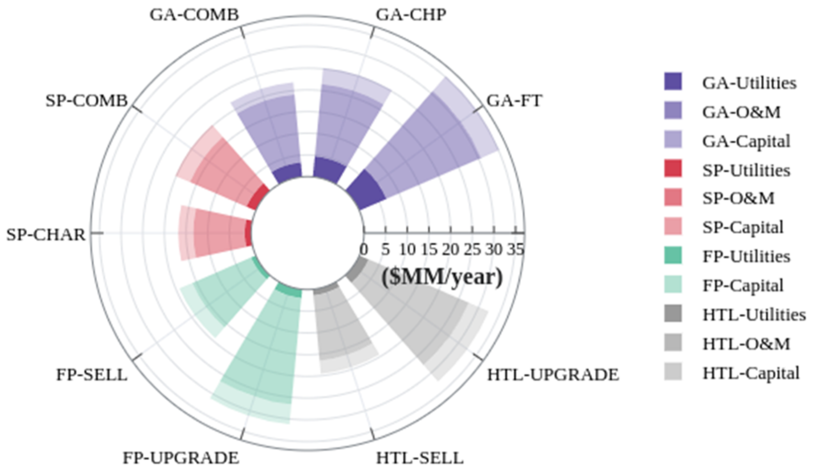


Figure 2. Rose diagram for comparison of total annualized costs as well as their breakdown for each system. The comparison of total annualized costs for each system can be done by considering the entire height of the bars. Each technology is represented by different colors as indicated in the legend. The breakdown for each case into utility costs, O&M costs, and capital costs can be seen through different shades of the respective base colors.

necessary to transport poultry litter from those CAFOs to their nearest biorefineries. Consequently, there are 10 biorefineries for scenario 3 of SP but only 8 biorefineries for FP due to the different cutoffs for building slow and FP plants. It is worth mentioning that due to the difficulty in estimating the transportation cost for biochar, it is excluded from the consideration of the biorefinery location and the NPV is calculated with the premise of trading biochar without transportation. Biochar breakeven price is subsequently calculated to illustrate the biochar application throughout the NYS.

■ RESULTS AND DISCUSSION

Once the Aspen Plus simulations were completed and found to be comparable with experimental studies, the results of those simulations were used as the basis for the economic and spatial analysis (additional details in Section 1 of the Supporting Information).[57] The selection and economic analysis of the nine different cases allows comparison not only between the four thermochemical conversion technologies but also within the same technologies with selection of different downstream processing parameters. Additionally, the spatial analysis leads to multiple scenarios and heat maps, by controlling the allowable number of SP or FP plants in NYS. It is important to note that the results and the values shown in the figures are base-case values without uncertainties indicated, and that the uncertainty ranges for the estimated costs for an immature technology such as HTL would be much larger as compared to the other technologies. The sensitivity analysis results are portrayed through Figure S4 and further discussed in Section 3.2. of the Supporting Information.

Annualized Production Costs. The fixed and variable annualized costs for each case (presented in Figure 2) shows the large impacts that downstream processing options can have on the capital and operating costs. The three most expensive combinations are GA-FT ($35.2MM/year), HTL-UPGRADE ($32.5MM/year) and FP-UPGRADE ($31.2MM/year), and each of these technologies involve utilization of downstream processing for the respective major products. Furthermore, GA-FT is 39 and 60% more expensive compared to the other two cases for gasification involving CHP (GA-CHP) and combustion (GA-COMB), respectively. SP-CHAR is the cheapest among all cases ($16.8MM/year) owing to lesser capital and operating costs. Similarly, the cases involving upgrading for both HTL (HTL-UPGRADE) and FP (FP-UPGRADE) are approximately 65% times more expensive than the cases without any downstream processing. For SP, interestingly, the two cases of SP-COMB ($20.3MM/year) and SP-CHAR ($16.8MM/year) only have a difference of 20% as both of them are considered to employ very similar processes. In all of the cases, the O&M costs contribute in the range of 65−80% to the total annualized costs, whereas the capital costs only cover 10−15% of the total costs. This can be attributed to the plant life of 20 years and the discount rate of 5% that is considered in our analysis.

Equipment Costs. Based on the equipment cost analysis (Figure 3, Tables S5−S8 in the Supporting Information), the gasification case (GA-FT) is found to have the most expensive equipment ($72MM), and the SP case (SP-COMB) has the lowest equipment cost ($41MM). The reactors and hydroprocessing units are found to be the most prominent factors, with contributions in the range of 20−41% for the reactors and in the range of 15−36% for the hydroprocessing units. The trends within the pie-charts for the four cases are relatively similar, but the distribution within each major equipment group is not. Dryers are found to be responsible for 85−90% of the "heat exchangers" group cost for SP, FP, as well as gasification. However, as expected, this cost is absent in the HTL case which does not require the feed to be dried. Similarly, compressors and pumps are found to dominate the "others" equipment group (59−90%), and this could be attributed to the high pressures involved as well as the pumping of viscous feed and bio-oil. The distribution within the remaining subgroups is fairly uniform, though distillation columns and hydrocrackers have significant contributions in the "separators" and "hydroprocessing" equipment groups, respectively.

NPV Results. Apart from analyzing the costs associated with the different cases and technologies, their NPVs are also calculated based on our assumptions to incorporate the revenue streams. The parameter values and assumptions used can be found in the Materials and Methods section as well as Section 1 of the Supporting Information. Based on the calculations for a plant of size 175 kton/year, it is found that the FP case involving upgrading of bio-oil (FP-UPGRADE) has the highest NPV ($315MM) at the end of the 20 year

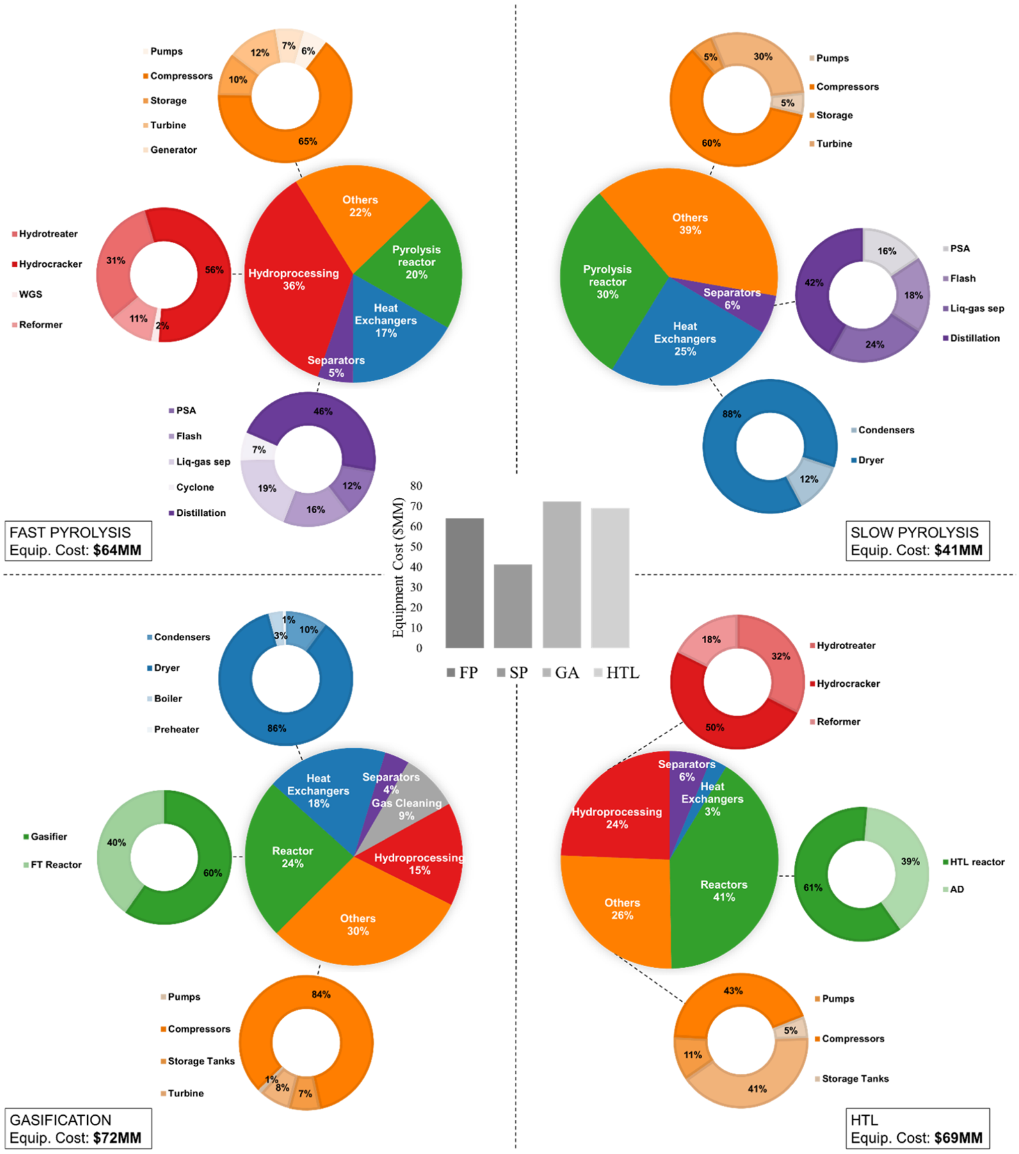


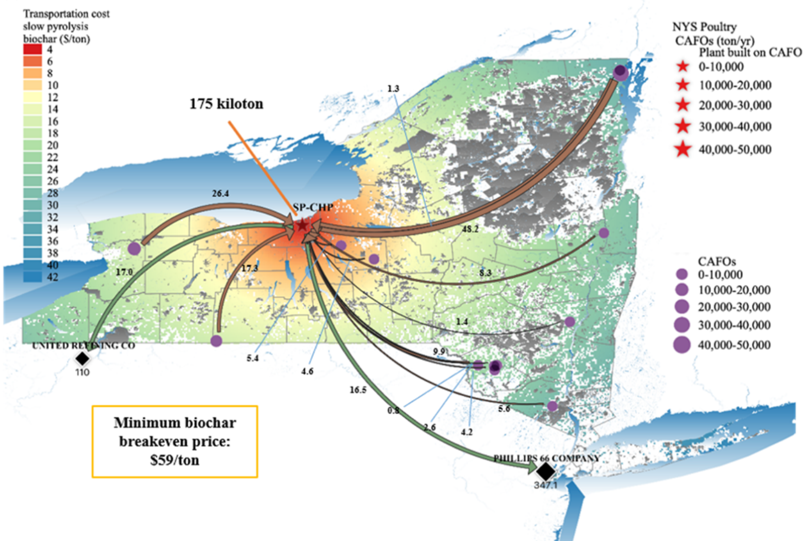
Figure 3. Equipment cost breakdown. This figure shows the major contributors to the equipment cost for each of the four technologies (in the pie-charts) while considering the respective cases with downstream options (FP-UPGRADE, SP-COMB, GA-FT, HTL-UPGRADE). The donut charts represent the further breakdown of a group of equipment with similar functions and are presented in the corresponding colors. The bar chart in the center provides absolute values for the equipment cost of each of the four cases.

horizon and a discount rate of 5%.[38] The other two cases with the highest NPVs are the GA-FT and HTL-UPGRADE cases. The results highlight the influential role that diesel and gasoline prices have on the overall economic performance of the processes. The cases with lower NPV values are the ones with minimal downstream processing and those that utilize their products internally. As an example, SP-COMB with the lowest NPV of \$10MM involves the combustion of biochar to produce energy, which could otherwise have been sold to generate much higher revenue, such as in the SP-Char case with an NPV of \$170MM (Figure S3, Table S16 in the Supporting Information).

GHG Emission Results. Apart from the NPV, it is also important to look at the corresponding environmental impacts while making a decision to choose a certain processing technology over another. Though none of the indirect environmental impacts (which did not fall within our system boundaries) are considered, a GHG inventory for each of the cases is compiled. This includes the sum of all of the GHGs (CO_2, N_2O, CH_4) emitted directly through the initial reactions, as well as in the downstream processing steps. On plotting these values against the corresponding NPVs for the cases (Figure S3, Table S16 in the Supporting Information), there is a clear identification of the trade-offs associated with the two parameters. The cases with gasification and HTL seem to have an average value of emissions higher than the corresponding slow and FP cases. Furthermore, the top three cases with high NPVs (FP-UPGRADE, GA-FT, HTL-UPGRADE) are also among the biggest emitters of GHGs (greater than 300 kg CO_2-eq/ton feedstock), whereas the ones with minimal or no downstream processing have correspondingly lower emissions. This result further emphasizes the need for spatial analysis and optimization to aid in determining the optimal choices for specific cases.

Spatial Analysis Results. The spatial analysis results are presented based on the three different scenarios that are

(a) SP Scenario 1



(b) FP Scenario 1

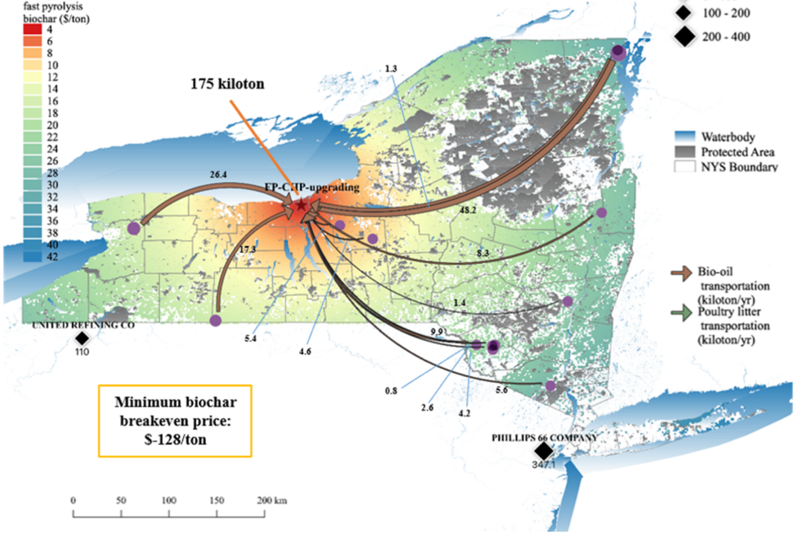


Figure 4. Transportation cost of biochar and illustration of biorefinery location, technology selection, capacity, transportation of feedstocks, and products in scenario 1 for (a) SP and (b) FP. The location of poultry CAFOs is depicted using purple dots with their size proportional to the farm's capacity. A red star is used to identify the optimal pyrolysis biorefinery built for each scenario, and its size represents the original capacity of the chosen CAFO. The capacity of the biorefinery is portrayed through the orange lines. The brown arrows represent the transportation of poultry litter from CAFOs to the pyrolysis biorefineries. Similarly, the location and capacity of crude refineries is shown in the figures using a black rhombus with its size proportional to capacity. The green arrows represent the transportation of bio-oil from pyrolysis plants to the crude refineries. Additionally, the color of each pixel corresponds to an associated value of biochar transportation cost in the color bar. Transportation volumes are also labeled besides the arrow or pointed out with blue lines. The labeling mentioned above is consistent with all the spatial analysis results presented in this paper and hence has not been repeated everywhere.

considered to treat NYS's poultry litter through either slow or FP. Each scenario differs in terms of the number of plants that can be built. Specifically, scenario 1 considers one plant, scenario 2 has two plants, and scenario 3 includes 8 and 10 plants for fast and SP, respectively (Table S3 in the Supporting Information). The following sections describe the results of each scenario, respectively.

Scenario 1: Building a Single Pyrolysis Biorefinery in NYS. The heat maps of biochar transportation cost across NYS and the optimal supply chain design for SP scenario 1 and FP scenario 1 are illustrated in Figure 4a,b, respectively (where SP stands for SP and FP stands for FP). It can be observed that the CAFO named Wayne County Eggs (Figure S2 in the Supporting Information) is chosen to be the location of the pyrolysis biorefinery for both SP scenario 1 and FP scenario 1. The large capacity (175.3 kton/year) helps satisfy the constraints associated with building the biorefineries and their downstream processing facilities, and both scenarios choose to process pyrolysis gas with a CHP unit. Furthermore, the FP Scenario 1 also chooses to upgrade the bio-oil instead of transporting and selling it to existing crude refineries. Under the given choice of technology and biorefinery capacity, the biorefinery location for FP scenario 1 is only determined by the poultry litter transportation, whereas the biorefinery location for SP scenario 1 is a result of the combined effect of poultry litter transportation and bio-oil transportation.

Factors Affecting the Choice of the Biorefinery. Transportation cost is based on the interaction between trans-

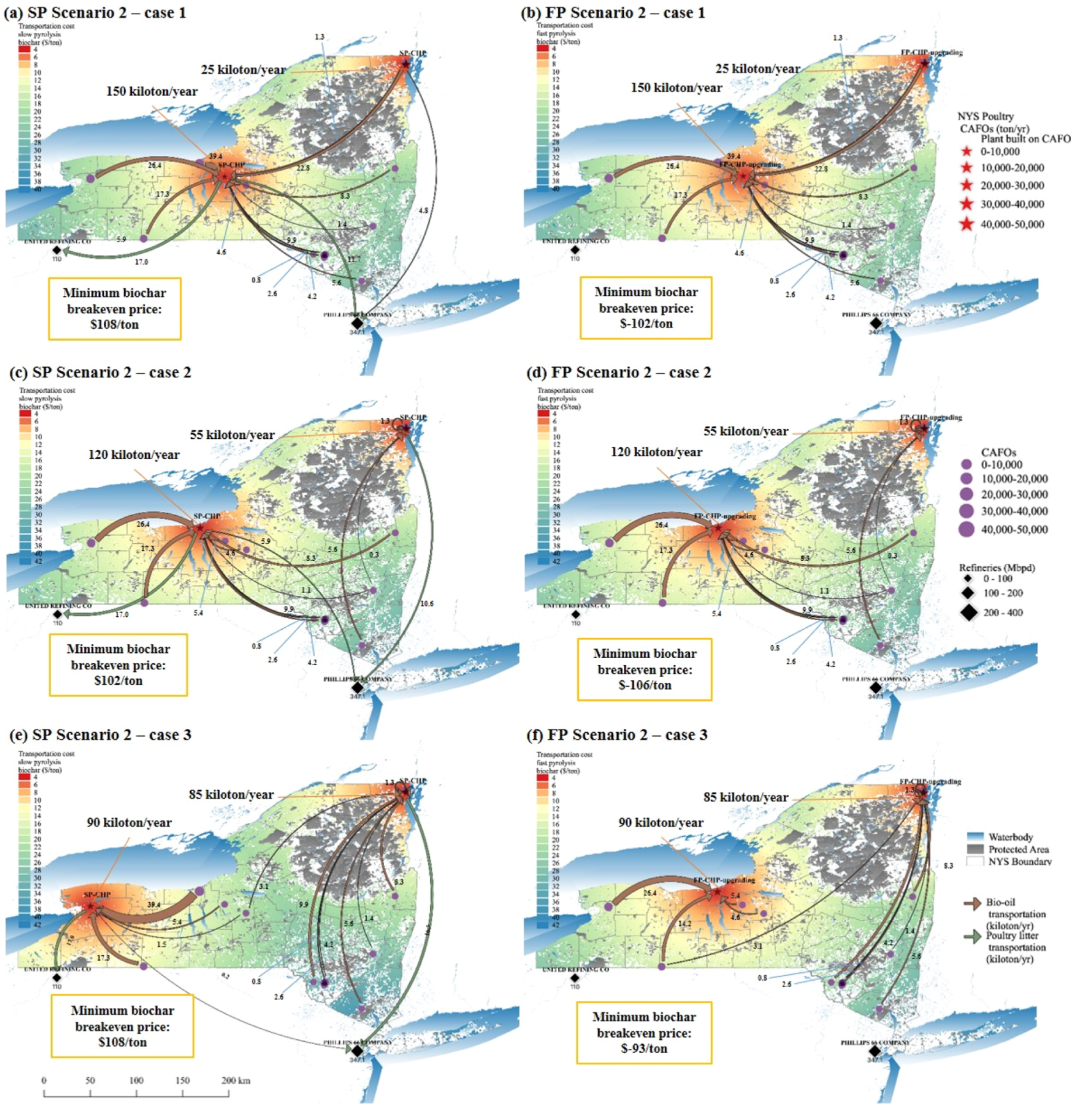


Figure 5. Transportation cost of biochar and illustration of biorefinery location, technology selection, capacity, transportation of feedstocks, and products in scenario 2 for the three cases of SP (a–e) and FP (b–f), respectively.

portation distances and loads; thus, a biorefinery is more likely to be built on a large CAFO with low total turnover of transportation (calculated through the multiplication of load and distance), in order to avoid as much poultry litter transportation as possible. The 39.4 kton/year capacity of Wayne County Eggs is the second highest among all of the CAFOs and is not far from the 48.2 kton/year capacity of Giroux's Poultry Farm (ranked first). While Giroux's Poultry Farm is comparatively far from 12 of the CAFOs and the two crude refineries, Wayne County Eggs is closer to most CAFOs, among which there are two CAFOs—Kreher's Farm Fresh Eggs and Whitesville Farms, whose capacities are the third and fourth highest, respectively. Consequently, the summation of poultry litter capacity of the three CAFOs, namely, Wayne County Eggs, Kreher's Farm Fresh Eggs and Whitesville Farms, accounts for 47% of all poultry litter feedstock from the 14 CAFOs. Because the remaining CAFOs do not have capacities comparable to the four largest ones, the FP biorefinery is most likely to be built at Wayne County Eggs.

While considering bio-oil transportation for SP, a biorefinery located toward the lower half of NYS would be preferable, such as at Whitesville Farms and Ace Farms (Figure S2 in the Supporting Information). However, the amount of bio-oil produced from SP (33 kton/year) is much less than the amount of poultry litter to be transported (127–175 kton/year), and the bio-oil transportation distance for each CAFO is not significantly higher than the average poultry litter transportation distance. Therefore, the bio-oil transportation did not prove to be an influential factor on the choice of biorefinery location in SP scenario 1. As a consequence, Wayne County Eggs is chosen to be the optimal location to build the pyrolysis biorefinery for both scenarios and the bio-oil from SP is transported to both crude refineries because the closest crude refinery, United Refining Co., is not able to accommodate all of the produced bio-oil based on the cutoff for the maximum bio-oil permissible in a conventional crude refinery (Table S22 in the Supporting Information).

Economic Profile. For both scenarios, the radial color pattern of the heat map arising from the biorefinery represents the biochar transportation cost varying from lower to higher values (Figure 4a,b). The biochar breakeven price is found to vary from \$59/ton to \$96/ton for SP while it changes from −\$128/ton to −\$91/ton for FP (summarized in Figure 7). The differences can be explained through the breakdown

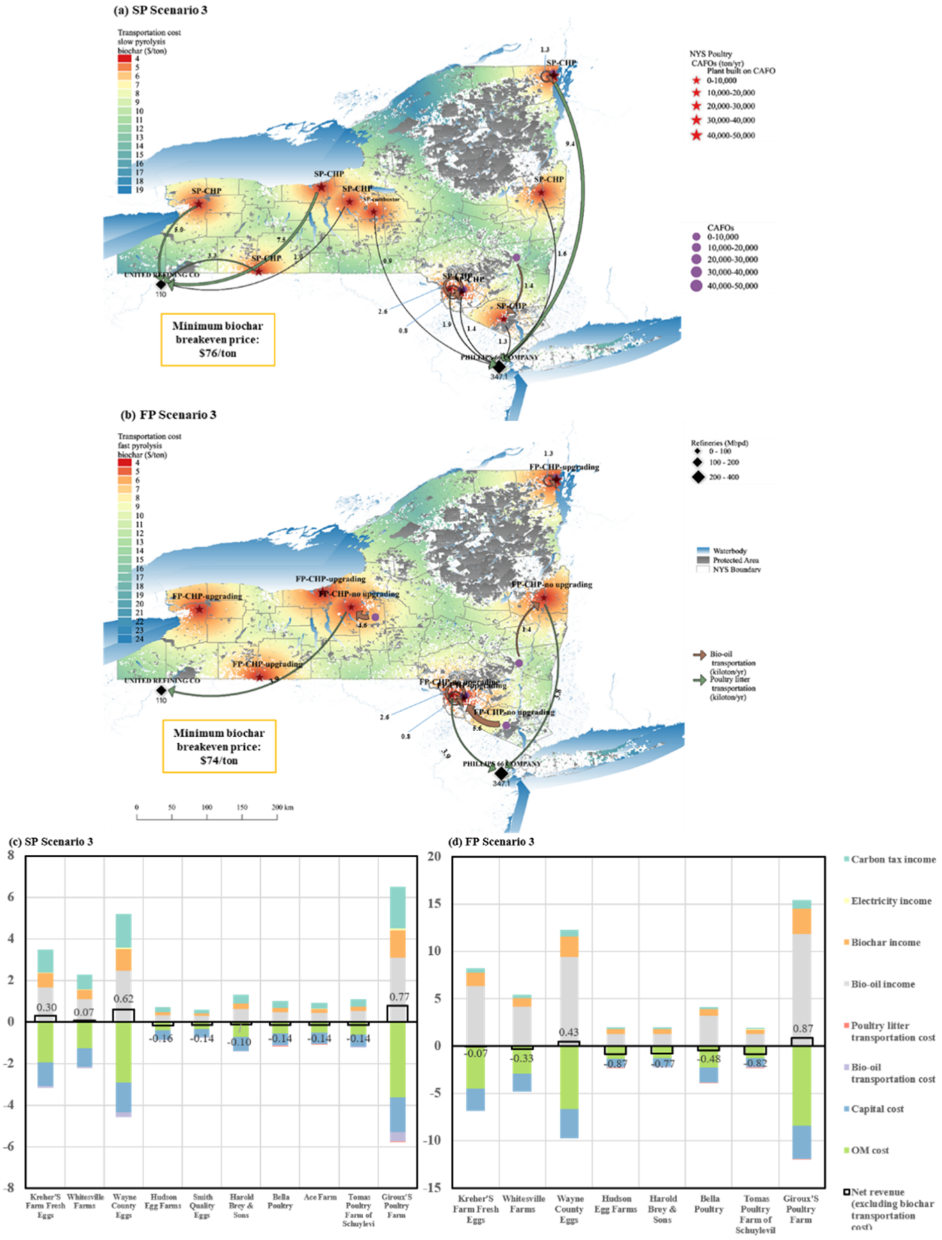


Figure 6. Transportation cost of biochar and illustration of biorefinery location, technology selection, capacity, transportation of feedstocks, and products in scenario 3 for (a) SP and (b) FP as well as annualized economic breakdowns of scenario 3 for (c) SP and (d) FP in NYS.

analysis of the economics (Figure S6 in the Supporting Information). All of the costs and sources of revenue are considered on an annual basis, and the revenue generated through bio-oil, biochar, carbon tax, and electricity account for 31.6, 47.0, 20.6, and 0.8% of the total income for the SP scenario 1, respectively. In contrast, the FP scenario 1 has the bio-oil, biochar, carbon tax, and electricity account for 76.7, 17.3, 5.7, and 0.3% of the total income, respectively. Because of higher biochar production in SP, its biochar and carbon tax revenues are found to be \$6.98MM and \$4.06MM more than that of FP. On the other hand, because the diesel (\$3.26/gal)[58] and gasoline prices (\$2.79/gal)[59] are much higher than the bio-oil price (\$45/barrel),[60] the upgraded fast-pyrolysis bio-oil is able to generate \$30.9MM more than the SP bio-oil (which is directly sold to the crude refineries).

In terms of fixed and variable costs, the capital cost, O&M cost, poultry litter transportation cost, and bio-oil transportation cost account for 16.6, 59.8, 18.0, and 5.6% of the total costs in SP scenario 1. For FP scenario 1, the capital cost, O&M cost, and poultry litter transportation cost account for 18.2, 72.4, and 9.4% of the total costs with the poultry litter transportation cost having the same values for both scenarios. As a result of the additional bio-oil upgrading equipment required for FP, FP scenario 1 has \$16.85MM higher annual O&M costs and \$3.91MM higher annualized capital costs compared to SP scenario 1. The resultant net revenues (derived from the earlier techno-economic analysis) are \$13.42MM and \$13.60MM for SP scenario 1 and FP scenario 1, respectively.

Scenario 2: Building Two Pyrolysis Biorefineries for NYS. The heat maps based on biochar transportation cost across NYS, and the optimal supply chain design for both SP scenario 2 and FP scenario 2 are illustrated in Figure 5, with parts (a−c) representing cases 1, 2, and 3 for SP Scenario 2

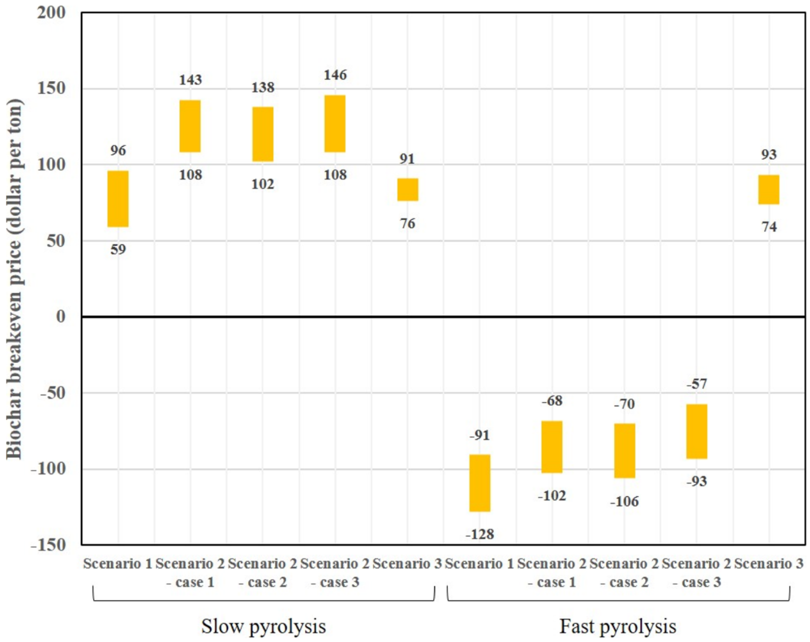


Figure 7. Range of biochar breakeven price for all considered scenarios of slow and FP across NYS.

and parts (d−f) illustrating the three similar cases for FP scenario 2. All cases in both scenarios choose to process pyrolysis gas with a CHP unit, and all cases of FP scenario 2 choose to upgrade the bio-oil instead of transporting and selling it to existing crude refineries. It is observed that the biorefinery with a smaller capacity for all cases in both scenarios is located on Giroux's Poultry Farm while the optimal location of the biorefinery with a larger capacity varies across different cases.

CASE 1: In case 1 of both scenarios, the larger biorefinery is located on Hudson Egg Farms with an annual capacity of 5.4 kton/year. In terms of the poultry litter transportation, compared to scenario 1, 25.3 kton/year of poultry litter remains within the smaller plant, while 22.8 kton/year poultry litter is transported. The optimal location of the larger plant is also found to shift from Wayne County Eggs to Hudson Egg Farms because the turnover of poultry litter is much less in the former.

CASE 2: In case 2 of both scenarios, the larger biorefinery is located at Wayne County Eggs. The annual capacity of Giroux's Poultry Farm (48.2 kton/year) is insufficient to supply the smaller biorefinery with a fixed capacity of 55.3 kton/year; thus, additional poultry litter is transported from two CAFOs located in the bottom right parts of NYS, namely, Ace Farm and Sunrise Farms Inc., to accommodate the need. Moreover, the poultry litter transportation appears to be similar for cases 1 and 2 of both scenarios and it is found that the bio-oil transportation does not play a critical role in decision making of the biorefinery locations.

CASE 3: In the case 3 for SP and FP scenario 2, the larger biorefinery is located on Kreher's Farm Fresh Eggs with an annual capacity of 26.4 kton/year and Wayne County Eggs, respectively. In this case, the larger biorefinery requires 90 kton/year feedstock which is slightly less than the combined capacity of the five CAFOs in the western parts of NYS. Thus, transportation of poultry litter from one of the five CAFOs becomes necessary in order to meet the capacity level of the smaller biorefinery.

Factors Affecting the Choice of the Biorefinery. For SP, in order to reduce the turnover of both bio-oil and poultry litter transportation, the larger biorefinery is located at Kreher's Farm Fresh Eggs and part of the poultry litter produced from Smith Quality Eggs is transported to the smaller biorefinery. However, because there is no need of bio-oil transportation for FP, the larger biorefinery is located on Wayne County Eggs and part of the poultry litter produced from Whitesville Farms is transported to the smaller biorefinery. The difference in optimal location of the larger biorefinery highlights the effects of bio-oil transportation when similar cases are encountered. In terms of the bio-oil transportation, for all cases of SP scenario 2, the larger biorefinery transports bio-oil to the two crude refineries, United Refining CO. and American Refining Group Inc.; the smaller biorefinery transports bio-oil only to the bottom-right crude refinery of NYS, Phillips 66 Co.

Economic Profile. As in the case of scenario 1, the radial color pattern of the heat map arising from the two biorefineries represents biochar transportation cost varying gradually from a lower to a higher value. As summarized in Figure 7, the biochar breakeven price for case 1, case 2, and case 3 of SP scenario 2 varies from \$108/ton to \$143/ton, \$102/ton to \$138/ton, and \$108/ton to \$146/ton, while it has a range of −\$102/ton to −\$68/ton, −\$106/ton to −\$70/ton, and −\$93/ton to −\$57/ton for the three cases of FP scenario 2, respectively. The breakdown of the income for all cases of SP scenario 2 is found to be the same as that for SP scenario 1 (Figure S6a). The conclusion is the same for FP.

In terms of the breakdown costs, the capital cost for case 1 is the lowest, and the capital cost for case 3 is the highest among all three cases as a consequence of the scaling effect. It can be observed from Figure S6b that capital costs for biorefineries in case 1, case 2 and case 3 do not linearly scale with the capacity but instead decrease as the biorefinery capacity increases. Because O&M cost is assumed to be linearly dependent on the biorefinery capacity, it is similar for all cases. Poultry litter transportation costs reach the same minimal value for case 2 of both scenarios, showing that the combination of capacity levels, 120 and 55.3 kton/year, appear to be the optimal solution for poultry litter supply under this scenario. There is no bio-oil transportation cost at all for FP scenario 2. For SP scenario 2, case 2 shows the highest bio-oil transportation cost. However, because the weak advantage of scale for case 1 and the minor advantage in bio-oil transportation cost are not able to offset the advantage of the poultry litter supply chain for case 2, case 2 is selected as the optimal supply chain design for both SP and FP scenario 2. Similar to the results of scenario 1, SP is able to generate slightly higher profits compared to FP despite the high bio-oil yields and value-added petroleum products from bio-oil upgrading. This could be attributed to the low capital and O&M costs as well as the high biochar yields for SP.

Scenario 3: Building Multiple Pyrolysis Biorefineries for NYS. The heat maps of biochar transportation cost distributed across NYS and the optimal supply chain design for SP and FP scenario 3 are illustrated in Figure 6a,b, respectively. Under this scenario, we aim to build biorefineries on all CAFOs. However, some CAFOs are too small to construct a pyrolysis biorefinery on, and therefore, poultry litter from these CAFOs is transported to the nearest biorefinery and further processed. It can be observed from Figure 6a that 10 CAFOs (namely Kreher's Farm Fresh Eggs, Whitesville Farms, Wayne County Eggs, Hudson Egg Farms, Smith Quality Eggs, Harold Brey & Sons, Bella Poultry, Ace Farm, Tomas Poultry Farm of Schuylevil and Giroux's Poultry Farm) are chosen as SP biorefineries with annual capacities of 26.4, 17.3, 39.4, 5.4, 4.6, 9.9, 7.6, 7.1, 8.3, and 49.5 kton/year, respectively. Among these, only Smith Quality Eggs processes its pyrolysis gas with a combustor due to the minimum capacity limitation for CHP units, while the other biorefineries could utilize CHP units. In Figure 6b, eight CAFOs are chosen as FP biorefineries, namely, Kreher's Farm Fresh Eggs, Whitesville Farms, Wayne County Eggs, Hudson Egg Farms, Harold Brey & Sons, Bella Poultry, Tomas Poultry Farm of Schuylevil, and Giroux's Poultry Farm with annual capacities of 26.4, 17.3, 39.4, 9.97, 9.9, 13.2, 9.7, and 49.5, respectively. Among these, all biorefineries process their pyrolysis gas with a CHP unit. Three biorefineries, namely, Hudson Egg Farms, Harold Brey & Sons, and Tomas Poultry Farm of Schuylevil, transport and sell their bio-oil to crude refineries while the others satisfy the capacity constraint to upgrade bio-oil onsite.

Factors Affecting the Choice of the Biorefinery. In terms of bio-oil transportation, all SP biorefineries have to transport and sell bio-oil to their nearest crude refineries. Therefore, some biorefineries have geographic advantages while the others do not. For FP, only biorefineries which do not have sufficient capacity for the upgrading facilitites to be feasible would have to transport and sell bio-oil to their nearest crude refineries.

Economic Profile. As mentioned previously in scenario 1, the radial color pattern of the heat map arising from all biorefineries represents biochar transportation cost varying gradually from low to high value. As shown in Figure 7, the biochar breakeven price varies from $76/ton to $91/ton for SP, while it ranges from $74/ton to $93/ton for FP. Notably, the variance of biochar breakeven price becomes less compared to that under scenarios 1 and 2, suggesting that the biochar transportation cost does not vary much for each pixel of corn cropland across NYS. This benefits from the sparse distribution of biorefineries and greatly reduces the minimum transportation distance between corn cropland and biorefineries. However, the distributed design of biorefineries leads to economic infeasibility here. Total annual biochar income, carbon tax income, and O&M costs are the same for all scenarios of SP or FP. Under SP scenario 3, the annual electricity income is $7,620 less than that in SP scenarios 1 and 2 as a result of pyrolysis gas combustion on Smith Quality Eggs. Under FP scenario 3, the annual electricity income is the same as that in FP scenarios 1 and 2. The bio-oil income does not change for SP scenario 3, compared to SP scenarios 1 and 2. FP, in contrast, it earns 8.5% or $3.27MM less revenue through bio-oil than that earned in FP scenarios 1 and 2, suggesting that the distributed design of biorefineries is economically infeasible when many CAFOs with small capacities exist.

Total annualized capital costs for SP and FP scenario 3 are much higher compared to scenarios 1 and 2. To be specific, the total annualized capital cost in scenario 3 is 131.4 and 99.7% higher than that in scenario 1 for slow and FP, respectively. In contrast, the poultry litter transportation cost in scenario 1 is 95 and 28 times higher than that in scenario 3 for slow and FP, respectively. Bio-oil transportation costs in scenario 3 are slightly higher than that of scenario 1. The annual net revenue for scenario 3, which is calculated with a fixed biochar price of $300/ton and without biochar transportation cost, is found to be $12.48MM and $15.65MM less than those in scenario 1 for slow and FP, respectively. The reduction in biochar transportation cost is found to offset part of the reduction in the net revenue, bringing the range of biochar breakeven price for FP lower and comparable to those in cases 1 and 3 of scenario 2 for SP. However, for FP, the reduction in net revenue is too much to be offset significantly. Particularly, as shown in Figure 6d, only two out of eight FP biorefineries show slightly positive annual net revenues, while the others all possess negative net revenues. Therefore, the biochar breakeven price is brought up significantly from previous negative values to the range of $74 to $93 per ton.

■ CONCLUSIONS

In this paper, the techno-economic analysis for nine cases involving combinations of the four thermochemical technologies with different downstream processing options is achieved with the aid of rigorous process simulations. The resultant NPVs for the base-cases, ranging from $10MM to $170MM (SP), $89MM to $315MM (FP), $28MM to $196MM (HTL), and $25MM to $234MM (gasification) highlight the potential benefits of implementing these technologies, and the sensitivity analysis portrays the impact that parameters with high variability and uncertainty such as biochar price ($0/ton to $1900/ton), carbon credits ($0/ton to $500/ton), and plant capacity (25−175 kton/year) can have on the economic performance. The poultry litter supply chain in NYS illustrates the variability in transportation of feedstock and products associated with real practice. The centralized treatment of poultry litter is found to outperform the distributed system for FP in NYS by a large margin, thus revealing the advantage that large-scale facilities possess. For SP on the other hand, the differences in the biochar breakeven price between the two systems are much smaller, thus portraying that either of the two could be suitable for NYS based on policy and market demand. Moreover, FP is found to outperform SP under both centralized and distributed supply chain design, emphasizing the tremendous economic value that bio-oil currently possesses. This result is also consistent with the conclusions from previous studies on biomass/biofuel supply chain optimization.[61,62] In order to achieve greater economic benefits, higher bio-oil production and construction of bio-oil upgrading facilities are found to be favorable both through the techno-economic and spatial analysis. Furthermore, the choice of biorefinery locations is found to be highly dependent on the distribution and processing capacities of the CAFOs and the crude refineries. It is worth mentioning that the analyses conducted in this study could be applied not only to NYS's poultry litter but also to other regions with a comparable scale and availability of farm-level geographic data. The proposed model provides a basis for decisions regarding the choice of technologies in the future, as a particular pathway would be more suitable in some cases as compared to the others depending on scale, feedstock, operating conditions, products desired, finances, and geospatial distribution of the entities involved. A future study based on this work could include supply chain optimization to account for all of the factors mentioned above.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acssuschemeng.0c01229.

> Detailed simulation cases and parameters, spatial analysis parameters, economic results, sensitivity analysis results, tables on operating parameters, price distribution, utilities and product prices, NPV calculations, CAFO data, oil refinery data, and schematic process flow diagrams (PDF)

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Notes

The authors declare no competing financial interest.

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