Supporting Information

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


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## 1. SIMULATION CASES AND PARAMETERS

The major thermochemical technologies analyzed in the study are pyrolysis, gasification and hydrothermal liquefaction (HTL). Pyrolysis can be tuned based on reaction temperature and residence time to produce two useful products in the absence of oxygen.[1] With fast pyrolysis (FP) (500°C or lesser), the major product is bio-oil which can be further upgraded to green gasoline and diesel, whereas with slow pyrolysis (SP) (400-600°C), it is biochar, a soil amendment with potential for long-term carbon sequestration.[2-3] Gasification is a more mature thermochemical technology, with many large-scale coal processing plants operational owing to the benefits of the syngas product as compared to conventional combustion.[4] HTL (300-450$^{o}$C), unlike the others, is a novel technology which requires no drying of the feedstock, as it use subcritical water as the reaction medium.[5-7]

The important parameters in the simulations include operating conditions (pressure, temperature, flow rate) for each equipment unit, kinetic and thermodynamic parameters (reaction rates, product distribution, phase equilibrium and separation, heat recovery), as well as various ratios and efficiency considerations (equivalence ratio, conversion efficiency, product ratio). However, the values and assumptions associated with each of these parameters are different for each technology, and this is further explained through Table S1, Figure S1 and the following subsections. The input feed composition was derived after going through multiple papers on thermochemical treatment of poultry litter.[8-10] Importantly, the moisture content of the feed (22.81%) and the other elemental concentration reflects the average poultry litter composition in the northeastern states of USA, which includes NYS.[11] The operating conditions for the simulations for each of the technologies were based on multiple papers and government reports and have been summarized in Table S2.[12-15] The operating conditions were optimized to aid in processing poultry litter, though it has not been explicitly mentioned in the manuscript. First, the selection of initial operating parameters was done after going through multiple experimental studies. Additionally, during the simulations, an effort was made to continuously update certain operating parameters to ensure the best performance of the systems.

**Table S1.** Input poultry litter elemental composition.[8-9]

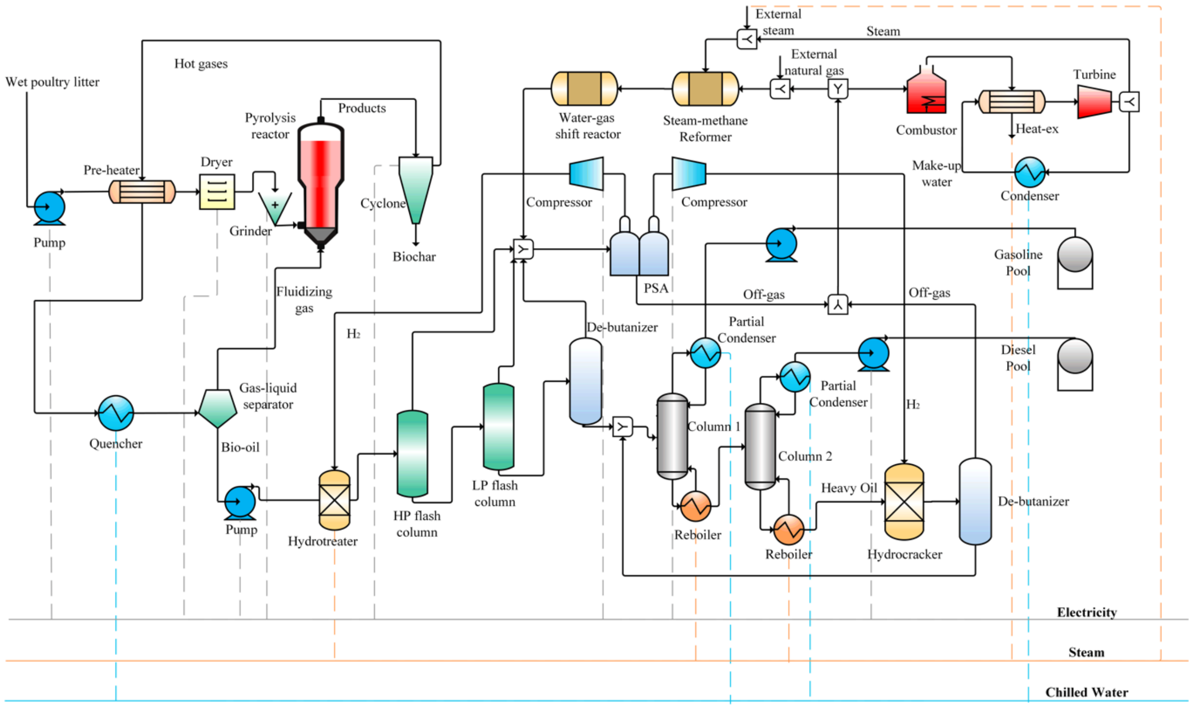
| Element | Amount (% w/w) |
|---|---|
| Moisture | 22.81 |
| Ash | 15.33 |
| C | 34.05 |
| H | 4.42 |
| N | 2.89 |
| O | 42.68 |
| S | 0.63 |

**1.1. Slow pyrolysis:** The main components of each slow pyrolysis system considered are the dryer, the pyrolysis reactor, the phase separators and other auxiliary equipment such as pumps and compressors. Poultry litter is dried from 22.8% to 10% moisture content using a rotary dryer. The output of the dryer is fed to the pyrolysis reactor which in turn produces biochar, bio-oil, and off gas. The bio-oil is considered to be sold to existing nearby refineries owing to its small production quantities.[16-17] The off-gas has the option to either be combusted or sent to a combined heat and power plant (CHP) in the spatial analysis depending on the scale of the plant. In the SP-COMB case, the biochar is considered to be combusted to produce additional heat and electricity, and to avoid additional transportation. As against this, the biochar is distributed and sold for land application in the SP-CHAR case, and is utilized for the spatial analysis scenarios, too. Unlike the other technologies, the optimum capacity for slow pyrolysis reactors so far has been found to be relatively small (1-2 tons/hour), so multiple parallel reactors are used to model plants with higher flowrates. The feed stream is assumed to go through drying and grinding before splitting into multiple parallel streams. The products from each reactor on separation then find their way into combined product streams.

**1.2. Fast pyrolysis:** The fast pyrolysis process is modeled in a similar way as the slow pyrolysis process, with only major differences in the reactor scaling and the downstream processing options.[18-19] The bio-oil has the option of being sold to an existing refinery (FP-SELL) or to be upgraded within a dedicated facility built specifically for hydrotreating and further processing the bio-oil (FP-UPGRADE). The off-gas is treated in a similar manner as that of slow pyrolysis, and the biochar is assumed to have the same market value as the biochar from slow pyrolysis too.[20] The upgrading plant for the bio-oil includes a hydrotreater, multiple separation and distillation units, as well as a hydrogen production unit (Figure S1).[9-10, 12, 21-22]

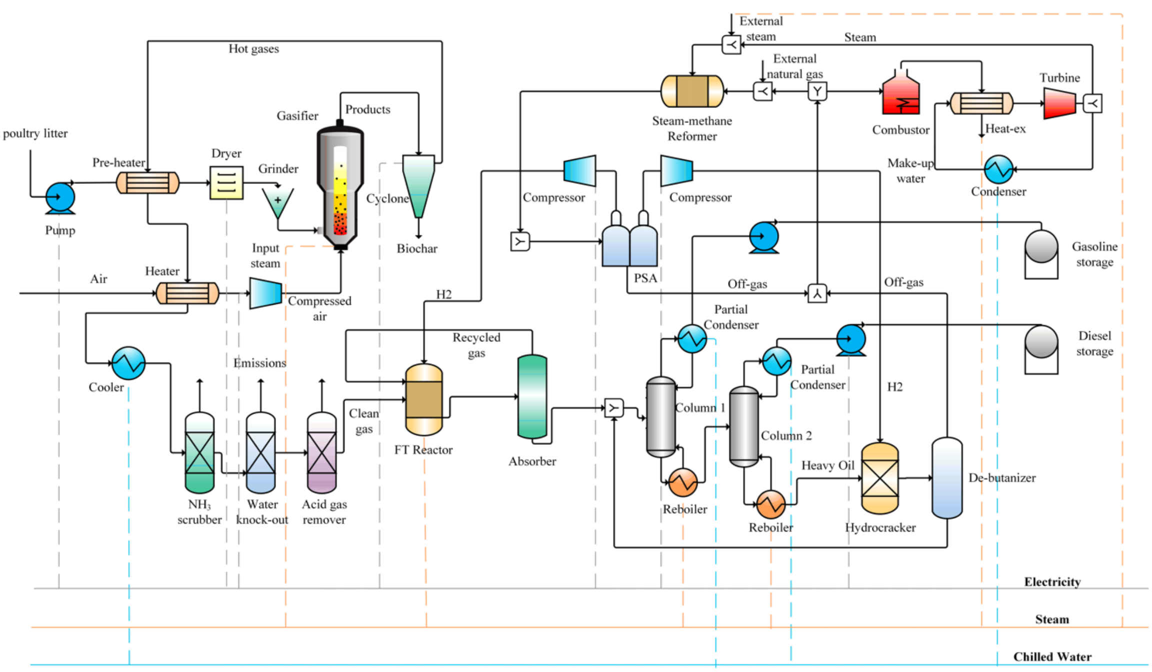
**1.3. Hydrothermal liquefaction:** For HTL, the poultry litter feed is sent to the reactor without the need for drying, and there is the production of four phases - bio-oil phase, a solid hydrochar phase, a gas phase, and an aqueous phase. The aqueous phase consisting of water and organic compounds is sent to an anaerobic digester (AD) to recover the organic contents and ameliorate environmental concerns, as well as to produce valuable biogas. The bio-oil, similar to the case of fast pyrolysis, is either sold to an existing refinery (HP-SELL) or sent to a customized upgrading unit (HP-UPGRADE) with slightly different configurations owing to the differences in the composition and properties of the two bio-oils. The gaseous phase is not considered useful owing to the high $CO_2$ levels, but the hydrochar is considered to be sold as a soil amendment without the carbon storage abilities present in biochar.[13-14]

**1.4. Gasification:** The gasification model consists of the gasification reactor, syngas cleaning unit, energy production unit and other auxiliary equipment.[15] The major products of the process are the syngas and relatively small amounts of biochar. The three cases for gasification are all based on how the gas phase is processed (Table 1 in the main body). The raw syngas is sent to a gas cleaning unit before undergoing the Fischer-Tropsch synthesis in the GA-FT case. The oil obtained is further sent to a hydroprocessing and separation unit for upgrading into valuable products like gasoline and diesel.[23-24] The other two cases for gasification involve either combusting the syngas or sending it to a CHP for recovery of both heat and electricity that could be used both within the process as well as used to generate revenue.[25-27]



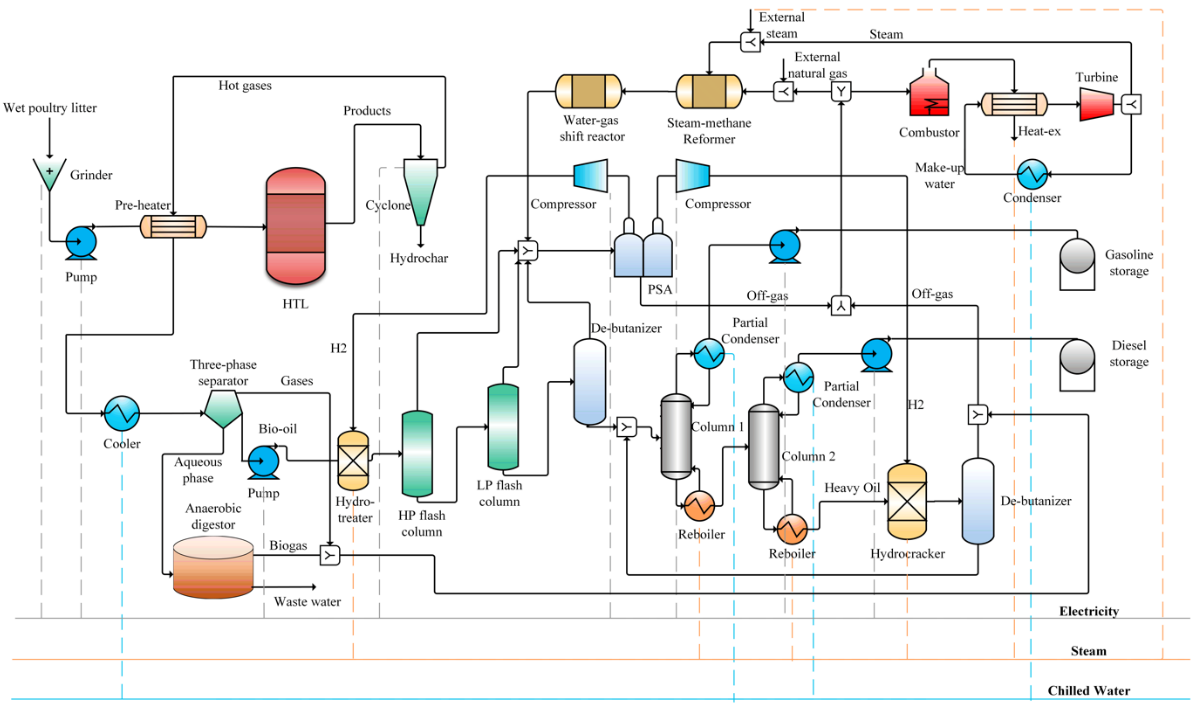
External steam
Steam
Hot gases
Wet poultry litter
Water-gas shift reactor
Steam-methane Reformer
External natural gas
Combustor
Heat-ex
Turbine
Make-up water
Condenser
Products
Pyrolysis reactor
Pre-heater
Dryer
Grinder
Cyclone
Biochar
Pump
Compressor
Compressor
PSA
Gasoline Pool
Fluidizing gas
H2
Off-gas
Off-gas
De-butanizer
Partial Condenser
Diesel Pool
Gas-liquid separator
Partial Condenser
H2
Quencher
Bio-oil
Column 1
Column 2
LP flash column
Heavy Oil
Pump
HP flash column
Hydrotreater
Reboiler
Reboiler
Hydrocracker
De-butanizer
Electricity
Steam
Chilled Water


(a)



External steam
Steam
External natural gas
Hot gases
Steam-methane Reformer
Combustor
Turbine
Heat-ex
Products
Gasifier
Make-up water
Condenser
Wet poultry litter
Pre-heater
Dryer
Grinder
Cyclone
Pump
Biochar
Input steam
Compressor
Compressor
PSA
Gasoline storage
Air
Heater
Compressed air
Off-gas
Off-gas
H2
Recycled gas
Partial Condenser
Diesel storage
Cooler
Emissions
Partial Condenser
H2
Clean gas
Column 1
Column 2
FT Reactor
Absorber
Heavy Oil
De-butanizer
NH3 scrubber
Water knock-out
Acid gas remover
Reboiler
Reboiler
Hydrocracker
Electricity
Steam
Chilled Water


(b)




(c)

**Figure S1.** Schematic process flow diagram of (a) fast pyrolysis pathway with downstream processing of the bio-oil to obtain transportation fuels (FP-UPGRADE) (b) gasification pathway involving Fischer Tropsch process to convert syngas into liquid fuels (GA-FT) (c) hydrothermal liquefaction pathways with upgrading of bio-oil to obtain transportation fuels (HTL-UPGRADE). All the other pathways involve certain parts of these flowsheets. The main utilities are represented through different colors with the gray streams representing electricity, orange streams representing heat, and blue streams representing chilled water.

**1.5. Other parameters:** In addition to the simulation and economic parameters, there are some other assumptions and parameters which have to be considered and assigned values based on either calculations or literature such as transportation, greenhouse gas emission and sensitivity analysis parameters. The average transportation distances of 50 km for poultry litter, biochar and bio-oil are used in the economic analysis. However, this value can easily vary based on the distribution of farms and plants and hence the spatial analysis is used to accurately obtain these values in the case study for NYS presented in the Spatial Analysis Section of the main manuscript. The greenhouse gas emission inventory is compiled entirely based on the simulations and certain literature values. Emissions from transportation, plant operation, direct utility consumption and biochar soil application are incorporated in the results. Furthermore, in order to identify the influential parameters which could have large impacts on the analysis, sensitivity analyses are conducted for both slow pyrolysis and fast pyrolysis cases. The parameters are chosen after identifying the parameters which lead to the highest change in the NPV values, and their range and base case values are derived from the simulations and literature (Table S20).

**Table S2.** Names, operating parameters and modeling units used for the important components in the Aspen Plus simulations[12-15, 20, 26, 28-31]

| Sr. No. | Equipment | Temperature (K) | Pressure (atm) | In scenario(s) | Modeled as | Reference |
|---|---|---|---|---|---|---|
| 1 | Gasification reactor | 1573 | 26 | GA-FT, GA-CHP, GA-COMB | RGibbs reactor | 15 |
| 2 | Fast pyrolysis reactor | 773 | 1 | FP-SELL, FP-UPGRADE | RStoic reactor | 12, 20 |
| 3 | Slow pyrolysis reactor | 923 | 1 | SP-COMB | RStoic reactor | 26, 31 |
| 4 | Hydrothermal liquefaction reactor | 623 | 200 | SP-CHAR | RYield reactor | 13, 14 |
| 5 | Preheater | 372 | 1 | ALL | HeatX | - |
| 6 | Air compressor | - | 26 | GA-FT, GA-CHP, GA-COMB | Compressor | - |

| | | | | | | |
|---|---|---|---|---|---|---|
| 7 | Dryer | 363 | 1 | GA-FT, GA-CHP, GA-COMB, FP-SELL, FP-UPGRADE, SP-COMB, SP-CHAR | RStoic + Flash | 30 |
| 8 | Hydrotreater | 672 | 172 | GA-FT, FP-UPGRADE, HTL-UPGRADE | RYield reactor | 13, 20 |
| 9 | Hydrocracker | 700 | 87 | GA-FT, FP-UPGRADE, HTL-UPGRADE | RYield reactor | 20 |
| 10 | Gasoline cooler | 283 | 32 | GA-FT, FP-UPGRADE, HTL-UPGRADE | HeatX | - |
| 11 | Diesel cooler | 283 | 32 | GA-FT, FP-UPGRADE, HTL-UPGRADE | HeatX | - |
| 12 | Fischer Tropsch Reactor | 473 | 25 | GA-FT | RYield reactor | 15, 29 |
| 13 | Steam methane reformer | 1123 | 45 | GA-FT, FP-UPGRADE, HTL-UPGRADE | RStoic reactor | 28 |
| 14 | Water-gas shift reactor | 573 | 29 | GA-FT, FP-UPGRADE, HTL-UPGRADE | RStoic reactor | 13 |
| 15 | Distillation Column | - | 23 | GA-FT, FP-UPGRADE, HTL-UPGRADE | RadFrac | - |
| 16 | Condenser | 344 | 1.7 | GA-FT, FP-UPGRADE, HTL-UPGRADE | - | - |

| | | | | | | |
|---|---|---|---|---|---|---|
| 17 | Reboiler | 590 | 1.7 | GA-FT, FP-UPGRADE, HTL-UPGRADE | - | - |
| 18 | Combustor | 823 | 1 | GA-COMB, SP-COMB | RGibbs reactor | - |

## 2. SPATIAL ANALYSIS

**2.1. Bio-oil upgrading:** The bio-oil can either be upgraded on-site or sent to an existing crude refinery, and the crude refinery data are derived from the simulations as well as through the U.S. Energy Information Administration (EIA) website.[32] Since bio-oil from pyrolysis is found to contain approximately 35% oxygen and 20% water in our simulations, the quality of the petroleum products could be negatively affected if a crude refinery is to accept too much bio-oil from the pyrolysis biorefinery.[33] To be conservative, it is assumed that each crude refinery can only accept bio-oil up to 1% of its capacity from the biorefineries.[34] As mentioned before, the bio-oil produced from slow pyrolysis is not upgraded at a dedicated facility since the amount and the quality of bio-oil from slow pyrolysis is not comparable with the bio-oil produced from fast pyrolysis. For on-site upgrading, the minimum capacity of a bio-oil upgrading facility on a fast pyrolysis biorefinery is assumed to be 10 kton/year based on the profitability analysis conducted in certain studies and by considering the capacities of currently operational refineries.[35]

**2.2. Biochar distribution and application:** The biochar is to be applied on corn cropland with an application rate derived from the county-wise recommended P application data for corn croplands as described in Section 4.1. Corn is selected owing to its prominent distribution across NYS unlike other crops which allows for minimization of the transportation distance for biochar.[36] The corn cropland data are collected from the NASS Cropland Data Layer[36] and later aggregated from a pixel resolution of 30 meters to a pixel resolution of 7.5 kilometers. In each scenario, the biochar breakeven price is computed for each pixel and presented on the map of NYS. It is worth mentioning that white pixels on the graphs represent absence of corn cropland and hence inability to transport and apply biochar on those pixels. The distribution of corn cropland in NYS is consistent with the protected areas and the areas of waterbodies acquired from the New York Protected Areas Database.[37] Figure S2 and Table S3 provide details about the distribution of the CAFOs in NYS and the scenarios considered in the spatial analysis.

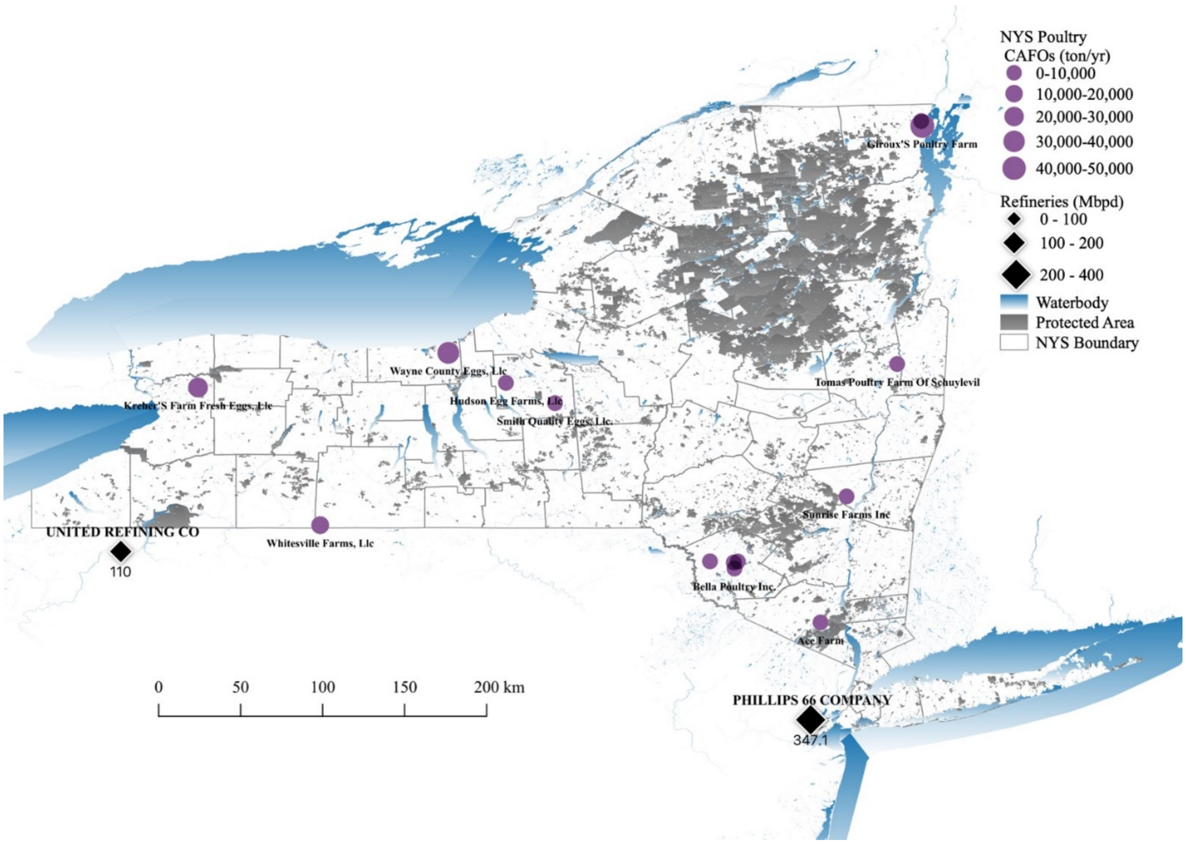



**Figure S2.** Map containing distribution, names, and annual poultry litter generation amounts (ton/year) for the CAFOs in NYS, as well as existing crude refineries near the State.

**Table S3.** Description of scenarios for spatial analysis in terms of number of plants, technology and capacity (SP and FP stand for slow pyrolysis and fast pyrolysis, respectively).

| Scenario name | No. of plants | Technology | Capacity (kton/year) |
|---|---|---|---|
| SP Scenario 1 | 1 | slow pyrolysis | 175.3 |
| SP Scenario 2 - case 1 | 2 | | 150, 25.3 |
| SP Scenario 2 - case 2 | 2 | | 120, 55.3 |

| | | | |
|---|---|---|---|
| SP Scenario 2 - case 3 | 2 | | 90, 85.3 |
| SP Scenario 3 | 10 | | 49.5, 39.4, 26.4, 17.3, 9.9, 8.3, 7.6, 7.1, 5.4, 4.6 |
| FP Scenario 1 | 1 | | 175.3 |
| FP Scenario 2 - case 1 | 2 | | 150, 25.3 |
| FP Scenario 2 - case 2 | 2 | | 120, 55.3 |
| FP Scenario 2 - case 3 | 2 | fast pyrolysis | 90, 85.3 |
| FP Scenario 3 | 8 | | 49.5, 39.4, 26.4, 17.3, 13.2, 9.97, 9.9, 9.7 |

**2.3. Economic considerations:** The annual net revenue is calculated based on the difference between the sum of bio-oil income, biochar income, electricity income and carbon tax income and the sum of capital cost, O&M cost, poultry litter transportation cost and bio-oil transportation cost along with a fixed biochar price of \$100/ton and without consideration of the biochar transportation cost. All the parameters needed for the calculations are assigned values based on the initial techno-economic calculations. Additionally, in order to show the relationship between the choice of biorefinery locations and the biochar transportation, the biochar breakeven price for all scenarios is also calculated. It is worth mentioning that when annual net revenue turns out to be positive, a negative biochar breakeven price is obtained, and vice versa. Capital cost, O&M cost, biochar income, bio-oil income, electricity income and carbon tax income are found to be dependent on the capacity and technology choices for the biorefinery, while the poultry litter, bio-oil and biochar transportation costs are related closely with the location of the biorefineries and corn croplands. The mode of transportation for all products is assumed to be through trucks, and Equation 1 taken from literature[38] is used to compute the transportation cost (\$/ton).

$$\text{Transportation cost} = 4.1 + 0.08 \cdot \text{Distance} \quad (1)$$

Where the distance is calculated in kilometers and '0.08' is the cost in \$/ton associated with the transportation of the material whereas '4.1' is the cost in \$/ton associated with loading and unloading the trucks.

To determine the optimal locations of the biorefineries among the 14 CAFOs, the pairwise route distances between each crude refinery and CAFO, from one CAFO to another, and between corn cropland pixels and each CAFO are computed and integrated in the calculation of the breakeven price for biochar.

## 3. ECONOMIC RESULTS

**3.1. Equipment costs and NPV calculation:** For the four cases with the highest fixed and variable annualized costs (GA-FT, HTL-UPGRADE, FP-UPGRADE and SP-COMB) the equipment costs are also analyzed to help identify the major contributors (Figure 3). Since the magnitude of the equipment costs is large and even a small proportion could make a difference, an attempt is made to include the minor contributors as shown in Figure 3 in the main manuscript and Tables S5-S8. Equipment with similar functions are combined into major groups in each of the pie-charts and the proportion within the group is displayed through three donut charts for each technology (Table S5-S8 contain all the absolute values). Among the major groups, the 'hydroprocessing' fraction consists of hydrotreaters, hydrocrackers and hydrogen production units. The 'separators' include flash vessels, distillation columns, cyclone separators, pressure swing adsorbers (PSA) and other phase separation equipment. The 'others' group within the pie-charts consists of an assortment of equipment that could not be associated with any other categories. It consists of equipment such as pumps, compressors, storage tanks, turbines and generators. The NPV results along with their trade-offs with the greenhouse gas emissions are also portrayed in this section (additional discussion in main body of the manuscript). Tables S4-S18 and Figure S3 summarize some of the simulations and economic results.

**Table S4.** Product phase distribution for the four thermochemical technologies (slow pyrolysis, fast pyrolysis, gasification and hydrothermal liquefaction).[10]

| | SP | FP | GA | HTL |
|---|---|---|---|---|
| Gas | 31.57 | 17.14 | 93.60 | 22.95 |
| Oil | 28.82 | 56.88 | 0.00 | 47.11 |
| Solid | 39.61 | 25.98 | 6.40 | 29.93 |

**Table S5.** Equipment price distribution for fast pyrolysis technology[39]

| **Equipment name** | **Cost ($)** | **Contribution (%)** |
|---|---|---|
| Bio-oil pump | 617,230 | 0.96 |
| Feed preheater | 69,455 | 0.11 |
| Gasoline cooler | 70,400 | 0.11 |
| Diesel cooler | 85,150 | 0.13 |
| Pressure swing adsorber 1 | 111,535 | 0.17 |
| Pressure swing adsorber 2 | 111,535 | 0.17 |
| Demister 1 | 117,315 | 0.18 |
| Gas-liquid separator | 130,510 | 0.20 |
| Demister 2 | 130,510 | 0.20 |
| Dry flash | 137,810 | 0.21 |
| LP Flash | 146,270 | 0.23 |
| Pressure swing adsorber 3 | 173,830 | 0.27 |
| Quencher | 192,505 | 0.30 |
| Pump | 206,305 | 0.32 |
| Cyclone separator | 228,942 | 0.35 |
| Demister 3 | 253,385 | 0.39 |
| HP-flash | 264,785 | 0.41 |
| Boiler | 300,091 | 0.46 |
| Gasoline storage tank | 309,640 | 0.48 |
| Sulfur removal | 310,215 | 0.48 |
| WGS reactor | 425,224 | 0.66 |
| Condenser | 536,000 | 0.83 |
| Diesel storage tank | 551,478 | 0.85 |
| wastewater storage | 570,159 | 0.88 |
| Distillation Column 1 | 700,005 | 1.08 |
| Distillation Column 2 | 853,490 | 1.32 |
| Generator | 960,450 | 1.49 |
| Turbine | 1,688,380 | 2.61 |
| Reformer | 2,499,887 | 3.87 |
| Compressor 2 | 2,765,390 | 4.28 |
| Compressor 1 | 2,898,910 | 4.49 |
| Compressor 3 | 3,350,415 | 5.19 |
| Hydrotreater | 7,286,741 | 11.28 |
| Dryer | 9,550,244 | 14.79 |
| Hydrocracker | 12,849,618 | 19.90 |
| Pyrolysis reactor | 13,123,210 | 20.32 |
| Total | 64,577,019 | 100.00 |

**Table S6.** Equipment price distribution for slow pyrolysis technology

| Equipment name | Cost ($) | Contribution (%) |
|---|---|---|
| Bio-oil pump | 693,930 | 1.33 |
| Pump | 208,170 | 0.40 |
| Compressor 1 | 64,740 | 0.12 |
| Preheater | 66,850 | 0.13 |
| Compressor 2 | 67,660 | 0.13 |
| Pressure swing adsorber 1 | 107,450 | 0.21 |
| Demister 1 | 107,450 | 0.21 |
| Pressure swing adsorber 2 | 119,995 | 0.23 |
| LP-Flash | 122,400 | 0.23 |
| Gas-liquid separator | 125,720 | 0.24 |
| Demister 2 | 125,720 | 0.24 |
| Gasoline storage tank | 132,642 | 0.25 |
| Dry flash tank | 132,655 | 0.25 |
| Pressure swing adsorber 3 | 167,030 | 0.32 |
| Quencher | 185,210 | 0.36 |
| WGS reactor | 193,040 | 0.37 |
| HP-Flash | 210,905 | 0.40 |
| Diesel storage tank | 224,026 | 0.43 |
| Demister 3 | 244,255 | 0.47 |
| Column | 254,665 | 0.49 |
| Reformer | 358,034 | 0.69 |
| Boiler | 375,965 | 0.72 |
| Distillation Column 1 | 496,270 | 0.95 |
| wastewater storage | 552,473 | 1.06 |
| Distillation column 2 | 555,360 | 1.06 |
| Condenser | 1,025,650 | 1.97 |
| Compressor 3 | 2,618,575 | 5.02 |
| Hydrotreater | 3,007,832 | 5.77 |
| Compressor 4 | 3,518,090 | 6.74 |
| Compressor 5 | 3,942,005 | 7.56 |
| Hydrocracker | 4,512,086 | 8.65 |
| Turbine | 4,974,258 | 9.54 |
| Dryer | 9,550,244 | 18.31 |
| Pyrolysis reactor | 13,123,210 | 25.16 |
| Total | 41,164,565 | 100.00 |

**Table S7.** Equipment price distribution for gasification technology

| Equipment name | Cost ($) | Contribution (%) |
|---|---|---|
| Condenser | 391,690 | 0.61 |
| Sulfur separator | 69,995 | 0.11 |
| Distillation column 2 | 971,650 | 1.51 |
| Dry flash tank | 137,810 | 0.21 |
| Compressor 1 | 2,132,910 | 3.32 |
| F-T water knock out | 117,090 | 0.18 |
| Steam generator | 272,225 | 0.42 |
| F-T liquid cooler | 1,774,550 | 2.76 |
| AIR-preheater | 46,577 | 0.07 |
| Column-1 | 955,645 | 1.49 |
| Feed-preheater | 44,857 | 0.07 |
| NH3-Scrubber | 139,380 | 0.22 |
| Gasoline cooler | 69,995 | 0.11 |
| Compressor-4 | 2,844,780 | 4.43 |
| F-T liquid absorber | 117,090 | 0.18 |
| 1st Sulfur Separator | 105,535 | 0.16 |
| Syngas-cooler | 581,440 | 0.91 |
| Compressor-2 | 2,091,465 | 3.26 |
| SC water knock out | 125,890 | 0.20 |
| Compressor-air | 4,321,445 | 6.73 |
| Wax pump | 185,625 | 0.29 |
| CO2-remover | 117,660 | 0.18 |
| Compressor-3 | 1,472,920 | 2.29 |
| PSA | 126,030 | 0.20 |
| Lock hopper | 144,139 | 0.22 |
| Turbine | 1,394,000 | 2.17 |
| Diesel-cooler | 86,165 | 0.13 |
| Cyclone | 85,399 | 0.13 |
| Compressor-5 | 2,708,995 | 4.22 |
| Gasoline storage tank | 456,759 | 0.71 |
| Diesel storage tank | 515,864 | 0.80 |
| wastewater storage | 420,091 | 0.65 |
| Gasifier | 8,884,322 | 13.84 |
| FT reactor | 5,981,756 | 9.32 |
| Dryer | 9,548,588 | 14.88 |
| Boiler | 375,965 | 0.59 |
| Hydrocracker | 7,585,565 | 11.82 |
| Reformer | 1,911,564 | 2.98 |
| Acid gas remover | 2,009,549 | 3.13 |

| | | |
|---|---|---|
| Claus Converter | 1,907,260 | 2.97 |
| Hydrolysis reactor | 956,988 | 1.49 |
| Total | 64,187,222 | 100.00 |

**Table S8.** Equipment price distribution for hydrothermal liquefaction technology

| Equipment name | Cost ($) | Contribution (%) |
|---|---|---|
| Preheater 1 | 280,615 | 0.39 |
| Feed heater | 620,890 | 0.87 |
| Compressor 1 | 2,489,825 | 3.50 |
| Pressure swing adsorber 1 | 131,590 | 0.18 |
| Preheater 2 | 141,730 | 0.20 |
| Pressure swing adsorber 2 | 126,420 | 0.18 |
| Flash | 131,590 | 0.18 |
| HP-Flash | 146,270 | 0.21 |
| Hydrocracker | 1,340,205 | 1.88 |
| Turbine | 7,304,560 | 10.26 |
| Condenser | 280,705 | 0.39 |
| Column | 982,780 | 1.38 |
| Adsorption | 175,130 | 0.25 |
| Heat exchanger | 117,610 | 0.17 |
| Distillation column | 1,245,415 | 1.75 |
| Compressor 3 | 2,952,445 | 4.15 |
| Distillation column | 69,815 | 0.10 |
| 3-phase-separator | 190,315 | 0.27 |
| Distillation Column | 73,050 | 0.10 |
| NH3 scrubber | 148,860 | 0.21 |
| F-p-ex | 64,855 | 0.09 |
| Hc-2-fl | 131,590 | 0.18 |
| Cooler 1 | 520,905 | 0.73 |
| Sulfur treatment | 190,315 | 0.27 |
| Cooler 2 | 71,260 | 0.10 |
| LP-Flash | 146,270 | 0.21 |
| Feed pump | 1,883,210 | 2.64 |
| Compressor 4 | 2,283,120 | 3.21 |
| Preheater 3 | 141,730 | 0.20 |
| Liquid gas separator | 124,415 | 0.17 |
| Pressure swing adsorber 3 | 126,030 | 0.18 |
| Cooler 3 | 105,945 | 0.15 |
| Gasoline storage tank | 252,410 | 0.35 |
| Diesel storage tank | 579,567 | 0.81 |
| Wastewater storage | 105,668 | 0.15 |
| Reformer | 2,962,192 | 4.16 |
| HTL reactor | 17,287,229 | 24.27 |
| Hydrotreater | 5,481,468 | 7.70 |
| Hydrocracker | 8,364,620 | 11.74 |

| | | |
|---|---|---|
| Boiler | 443,408 | 0.62 |
| AD reactor | 11,011,074 | 15.46 |
| Total | 71,227,102 | 100.00 |

**Table S9.** Price of the important utilities.[15, 40-41]

| Sr. No. | Utility name | Price | Units | Reference No. |
|---|---|---|---|---|
| 1 | Electricity | 5.4 | cents/kWh | 40 |
| 2 | Process Steam | 8.2 | $/ton | 15 |
| 3 | Cooling water | 0.31 | $/ton | 15 |
| 4 | Natural gas | 7.42 | $/thousand cubic feet ($/MCF) | 41 |
| 5 | Wastewater disposal | 3.3 | $/hundred cubic feet | 15 |

**Table S10.** Product market prices used for the revenue calculations.[38, 42-45]

| **Product** | **Price** | **Units** |
|---|---|---|
| oil | 0.33 | $M/kt |
| diesel | 1.03 | $M/kt |
| gasoline | 0.99 | $M/kt |
| biochar | 0.10 | $M/kt |
| electricity | 8.00 | cents/kWh |
| carbon tax | 0.10 | $M/kt |
| biochar | 0.20 | $M/ton |

**Table S11.** Revenue generation distribution for the nine cases considered.

| **Case** | **Oil** | **Diesel** | **Gasoline** | **Biochar ($MM)** | **Electricity** | **Carbon** | **Total** |
|---|---|---|---|---|---|---|---|
| GA-COMB | | | | | 13.46 | | 13.46 |
| FP-SELL | 22.54 | | | 3.12 | 0.98 | 0.94 | 27.58 |
| HTL-SELL | 11.56 | | | 2.36 | | | 13.92 |
| SP-CHAR | 11.03 | | | 9.19 | 2.79 | 1.83 | 24.84 |
| GA-CHP | | | | | | | 26.91 |
| SP-COMB | 11.03 | | | | 4.28 | | 15.31 |
| FP-UPGRADE | | 31.11 | 10.82 | 1.56 | 0.49 | 0.47 | 44.45 |
| HTL-UPGRADE | | 25.46 | 7.33 | 2.36 | | | 35.15 |
| GA-FT | | 24.68 | 17.48 | | | | 42.17 |

**Table S12.** NPV calculation for FP-SELL case.

| **FP-SELL year** | | | |
|---|---|---|---|
| 0 | -55,109,214 | -55,109,214 | -55,109,214 |
| 1 | 11,627,132 | 11,073,459 | -44,035,755 |
| 2 | 11,627,132 | 10,546,152 | -33,489,603 |
| 3 | 11,627,132 | 10,043,954 | -23,445,649 |
| 4 | 11,627,132 | 9,565,670 | -13,879,979 |
| 5 | 11,627,132 | 9,110,162 | -4,769,817 |
| 6 | 11,627,132 | 8,676,345 | 3,906,528 |
| 7 | 11,627,132 | 8,263,186 | 12,169,714 |
| 8 | 11,627,132 | 7,869,701 | 20,039,415 |
| 9 | 11,627,132 | 7,494,953 | 27,534,368 |
| 10 | 11,627,132 | 7,138,051 | 34,672,418 |
| 11 | 11,627,132 | 6,798,143 | 41,470,562 |
| 12 | 11,627,132 | 6,474,422 | 47,944,984 |
| 13 | 11,627,132 | 6,166,116 | 54,111,101 |
| 14 | 11,627,132 | 5,872,492 | 59,983,592 |
| 15 | 11,627,132 | 5,592,849 | 65,576,442 |
| 16 | 11,627,132 | 5,326,523 | 70,902,965 |
| 17 | 11,627,132 | 5,072,879 | 75,975,844 |
| 18 | 11,627,132 | 4,831,314 | 80,807,158 |
| 19 | 11,627,132 | 4,601,251 | 85,408,409 |
| 20 | 11,627,132 | 4,382,144 | 89,790,553 |
| | | | 89.79 |

**Table S13.** NPV calculation for SP-CHAR case.

| **SP-CHAR year** | | | |
|---|---|---|---|
| 0 | -38,871,805 | -38,871,805 | -38,871,805 |
| 1 | 16,785,210 | 15,985,914 | -22,885,891 |
| 2 | 16,785,210 | 15,224,680 | -7,661,211 |
| 3 | 16,785,210 | 14,499,695 | 6,838,485 |
| 4 | 16,785,210 | 13,809,234 | 20,647,718 |
| 5 | 16,785,210 | 13,151,651 | 33,799,370 |
| 6 | 16,785,210 | 12,525,382 | 46,324,752 |
| 7 | 16,785,210 | 11,928,935 | 58,253,687 |
| 8 | 16,785,210 | 11,360,891 | 69,614,578 |
| 9 | 16,785,210 | 10,819,896 | 80,434,474 |
| 10 | 16,785,210 | 10,304,663 | 90,739,137 |
| 11 | 16,785,210 | 9,813,965 | 100,553,101 |
| 12 | 16,785,210 | 9,346,633 | 109,899,734 |
| 13 | 16,785,210 | 8,901,555 | 118,801,289 |
| 14 | 16,785,210 | 8,477,672 | 127,278,961 |
| 15 | 16,785,210 | 8,073,973 | 135,352,934 |
| 16 | 16,785,210 | 7,689,498 | 143,042,432 |
| 17 | 16,785,210 | 7,323,331 | 150,365,764 |
| 18 | 16,785,210 | 6,974,601 | 157,340,365 |
| 19 | 16,785,210 | 6,642,478 | 163,982,843 |
| 20 | 16,785,210 | 6,326,169 | 170,309,012 |
| | | | 170.31 |

**Table S14.** NPV calculation for SP-COMB case.

| **SP-COMB year** | | | |
|---|---|---|---|
| 0 | -41,258,986 | -41,258,986 | -41,258,986 |
| 1 | 4,121,929 | 3,925,647 | -37,333,339 |
| 2 | 4,121,929 | 3,738,711 | -33,594,627 |
| 3 | 4,121,929 | 3,560,678 | -30,033,950 |
| 4 | 4,121,929 | 3,391,121 | -26,642,828 |
| 5 | 4,121,929 | 3,229,639 | -23,413,189 |
| 6 | 4,121,929 | 3,075,847 | -20,337,342 |
| 7 | 4,121,929 | 2,929,378 | -17,407,963 |
| 8 | 4,121,929 | 2,789,884 | -14,618,079 |
| 9 | 4,121,929 | 2,657,032 | -11,961,047 |
| 10 | 4,121,929 | 2,530,507 | -9,430,540 |
| 11 | 4,121,929 | 2,410,007 | -7,020,533 |
| 12 | 4,121,929 | 2,295,244 | -4,725,289 |
| 13 | 4,121,929 | 2,185,947 | -2,539,342 |
| 14 | 4,121,929 | 2,081,854 | -457,487 |
| 15 | 4,121,929 | 1,982,718 | 1,525,231 |
| 16 | 4,121,929 | 1,888,303 | 3,413,535 |
| 17 | 4,121,929 | 1,798,384 | 5,211,919 |
| 18 | 4,121,929 | 1,712,747 | 6,924,666 |
| 19 | 4,121,929 | 1,631,187 | 8,555,853 |
| 20 | 4,121,929 | 1,553,512 | 10,109,365 |
| | | | 10.11 |

**Table S15.** GWP 100-year factors of some of the chemicals involved in the simulations. The values are directly obtained from the IPCC report on Climate Change in 2013[46]

| Sr. No. | Acronym, Common Name | Chemical Formula | GWP 100-year (kg $CO_2$-Eq) |
|---|---|---|---|
| 1 | Carbon dioxide | $CO_2$ | 1 |
| 2 | Methane | $CH_4$ | 28 |
| 3 | Nitrous oxide | $N_2O$ | 265 |
| 4 | Nitrous oxides | $NO_x$ | -8.2 |
| 5 | Carbon monoxide | CO | 1.8 |
| 6 | Sulphur dioxide | $SO_2$ | -38.4 |

**Table S16.** Net present value (NPV) and greenhouse gas (GHG) inventory results for the nine considered cases.

| **Case** | **GHG (kg $CO_2$-eq)** | **NPV ($MM)** |
|---|---|---|
| GA-FT | 339.00 | 234.33 |
| GA-CHP | 378.35 | 72.15 |
| GA-COMB | 400.00 | 25.02 |
| SP-COMB | 270.00 | 10.00 |
| SP-CHAR | 279.00 | 170.00 |
| FP-SELL | 217.00 | 89.79 |
| FP-UPGRADE | 361.50 | 314.49 |
| HTL-SELL | 339.40 | 28.40 |
| HTL-UPGRADE | 494.50 | 196.27 |

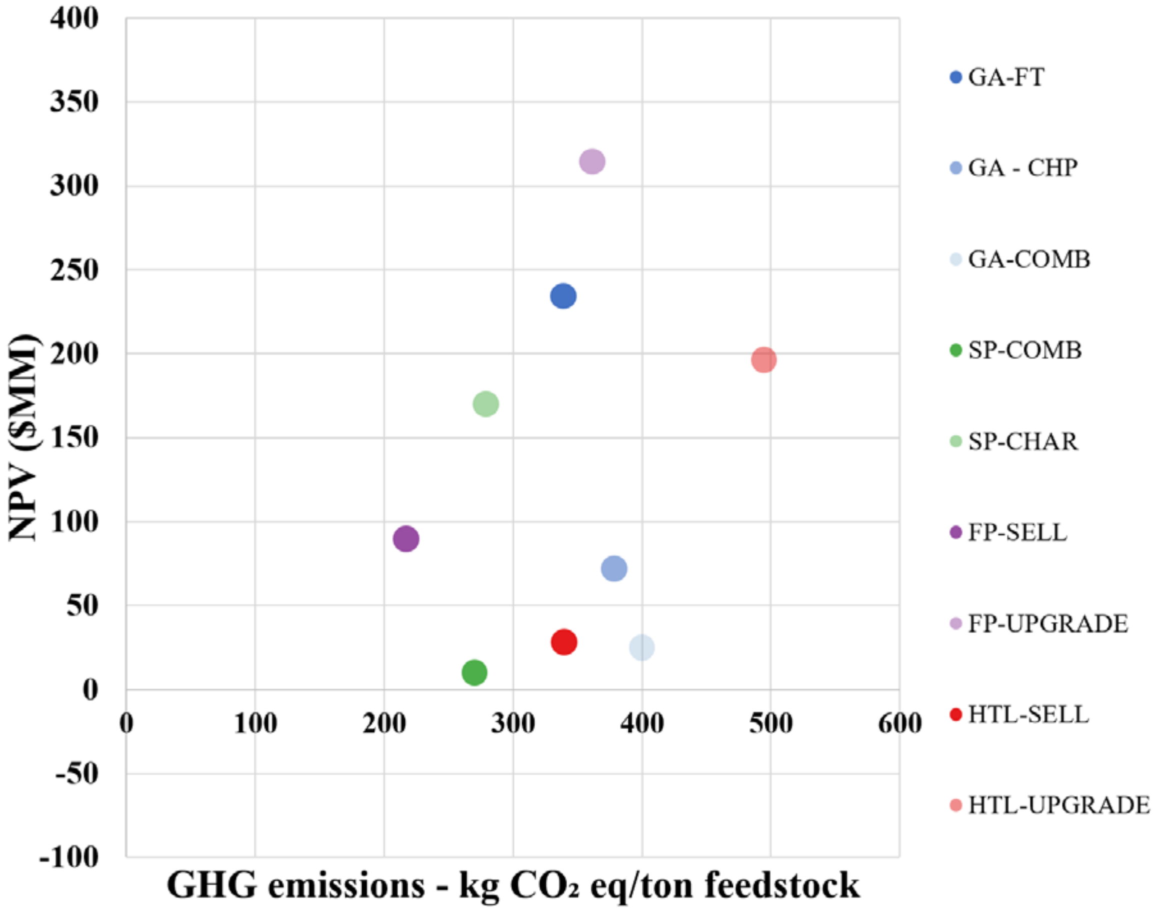



**Figure S3.** Trade-off between economic and environmental performance illustrated through the plot of NPVs ($MM) against greenhouse gas emissions (GHG) for the nine cases.

**Table S17.** Syngas production potential through slow pyrolysis for the 14 CAFOs and the corresponding power that can be generated.[16]

| Sr. No. | Syngas (kg/hr) | Energy (MW) | Electricity (MW) | Heat (MJ/hr) |
|---|---|---|---|---|
| 1 | 1,234.66 | 3.92 | 1.18 | 7,053.28 |
| 2 | 811.00 | 2.57 | 0.77 | 4,633.05 |
| 3 | 1,843.45 | 5.85 | 1.76 | 10,531.14 |
| 4 | 251.90 | 0.80 | 0.24 | 1,439.04 |
| 5 | 214.61 | 0.68 | 0.20 | 1,226.02 |
| 6 | 463.19 | 1.47 | 0.44 | 2,646.08 |
| 7 | 37.66 | 0.12 | 0.04 | 215.16 |
| 8 | 121.55 | 0.39 | 0.12 | 694.40 |
| 9 | 195.19 | 0.62 | 0.19 | 1,115.10 |

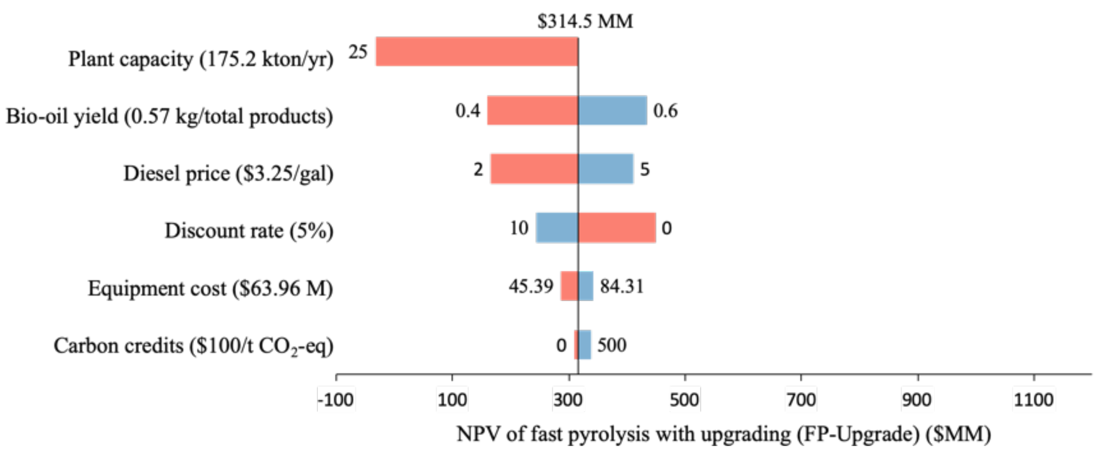
| | | | | |
|---|---|---|---|---|
| 10 | 263.60 | 0.84 | 0.25 | 1,505.86 |
| 11 | 66.11 | 0.21 | 0.06 | 377.67 |
| 12 | 387.58 | 1.23 | 0.37 | 2,214.16 |
| 13 | 60.12 | 0.19 | 0.06 | 343.46 |
| 14 | 2,254.19 | 7.15 | 2.15 | 12,877.60 |
| Min gas | 1,050.28 | | 1.00 | 6,000.00 |

**Table S18.** Syngas production potential through fast pyrolysis for the 14 CAFOs and the corresponding power that can be generated.[9]

| Sr. No. | Syngas (kg/hr) | Energy (MW) | Electricity (MW) | Heat (MJ/hr) |
|---|---|---|---|---|
| 1 | 878.81 | 1.75 | 0.52 | 3,141.57 |
| 2 | 577.26 | 1.15 | 0.34 | 2,063.59 |
| 3 | 1,312.14 | 2.61 | 0.78 | 4,690.63 |
| 4 | 179.30 | 0.36 | 0.11 | 640.96 |
| 5 | 152.76 | 0.30 | 0.09 | 546.08 |
| 6 | 329.69 | 0.65 | 0.20 | 1,178.58 |
| 7 | 26.81 | 0.05 | 0.02 | 95.83 |
| 8 | 86.52 | 0.17 | 0.05 | 309.29 |
| 9 | 138.94 | 0.28 | 0.08 | 496.67 |
| 10 | 187.62 | 0.37 | 0.11 | 670.72 |
| 11 | 47.06 | 0.09 | 0.03 | 168.22 |
| 12 | 275.88 | 0.55 | 0.16 | 986.20 |
| 13 | 42.79 | 0.08 | 0.03 | 152.98 |
| 14 | 1,604.50 | 3.19 | 0.96 | 5,735.76 |
| Min gas | 1,678.42 | | 1.00 | 6,000.00 |

**3.2. Sensitivity analysis results.** Through the sensitivity analysis for both the slow pyrolysis and fast pyrolysis cases, parameters which would have a major impact on the NPV values for each case are identified (Figure S4). For the fast pyrolysis case (FP-UPGRADE), the plant capacity is the dominating factor with a negative NPV of -$32MM (decrease of 110%) on moving from the existing capacity (175 kton/year) to the lowest capacity (25 kton/year, as determined in the spatial analysis for NYS later). This could be explained by the fact that the building of an upgrading facility dedicated solely to process bio-oil would be a very expensive proposition if the scale is not large enough. Both bio-oil yield (ranging from -49.0% to +38.2%) and diesel price (-47.4% to +30.8%) are other influential parameters, thus further establishing the importance of optimizing the utilization and processing steps of bio-oil for fast pyrolysis. Other parameters such as discount rate, equipment cost and carbon credits have a smaller impact on the NPV, which is positive even for the lower bounds of all parameter values except for plant capacity.

For slow pyrolysis on the other hand, the biochar price (with a base value of $100/ton) is found to be capable of dictating the overall economic performance of the plant, with a meagre NPV of $12MM at $0/ton biochar, and a substantial NPV of $298MM at $500/ton biochar. Towards the higher end of the biochar price spectrum, it is found that the slow pyrolysis system could compete with the fast pyrolysis system in terms of NPV and even surpass it if in combination with a high carbon credit value (+73% for $500/t $CO_2$-eq). Additionally, there are other environmental benefits that slow pyrolysis possesses which have not been monetized or incentivized yet. Thus, the biochar and carbon credit prices in the future could play a huge role in dictating which of the two technologies would be deployed at a larger scale.



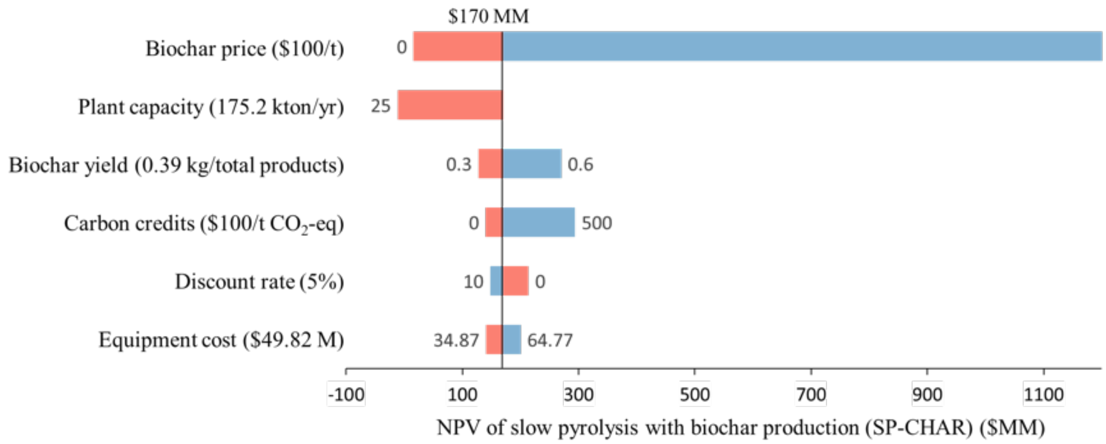



**Figure S4.** Sensitivity analysis results for the FP-UPGRADE (above) and SP-CHAR (below) cases. The text on the left refers to the parameters being varied, and their base values are placed in parenthesis. The labels at the end of each bar represent the extreme values of the parameter considered. The single number near the central axis for both the cases refers to the base value of the NPV ($315MM for the fast pyrolysis case, and $170MM for the slow pyrolysis case).

# 4. SPATIAL ANALYSIS RESULTS

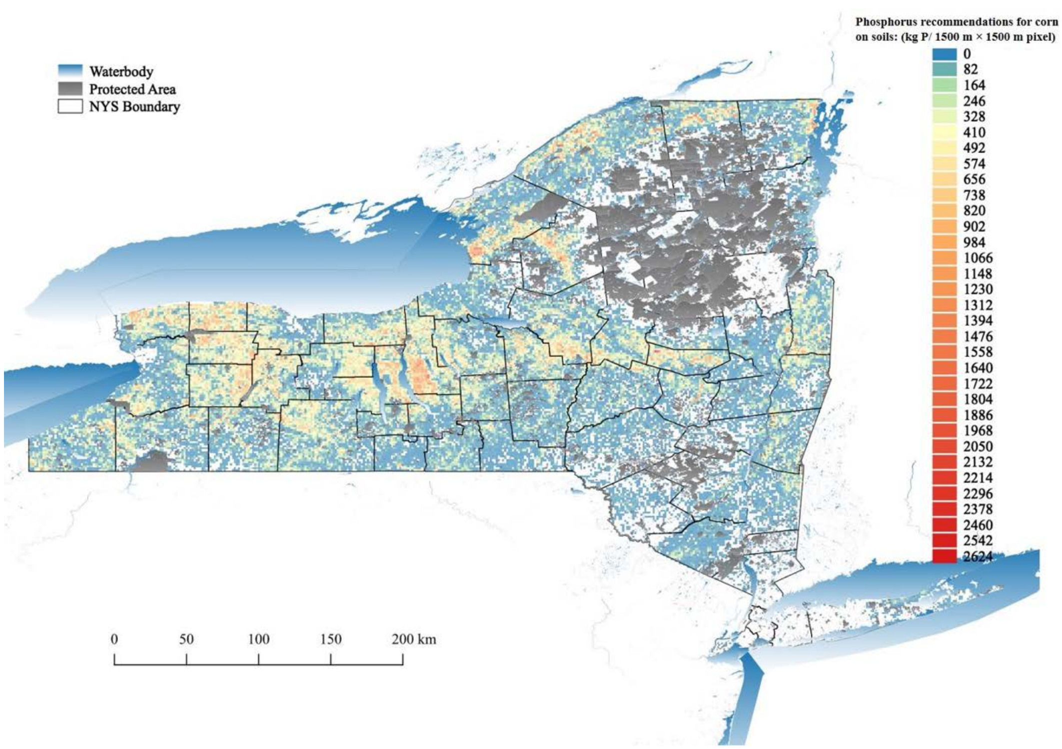


**Figure S5.** Spatial distribution of phosphorus in New York State (NYS).

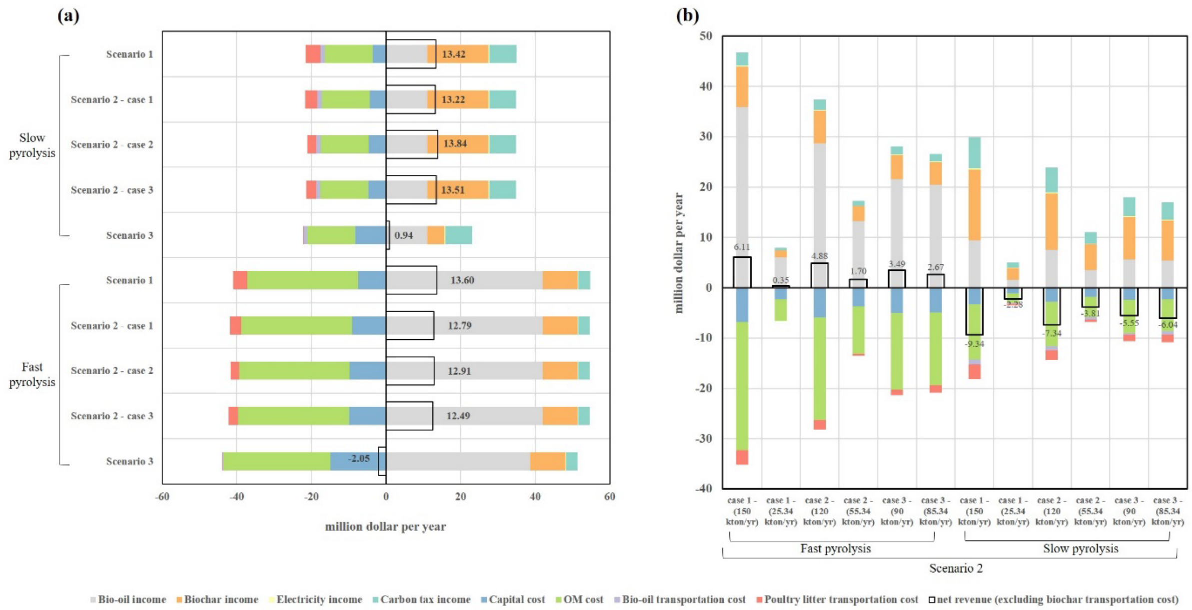



**Figure S6. (a)** Annualized economic breakdown of all scenarios for slow and fast pyrolysis in NYS **(b)** Annualized economic breakdown of all cases of Scenario 2 for slow and fast pyrolysis in NYS.

**4.1. Spatial distribution of soil phosphorus contents does not constrain application:** Since most of the P present in the feedstock is assumed to be transferred into the biochar during the pyrolysis processes, due consideration must be given to the changes in the soil P contents to avoid overfertilization and consequent nutrient run-off after biochar application. The best available data for the spatial distribution of P in NYS is based on the county level data instead of pixel level or farm level (Figure S5). Even with that approximation, data for certain counties such as Warren and Hamilton cannot be obtained. Thus, we combined the county-wise recommended P application data for soils on which corn is growing with the pixel (1500 × 1500 meter resolution) level corn cropland data in NYS. Then, we identified and plotted the corn cropland pixels where it is recommended to apply P (i.e. for those pixels where neither existence of corn cropland = 0 nor recommended P application value = 0) as shown in Figure S5. This provides a profile of biochar applicability on corn croplands in NYS. We then calculate the transportation of biochar based on these assumptions and then create Figures 4-6. Furthermore, the maximum possible P that can be found in the biochar from the entire state's CAFO poultry litter is 2.1 kton/year which is much lower than the recommended 5.7 kton/year for NYS. Hence, when looking at the entire state as a whole, over-application of P can be avoided with appropriate transportation within the state.

## 5. ADDITIONAL INFORMATION AND DATA

**Table S19.** Details and poultry numbers in each CAFO for NYS.[36, 47]

| Facility Name | County | Broilers | Layers | Manure (MT/yr) | Latitude | Longitude |
|---|---|---|---|---|---|---|
| C.A.C.L. Properties Llc. | Clinton | 0.00 | 40,000.00 | 1,285.00 | 43.00 | -78.58 |
| Giroux'S Poultry Farm | Clinton | 0.00 | 1,500,000.00 | 48,180.00 | 42.02 | -77.71 |
| Kreher'S Farm Fresh Eggs, Llc | Erie | 251,531.00 | 640,070.00 | 26,389.00 | 43.24 | -76.80 |
| Sunrise Farms Inc | Greene | 0.00 | 44,000.00 | 1,413.00 | 43.03 | -76.39 |
| Hudson Egg Farms, Llc | Onondaga | 0.00 | 167,616.00 | 5,384.00 | 42.89 | -76.04 |
| Smith Quality Eggs, Llc. | Onondaga | 51,000.00 | 106,000.00 | 4,587.00 | 41.76 | -74.94 |
| Ace Farm | Orange | 56,000.00 | 135,000.00 | 5,634.00 | 41.75 | -74.77 |
| Tomas Poultry Farm Of Schuylevil | Saratoga | 69,206.00 | 207,957.00 | 8,284.00 | 41.76 | -74.74 |
| Whitesville Farms, Llc | Steuben | 150,595.00 | 431,004.00 | 17,334.00 | 41.71 | -74.76 |
| Harold Brey & Sons Inc | Sullivan | 180,000.00 | 0.00 | 4,172.00 | 41.33 | -74.15 |
| Labelle Farm | Sullivan | 80,000.00 | 240,000.00 | 9,900.00 | 42.22 | -73.97 |
| Hvfg, Llc | Sullivan | 0.00 | 0.00 | 2,598.00 | 43.16 | -73.61 |
| Bella Poultry Inc. | Sullivan | 0.00 | 0.00 | 805.00 | 44.89 | -73.44 |
| Wayne County Eggs, Llc | Wayne | 213,357.00 | 1,072,724.00 | 39,401.00 | 44.86 | -73.43 |

**Table S20.** Distribution of poultry numbers in NYS based on counties.[47]

| County | Layers | Broilers | Turkeys | Latitude | Longitude |
|---|---|---|---|---|---|
| Albany | 3,557.00 | 406.00 | D | 42.60 | -73.97 |
| Allegany | 18,772.00 | 344.00 | 98.00 | 42.26 | -78.03 |
| Bronx | NA | NA | NA | 40.85 | -73.85 |
| Broome | 3,025.00 | 296.00 | 126.00 | 42.16 | -75.82 |
| Cattaraugus | 3,539.00 | 1,058.00 | 153.00 | 42.25 | -78.68 |
| Cayuga | 34,492.00 | 462.00 | 118.00 | 43.01 | -76.57 |
| Chautauqua | 5,887.00 | 2,725.00 | 665.00 | 42.30 | -79.41 |
| Chemung | 1,114.00 | D | 256.00 | 42.14 | -76.76 |
| Chenango | 5,453.00 | D | 424.00 | 42.49 | -75.61 |
| Clinton | D | 1,040.00 | 48.00 | 44.75 | -73.68 |
| Columbia | 9,359.00 | 2,558.00 | 393.00 | 42.25 | -73.63 |
| Cortland | 1,710.00 | D | D | 42.60 | -76.07 |
| Delaware | 5,905.00 | 1,254.00 | 562.00 | 42.20 | -74.97 |
| Dutchess | 4,542.00 | 14,301.00 | 57.00 | 41.77 | -73.74 |
| Erie | D | 11,660.00 | D | 42.76 | -78.78 |
| Essex | 6,317.00 | 3,814.00 | 583.00 | 44.12 | -73.77 |
| Franklin | 84,234.00 | 636.00 | 78.00 | 44.59 | -74.30 |
| Fulton | 5,228.00 | 126.00 | 21.00 | 43.11 | -74.42 |
| Genesee | D | 466.00 | 258.00 | 43.00 | -78.19 |
| Greene | D | 206.00 | 83.00 | 42.28 | -74.12 |
| Hamilton | NA | NA | NA | 43.66 | -74.50 |
| Herkimer | 10,079.00 | 4,372.00 | 77.00 | 43.42 | -74.96 |
| Jefferson | D | 870.00 | 149.00 | 44.00 | -76.05 |
| Kings | 28.00 | NA | NA | 40.63 | -73.95 |
| Lewis | 2,772.00 | 360.00 | 46.00 | 43.78 | -75.45 |
| Livingston | 2,577.00 | 282.00 | 39.00 | 42.73 | -77.78 |
| Madison | 2,902.00 | 1,288.00 | 332.00 | 42.91 | -75.67 |
| Monroe | 1,902.00 | 723.00 | 189.00 | 43.31 | -77.68 |
| Montgomery | 5,034.00 | 815.00 | 252.00 | 42.90 | -74.44 |
| Nassau | 60.00 | NA | NA | 40.73 | -73.59 |
| New York | 36.00 | NA | NA | 40.77 | -73.97 |
| Niagara | 4,067.00 | 1,881.00 | 280.00 | 43.34 | -78.77 |
| Oneida | 5,744.00 | 1,142.00 | 131.00 | 43.24 | -75.44 |
| Onondaga | 703,150.00 | 751.00 | D | 43.01 | -76.19 |
| Ontario | 40,723.00 | 643.00 | 116.00 | 42.85 | -77.30 |
| Orange | D | 619.00 | 87.00 | 41.40 | -74.31 |
| Orleans | 2,832.00 | 310.00 | D | 43.38 | -78.23 |

| | | | | | |
|---|---|---|---|---|---|
| Oswego | 2,607.00 | 832.00 | 274.00 | 43.46 | -76.21 |
| Otsego | 8,161.00 | 1,005.00 | 122.00 | 42.63 | -75.03 |
| Putnam | 899.00 | 133.00 | 12.00 | 41.43 | -73.75 |
| Queens | 550.00 | NA | NA | 40.66 | -73.84 |
| Rensselaer | 6,252.00 | 1,620.00 | 354.00 | 42.71 | -73.51 |
| Richmond | NA | NA | NA | 40.56 | -74.14 |
| Rockland | 359.00 | NA | NA | 41.15 | -74.02 |
| St Lawrence | 7,038.00 | 2,874.00 | 726.00 | 44.50 | -75.07 |
| Saratoga | D | 697.00 | 243.00 | 43.11 | -73.86 |
| Schenectady | 665.00 | 100.00 | D | 42.82 | -74.06 |
| Schoharie | 5,965.00 | 2,080.00 | 247.00 | 42.59 | -74.44 |
| Schuyler | 15,219.00 | 338.00 | D | 42.39 | -76.88 |
| Seneca | 68,095.00 | D | 1,259.00 | 42.78 | -76.82 |
| Steuben | D | 1,034.00 | 213.00 | 42.27 | -77.38 |
| Suffolk | 8,065.00 | D | 5,190.00 | 40.94 | -72.69 |
| Sullivan | D | D | D | 41.72 | -74.77 |
| Tioga | 2,317.00 | 405.00 | 211.00 | 42.17 | -76.31 |
| Tompkins | 2,724.00 | 305.00 | 59.00 | 42.45 | -76.47 |
| Ulster | 4,855.00 | 1,395.00 | 349.00 | 41.89 | -74.26 |
| Warren | 782.00 | 70.00 | D | 43.56 | -73.85 |
| Washington | 7,395.00 | D | 1,146.00 | 43.31 | -73.43 |
| Wayne | D | 810.00 | 57.00 | 43.33 | -77.05 |
| Westchester | 4,134.00 | 440.00 | D | 41.15 | -73.75 |
| Wyoming | 2,485.00 | 267.00 | 125.00 | 42.70 | -78.22 |
| Yates | 82,637.00 | 1,371.00 | 137.00 | 42.63 | -77.11 |

**Table S21.** Parameters and their values, units and meaning for the spatial analysis.

| **Parameter** | **Value** | **Unit** |
|---|---|---|
| discount rate | 0.050 | |
| project lifetime | 20.000 | years |
| ratio of carbon content of biochar for SP | 0.397 | |
| ratio of carbon content of biochar for FP | 0.300 | |
| ratio of biochar production for SP | 0.262 | |
| ratio of biochar production for FP | 0.178 | |
| ratio of bio-crude production for SP | 0.191 | |
| ratio of bio-crude production for FP | 0.390 | |
| ratio of gas production for SP | 0.209 | |
| ratio of gas production for FP | 0.118 | |
| ratio of diesel production from FP oil | 0.440 | |
| ratio of gasoline production from FP oil | 0.160 | |
| OM cost for SP with CHP (175.2 kt/yr) | 21.336 | |
| OM cost for SP with combustion (175.2 kt/yr) | 21.200 | |
| OM cost for FP with CHP and upgrading (175.2 kt/yr) | 29.692 | |
| OM cost for FP with CHP and no upgrading (175.2 kt/yr) | 23.107 | |
| OM cost for FP with combustion and upgrading (175.2 kt/yr) | 29.623 | |
| OM cost for FP with combustion and no upgrading (175.2 kt/yr) | 23.039 | |
| CC cost for SP with CHP (175.2 kt/yr) | 63.793 | |
| CC cost for SP with combustion (175.2 kt/yr) | 61.127 | |
| CC cost for FP with CHP and upgrading (175.2 kt/yr) | 93.182 | |
| CC cost for FP with CHP and no upgrading (175.2 kt/yr) | 59.195 | |
| CC cost for FP with combustion and upgrading (175.2 kt/yr) | 91.849 | |
| CC cost for FP with combustion and no upgrading (175.2 kt/yr) | 57.862 | |
| SP biochar price | 0.300 | $ M/kt |
| FP biochar price | 0.300 | $ M/kt |
| bio-crude price for both SP and FP (derived from $45/barrel and 7.33 barrel/t bio-crude) | 0.330 | $ M/kt |
| diesel price (derived from 325.9 cent/gal and 6.943 lb/gal diesel) | 1.035 | $ M/kt |
| gasoline price (derived from 279.0 cent/gal and 2.79 lb/gal diesel) | 0.989 | $ M/kt |
| the maximum ratio that can be accepted to each refinery | 0.010 | |
| Carbon Tax | 100.000 | $/t$CO_2$eq |
| Min gas flow for CHP - SP (for 500 MWe) | 4.600 | kton/yr |
| Min gas flow for CHP - FP (for 250 MWe) | 3.676 | kton/yr |
| CHP efficiency | 0.800 | |
| CHP electricity efficiency | 0.300 | |
| CHP heat efficiency | 0.500 | |

**Table S22.** List of considered existing refinery equipment that is capable of processing certain amounts of produced bio-oil.[34] Total operable capacity was considered while calculating the fraction of bio-oil that could potentially be accepted in each refinery. Ultimately, only the last two refineries listed in the table were considered in the analysis.

| **Company_name** | **Site** | **Product** | **Quantity (barrels/stream day)** |
|---|---|---|---|
| American refining group inc | Bradford | Asphalt & road oil | 65 |
| American refining group inc | Bradford | Asphalt & road oil | 65 |
| American refining group inc | Bradford | Cat reforming: high pressure | 1800 |
| American refining group inc | Bradford | Cat reforming: high pressure | 2200 |
| American refining group inc | Bradford | Cat reforming: high pressure | 2200 |
| American refining group inc | Bradford | Desulfurization, naphtha/reformer feed | 3600 |
| American refining group inc | Bradford | Desulfurization, naphtha/reformer feed | 3600 |
| American refining group inc | Bradford | Lubricants | 2945 |
| American refining group inc | Bradford | Lubricants | 2945 |
| American refining group inc | Bradford | Operating capacity | 11000 |
| American refining group inc | Bradford | Operating capacity | 11800 |
| American refining group inc | Bradford | Total oper cap (projected, next year) | 11800 |
| American refining group inc | Bradford | Total operable capacity | 11000 |
| American refining group inc | Bradford | Total operable capacity | 11800 |
| Monroe energy llc | Trainer | Alkylates | 12000 |
| Monroe energy llc | Trainer | Alkylates | 12000 |
| Monroe energy llc | Trainer | Cat cracking: fresh feed | 51500 |
| Monroe energy llc | Trainer | Cat cracking: fresh feed | 53000 |
| Monroe energy llc | Trainer | Cat cracking: fresh feed | 53000 |
| Monroe energy llc | Trainer | Cat hydrocracking, distillate | 21500 |
| Monroe energy llc | Trainer | Cat hydrocracking, distillate | 23000 |
| Monroe energy llc | Trainer | Cat hydrocracking, distillate | 23000 |
| Monroe energy llc | Trainer | Cat reforming: low pressure | 45000 |
| Monroe energy llc | Trainer | Cat reforming: low pressure | 50000 |
| Monroe energy llc | Trainer | Cat reforming: low pressure | 50000 |
| Monroe energy llc | Trainer | Desulfurization, diesel fuel | 53300 |
| Monroe energy llc | Trainer | Desulfurization, diesel fuel | 53300 |
| Monroe energy llc | Trainer | Desulfurization, gasoline | 34000 |
| Monroe energy llc | Trainer | Desulfurization, gasoline | 34000 |
| Monroe energy llc | Trainer | Desulfurization, kerosene and jet | 23300 |
| Monroe energy llc | Trainer | Desulfurization, kerosene and jet | 23300 |
| Monroe energy llc | Trainer | Desulfurization, naphtha/reformer feed | 80000 |
| Monroe energy llc | Trainer | Desulfurization, naphtha/reformer feed | 80000 |
| Monroe energy llc | Trainer | Operating capacity | 190000 |
| Monroe energy llc | Trainer | Operating capacity | 208000 |

| | | | |
|---|---|---|---|
| Monroe energy llc | Trainer | Sulfur (short tons/day) | 90 |
| Monroe energy llc | Trainer | Sulfur (short tons/day) | 90 |
| Monroe energy llc | Trainer | Total oper cap (projected, next year) | 208000 |
| Monroe energy llc | Trainer | Total operable capacity | 190000 |
| Monroe energy llc | Trainer | Total operable capacity | 208000 |
| Monroe energy llc | Trainer | Vacuum distillation | 73000 |
| Monroe energy llc | Trainer | Vacuum distillation | 73000 |
| Paulsboro refining co llc | Paulsboro | Alkylates | 11200 |
| Paulsboro refining co llc | Paulsboro | Alkylates | 11200 |
| Paulsboro refining co llc | Paulsboro | Asphalt & road oil | 21000 |
| Paulsboro refining co llc | Paulsboro | Asphalt & road oil | 21000 |
| Paulsboro refining co llc | Paulsboro | Cat cracking: fresh feed | 54000 |
| Paulsboro refining co llc | Paulsboro | Cat cracking: fresh feed | 55000 |
| Paulsboro refining co llc | Paulsboro | Cat cracking: fresh feed | 55000 |
| Paulsboro refining co llc | Paulsboro | Cat reforming: low pressure | 28500 |
| Paulsboro refining co llc | Paulsboro | Cat reforming: low pressure | 32000 |
| Paulsboro refining co llc | Paulsboro | Cat reforming: low pressure | 32000 |
| Paulsboro refining co llc | Paulsboro | Desulfurization, diesel fuel | 46000 |
| Paulsboro refining co llc | Paulsboro | Desulfurization, diesel fuel | 46000 |
| Paulsboro refining co llc | Paulsboro | Desulfurization, gasoline | 37000 |
| Paulsboro refining co llc | Paulsboro | Desulfurization, gasoline | 37000 |
| Paulsboro refining co llc | Paulsboro | Desulfurization, kerosene and jet | 29100 |
| Paulsboro refining co llc | Paulsboro | Desulfurization, kerosene and jet | 29100 |
| Paulsboro refining co llc | Paulsboro | Desulfurization, naphtha/reformer feed | 32000 |
| Paulsboro refining co llc | Paulsboro | Desulfurization, naphtha/reformer feed | 32000 |
| Paulsboro refining co llc | Paulsboro | Hydrogen (mmcfd) | 9 |
| Paulsboro refining co llc | Paulsboro | Hydrogen (mmcfd) | 9 |
| Paulsboro refining co llc | Paulsboro | Lubricants | 12000 |
| Paulsboro refining co llc | Paulsboro | Lubricants | 12000 |
| Paulsboro refining co llc | Paulsboro | Operating capacity | 160000 |
| Paulsboro refining co llc | Paulsboro | Operating capacity | 166000 |
| Paulsboro refining co llc | Paulsboro | Petcoke,market | 7500 |
| Paulsboro refining co llc | Paulsboro | Petcoke,market | 7500 |
| Paulsboro refining co llc | Paulsboro | Sulfur (short tons/day) | 280 |
| Paulsboro refining co llc | Paulsboro | Sulfur (short tons/day) | 350 |
| Paulsboro refining co llc | Paulsboro | Therm cracking, delayed coking | 26500 |
| Paulsboro refining co llc | Paulsboro | Therm cracking, delayed coking | 27000 |
| Paulsboro refining co llc | Paulsboro | Therm cracking, delayed coking | 27000 |
| Paulsboro refining co llc | Paulsboro | Total oper cap (projected, next year) | 166000 |
| Paulsboro refining co llc | Paulsboro | Total operable capacity | 160000 |
| Paulsboro refining co llc | Paulsboro | Total operable capacity | 166000 |
| Paulsboro refining co llc | Paulsboro | Vacuum distillation | 90000 |
| Paulsboro refining co llc | Paulsboro | Vacuum distillation | 90000 |

| | | | |
|---|---|---|---|
| Philadelphia energy solutions | Philadelphia | Alkylates | 26500 |
| Philadelphia energy solutions | Philadelphia | Alkylates | 26500 |
| Philadelphia energy solutions | Philadelphia | Aromatics | 4920 |
| Philadelphia energy solutions | Philadelphia | Aromatics | 4920 |
| Philadelphia energy solutions | Philadelphia | Cat cracking: fresh feed | 127300 |
| Philadelphia energy solutions | Philadelphia | Cat cracking: fresh feed | 137500 |
| Philadelphia energy solutions | Philadelphia | Cat cracking: fresh feed | 137500 |
| Philadelphia energy solutions | Philadelphia | Cat reforming: high pressure | 77400 |
| Philadelphia energy solutions | Philadelphia | Cat reforming: high pressure | 86000 |
| Philadelphia energy solutions | Philadelphia | Cat reforming: high pressure | 86000 |
| Philadelphia energy solutions | Philadelphia | Desulfurization, gasoline | 65000 |
| Philadelphia energy solutions | Philadelphia | Desulfurization, gasoline | 65000 |
| Philadelphia energy solutions | Philadelphia | Desulfurization, naphtha/reformer feed | 78000 |
| Philadelphia energy solutions | Philadelphia | Desulfurization, naphtha/reformer feed | 78000 |
| Philadelphia energy solutions | Philadelphia | Desulfurization, other distillate | 157000 |
| Philadelphia energy solutions | Philadelphia | Desulfurization, other distillate | 157000 |
| Philadelphia energy solutions | Philadelphia | Isomerization (isobutane) | 3800 |
| Philadelphia energy solutions | Philadelphia | Isomerization (isobutane) | 3800 |
| Philadelphia energy solutions | Philadelphia | Operating capacity | 335000 |
| Philadelphia energy solutions | Philadelphia | Operating capacity | 350000 |
| Philadelphia energy solutions | Philadelphia | Sulfur (short tons/day) | 76 |
| Philadelphia energy solutions | Philadelphia | Sulfur (short tons/day) | 76 |
| Philadelphia energy solutions | Philadelphia | Total oper cap (projected, next year) | 350000 |
| Philadelphia energy solutions | Philadelphia | Total operable capacity | 335000 |
| Philadelphia energy solutions | Philadelphia | Total operable capacity | 350000 |
| Philadelphia energy solutions | Philadelphia | Vacuum distillation | 163200 |
| Philadelphia energy solutions | Philadelphia | Vacuum distillation | 163200 |
| Phillips 66 company | Linden | Alkylates | 18800 |
| Phillips 66 company | Linden | Alkylates | 18800 |
| Phillips 66 company | Linden | Cat cracking: fresh feed | 128000 |
| Phillips 66 company | Linden | Cat cracking: fresh feed | 145000 |
| Phillips 66 company | Linden | Cat cracking: fresh feed | 145000 |
| Phillips 66 company | Linden | Cat reforming: low pressure | 32300 |
| Phillips 66 company | Linden | Cat reforming: low pressure | 35900 |
| Phillips 66 company | Linden | Cat reforming: low pressure | 35900 |
| Phillips 66 company | Linden | Desulfurization, diesel fuel | 108000 |
| Phillips 66 company | Linden | Desulfurization, diesel fuel | 108000 |
| Phillips 66 company | Linden | Desulfurization, naphtha/reformer feed | 65500 |
| Phillips 66 company | Linden | Desulfurization, naphtha/reformer feed | 65500 |
| Phillips 66 company | Linden | Desulfurization, other distillate | 17500 |
| Phillips 66 company | Linden | Desulfurization, other distillate | 17500 |
| Phillips 66 company | Linden | Fuels solvent deasphalting | 22000 |
| Phillips 66 company | Linden | Fuels solvent deasphalting | 22000 |

| | | | |
|---|---|---|---|
| Phillips 66 company | Linden | Hydrogen (mmcfd) | 22 |
| Phillips 66 company | Linden | Hydrogen (mmcfd) | 22 |
| Phillips 66 company | Linden | Isomerization (isobutane) | 4000 |
| Phillips 66 company | Linden | Isomerization (isobutane) | 4000 |
| Phillips 66 company | Linden | Operating capacity | 258500 |
| Phillips 66 company | Linden | Operating capacity | 272100 |
| Phillips 66 company | Linden | Total oper cap (projected, next year) | 272100 |
| Phillips 66 company | Linden | Total operable capacity | 258500 |
| Phillips 66 company | Linden | Total operable capacity | 272100 |
| Phillips 66 company | Linden | Vacuum distillation | 75000 |
| Phillips 66 company | Linden | Vacuum distillation | 75000 |
| United refining co | Warren | Alkylates | 4500 |
| United refining co | Warren | Alkylates | 4500 |
| United refining co | Warren | Asphalt & road oil | 22000 |
| United refining co | Warren | Asphalt & road oil | 22000 |
| United refining co | Warren | Cat cracking: fresh feed | 24000 |
| United refining co | Warren | Cat cracking: fresh feed | 25000 |
| United refining co | Warren | Cat cracking: fresh feed | 25000 |
| United refining co | Warren | Cat cracking: recycled feed | 1000 |
| United refining co | Warren | Cat cracking: recycled feed | 1000 |
| United refining co | Warren | Cat reforming: high pressure | 13000 |
| United refining co | Warren | Cat reforming: high pressure | 14000 |
| United refining co | Warren | Cat reforming: high pressure | 14000 |
| United refining co | Warren | Desulfurization, diesel fuel | 17000 |
| United refining co | Warren | Desulfurization, diesel fuel | 17000 |
| United refining co | Warren | Desulfurization, gasoline | 5000 |
| United refining co | Warren | Desulfurization, gasoline | 5000 |
| United refining co | Warren | Desulfurization, kerosene and jet | 5000 |
| United refining co | Warren | Desulfurization, kerosene and jet | 5000 |
| United refining co | Warren | Desulfurization, naphtha/reformer feed | 26000 |
| United refining co | Warren | Desulfurization, naphtha/reformer feed | 26000 |
| United refining co | Warren | Hydrogen (mmcfd) | 10 |
| United refining co | Warren | Hydrogen (mmcfd) | 10 |
| United refining co | Warren | Isomerization (isopentane/isohexane) | 8500 |
| United refining co | Warren | Isomerization (isopentane/isohexane) | 8500 |
| United refining co | Warren | Operating capacity | 65000 |
| United refining co | Warren | Operating capacity | 70000 |
| United refining co | Warren | Sulfur (short tons/day) | 67 |
| United refining co | Warren | Sulfur (short tons/day) | 67 |
| United refining co | Warren | Total oper cap (projected, next year) | 70000 |
| United refining co | Warren | Total operable capacity | 65000 |
| United refining co | Warren | Total operable capacity | 70000 |
| United refining co | Warren | Vacuum distillation | 40000 |

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