Supporting Information

Opening pathways for the conversion of woody biomass into sustainable aviation fuel via catalytic fast pyrolysis and hydrotreating

Michael B. Griffin*[a], Kristiina Iisa[a], Abhijit Dutta[a], Xiaolin Chen[a], Cody Wrasman[a], Calvin Mukarakate[a], Matthew M. Yung [a], Mark R. Nimlos [a], Luke Tuxworth[b], Xavier Baucherel[b], Steven M. Rowland [a], Susan E. Habas [a]

Table S1. Compositional analysis of the biomass feedstock	
C, wt%	49.4%
H, wt%	6.1%
N, wt%	0.2%
Ash, wt%	1.0%
H_2O, wt%	3.3%
O by difference, wt%	43.3%
O dry basis, wt%	41.8%

Table S2. Carbon yields of gases produced during CFP gC/gC in biomass x 100%		
	17-O CFP	20-O CFP
CO	11.9	12.8
CO_2	4.9	4.6
CH_4	2.8	2.4
Ethene	2.7	2.2
Propene	2.3	1.9
Butenes	0.7	0.8
Ethane	0.2	0.2
Propane	0.4	0.3
Total	25.8	25.1

Table S3. Compositional analysis of CFP-oils by GC-MS, wt%		
	17-O CFP	20-O CFP
Aromatic hydrocarbons	14.1	7.9
Phenols (monofunctional)	3.3	2.6
Benzenediols	0	0
Methoxyphenols	3.2	3.7
Naphthols/Indenols	0.8	0.6
Ketones	1.3	1.7
Aldehydes	0.4	1.1
Furans	0.3	0.6
Acids	0.2	0.4
Anhydrosugars	1.9	2.9
Total	25.5	21.6

Table S4. Characterization of Pre-Reaction, Post-Reaction, and Regenerated ZSM-5 Catalysts

	Surface Area, m^2/g	Acid Site Density, μmol NH_3/g
Pre-Reaction	340	765
Post-Reaction	85	516
Regenerated	336	722

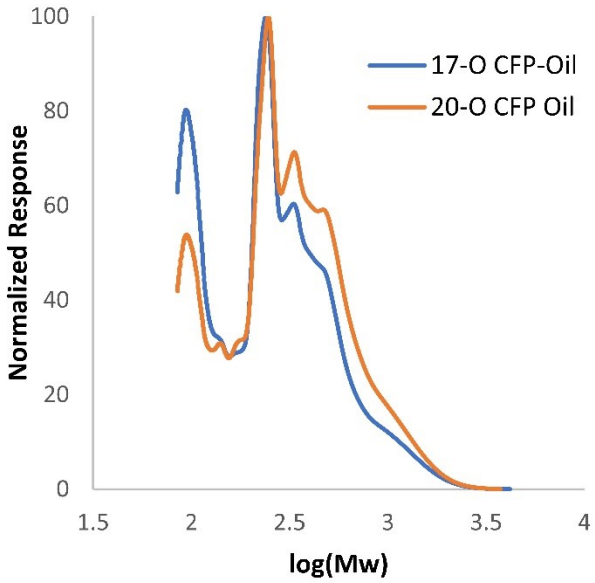

Figure S1. Gel permeation chromatography illustrating the comparatively low molecular weight distribution of the 17-O vs 20-O CFP-oils.

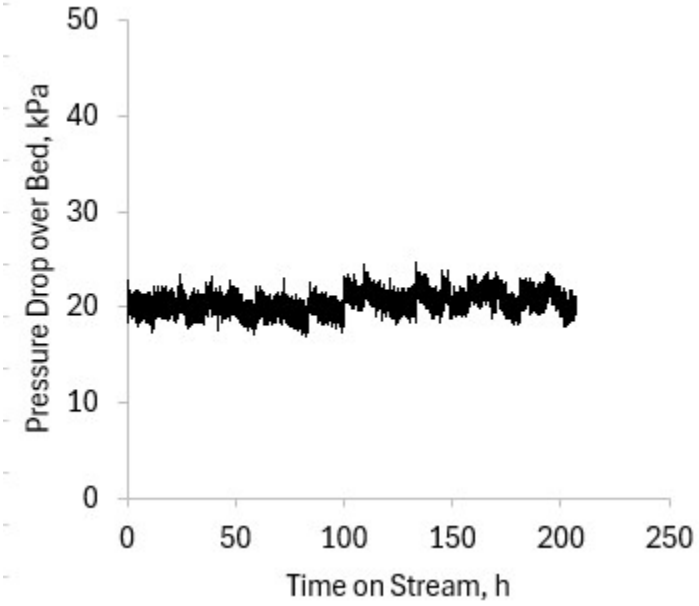

Figure S2. Measured pressure drop over the catalyst bed during hydrotreating of the 17-O CFP-oil

Table S5. Mass yields of gases produced during hydrotreating, g/g CFP-oil x 100%		
	17-O CFP	20-O CFP
CO	0	0
CO_2	0	0
CH_4	1.5	2.2
C_2	0.7	1.3
C_3	1.1	2.4
C_4	0.3	0.5
C_5	0.4	0.6

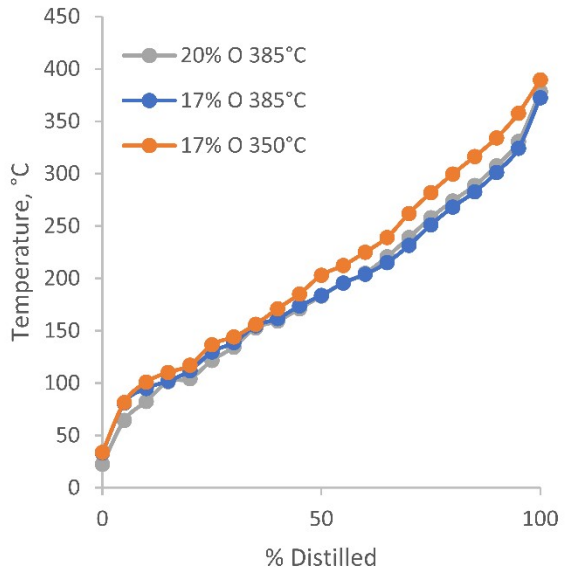

Figure S5. Simulated distillation (ASTM D2887) of 17-O and 20-O CFP-oils hydrotreated at 385 and 350 °C.

Table S6. Unit prices of key inputs* for TEA			
	Unit	Value	Cost Year
Feedstock (50 wt% pine /50 wt% residues)	$/dry US ton	67	2016
CFP catalyst §	$/lb	9.75	2011
Hydrotreating Catalyst	$/lb	20	2011

*Other than feedstock, all assumptions are maintained from 2015 design report: https://www.nrel.gov/docs/fy15osti/62455.pdf .

‡ As in our other work, PPI industry sub-sector data for Chemical Manufacturing was used to update prices to 2016$

§ A different catalyst unit cost can be prorated in the cost contribution tables to evaluate sensitivity to catalyst costs .

Table S7. Total Capital Investment in 2016$ (17-O base case)

Process Area		Purchased Equip. Cost	Installed Cost
Area 100: Feed Handling & Drying		$300,000	$580,000
Area 200: Fast Pyrolysis & Vapor Upgrading		$64,240,000	$179,200,000
Area 300: Pyrolysis Vapor Quench		$6,210,000	$11,410,000
Area 400: Hydroprocessing and Separation		$22,680,000	$36,040,000
Area 500: Hydrogen Plant		$24,760,000	$50,060,000
Area 600: Steam System and Power Generation		$40,820,000	$73,760,000
Area 700: Cooling Water and Other Utilities		$4,980,000	$10,000,000
Area 800: Water Management		$8,400,000	$19,850,000
Totals		**$172,390,000**	**$380,910,000**
Total Purchased Equipment Cost (TPEC)			**$172,390,000**
Installation Factor			2.210
Total Installed Cost (TIC)			**$380,910,000**
Other Direct Costs			
Land (Not Depreciated)			$1,610,000
Warehouse	4.0%	of ISBL	$9,090,000
Site Development	10.0%	of ISBL	$22,720,000
Additional Piping	4.5%	of ISBL	$10,230,000
Total Direct Costs (TDC)			**$422,940,000**
Indirect Costs		% of TDC	
Prorated Expenses		10.0%	$42,290,000
Home Office & Construction Fees		20.0%	$84,590,000
Field Expenses		10.0%	$42,290,000
Project Contingency		10.0%	$42,290,000
Other Costs (Start-Up & Permits)		10.0%	$42,290,000
Total Indirect Costs		**60.0%**	**$253,770,000**
Fixed Capital Investment (FCI)			**$676,710,000**
Working Capital	5.0%	of FCI (ex Land)	$33,840,000
Total Capital Investment (TCI)			**$710,550,000**

Table S8. Total Capital Investment in 2016$ (20-O base case)

Process Area		**Purchased Equip. Cost**	**Installed Cost**
Area 100: Feed Handling & Drying		$340,000	$650,000
Area 200: Fast Pyrolysis & Vapor Upgrading		$63,270,000	$176,420,000
Area 300: Pyrolysis Vapor Quench		$6,330,000	$11,620,000
Area 400: Hydroprocessing and Separation		$25,290,000	$40,200,000
Area 500: Hydrogen Plant		$26,100,000	$52,110,000
Area 600: Steam System and Power Generation		$38,560,000	$70,040,000
Area 700: Cooling Water and Other Utilities		$4,890,000	$9,900,000
Area 800: Water Management		$12,190,000	$28,670,000
Totals		**$176,960,000**	**$389,610,000**
Total Purchased Equipment Cost (TPEC)			**$176,960,000**
Installation Factor			2.202
Total Installed Cost (TIC)			**$389,610,000**
Other Direct Costs			
Land (Not Depreciated)			$1,610,000
Warehouse	4.0%	of ISBL	$9,160,000
Site Development	10.0%	of ISBL	$22,890,000
Additional Piping	4.5%	of ISBL	$10,300,000
Total Direct Costs (TDC)			**$431,960,000**
Indirect Costs		% of TDC	
Prorated Expenses		10.0%	$43,200,000
Home Office & Construction Fees		20.0%	$86,390,000
Field Expenses		10.0%	$43,200,000
Project Contingency		10.0%	$43,200,000
Other Costs (Start-Up & Permits)		10.0%	$43,200,000
Total Indirect Costs		**60.0%**	**$259,170,000**
Fixed Capital Investment (FCI)			**$691,130,000**
Working Capital	5.0%	of FCI (ex Land)	$34,560,000
Total Capital Investment (TCI)			**$725,690,000**

Table S9. Modeled Cost Contributions in 2016$ (17-O base case)	**cents/GGE**

Feedstock	176.9
Natural Gas	0.1
Catalysts*	96.4
Sand	0.8
Other Raw Materials	9.5
Waste Disposal	3.6
Purchased Electricity	0.0
Fixed Costs	117.4
Refinery Coprocessing Cost	0.0
Electricity Coproduct Credit	-73.0
Capital Depreciation	124.3
Average Income Tax	26.1
Average Return on Investment	186.4
Total	**668.6**
* Modeled CFP catalyst contribution = 68.4 cents/GGE	
* Modeled hydrotreating catalyst contribution = 27.2 cents/GGE	

Table S10. Modeled Cost Contributions in 2016$ (20-O base case)	**cents/GGE**
Feedstock	156.6
Natural Gas	0.2
Catalysts*	89.4
Sand	0.7
Other Raw Materials	8.5
Waste Disposal	3.3
Purchased Electricity	0.0
Fixed Costs	105.6
Refinery Coprocessing Cost	0.0
Electricity Coproduct Credit	-53.9
Capital Depreciation	112.4
Average Income Tax	23.5
Average Return on Investment	168.7
Total	**615.0**
* Modeled CFP catalyst contribution = 60.6 cents/GGE	
* Modeled hydrotreating catalyst contribution = 28.1 cents/GGE	

Table S11. Breakdown of GHG Emissions (17-O base case)

Operation	Emissions (g CO2e/MJ)
Forest residue processing	3.7
Forest residue transportation	2.8
Receiving handling and storage	0.3
Forest residue preprocessing	13.2
Pine collection	8.5
Pine processing	0.3
Pine transportation	1.6
Pine handling and storage	0.1
Pine preprocessing	15.5
Fuel production	-40.0
Fuel combustion	1.1
Total	**7.0**
Petroleum Jet Fuel (PJF) incumbent	88.7
GHG reduction compared to incumbent	92%

Table S12. Breakdown of GHG Emissions (20-O base case)

Operation	Emissions (g CO2e/MJ)
Forest residue processing	3.3
Forest residue transportation	2.4
Receiving handling and storage	0.2
Forest residue preprocessing	11.7
Pine collection	7.5
Pine processing	0.3
Pine transportation	1.4
Pine handling and storage	0.1
Pine preprocessing	13.7
Fuel production	-28.4
Fuel combustion	1.1
Total	**13.3**
Petroleum Jet Fuel (PJF) incumbent	88.7
GHG reduction compared to incumbent	85%