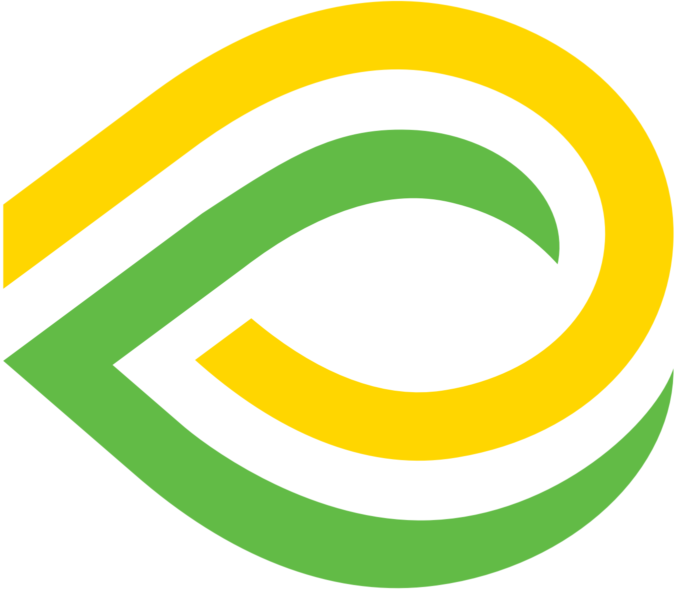
U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM

Comparative Techno-Economic Analysis of Available Feedstocks for High-Temperature Conversion: Whole Tree Thinnings and Mature Pine Residues



DOE/EE- 2738 • July 2023

Disclaimer

About the Feedstock-Conversion Interface Consortium

The Feedstock-Conversion Interface Consortium (FCIC) develops first-principles-based knowledge and tools to understand, quantify, and mitigate the effects of feedstock and process variability across the bioenergy value chain, from the field and forest through downstream conversion. The FCIC is a collaborative and coordinated effort involving researchers in many different disciplines. It is led by the U.S. Department of Energy's Bioenergy Technologies Office (BETO) and includes researchers from nine national laboratories: Argonne National Laboratory, Idaho National Laboratory, Lawrence Berkeley National Laboratory, Los Alamos National Laboratory, National Energy Technology Laboratory, National Renewable Energy Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, and Sandia National Laboratories.

Research within the FCIC focuses on two complementary conversion pathways: (1) the low-temperature conversion of corn stover to fuels and chemicals using deacetylation and mechanical refining, enzymatic hydrolysis, and biological upgrading of the sugar- and lignin-rich streams; and (2) the high-temperature conversion of pine residues to fuels using catalytic fast pyrolysis and hydrotreating. Each pathway covers three sequential process areas—biomass harvest and storage, preprocessing, and conversion.

The FCIC is organized into eight collaborative tasks working in each of these process areas. The Feedstock Variability task investigates biomass attribute variations that originate in the harvest and storage process area; the Preprocessing, Materials Handling, and Materials of Construction tasks investigate the effects of biomass variability in the preprocessing area; and the High-Temperature Conversion and Low-Temperature Conversion tasks investigate the effects of biomass variability in the conversion process area. Two supporting tasks (Crosscutting Analyses and Scientific Data Management) support all FCIC research.

The Feedstock-Conversion Interface Consortium uses first-principles-based science to de-risk biorefinery scale-up and deployment by understanding and mitigating the impacts of feedstock variability on bioenergy conversion processes.

energy.gov/fcic

Availability

This report is available electronically at no cost from http://www.osti.gov.

Report Author

Matthew Wiatrowski, National Renewable Energy Laboratory

List of Acronyms

CFP	Catalytic fast pyrolysis
FCIC	Feedstock-Conversion Interface Consortium
FP	Fast pyrolysis
GGE	Gasoline gallon equivalent
LCI	Life cycle inventory
MFSP	Minimum fuel selling price
TEA	Techno-economic analysis

Executive Summary

The techno-economic and life cycle implications of utilizing low-cost feedstocks in a high-temperature conversion process are of great interest. Here, we investigate the conversion cost impacts of two underutilized feedstocks from the commercial pine industry: 13-year-old whole trees, representing trees removed for the purpose of precommercial thinning, and 23-year-old pine residues, representing a waste stream produced from the deconstruction of mature trees for other purposes. Experimental fast pyrolysis (FP) yields for each feedstock were adjusted to a catalytic fast pyrolysis (CFP) basis and used to estimate process economics by employing published correlations based on rigorous techno-economic modeling. These correlations were used in tandem with results from supply and preprocessing analyses to evaluate the field-to-fuel economics of each feedstock. A small difference in minimum fuel selling price (MFSP) was found between the conversion costs for the two feedstocks, with 23-year-old residues demonstrating a net benefit of $0.27 per gasoline gallon equivalent (GGE) compared to the 13-year-old whole tree thinnings, driven primarily by feedstock supply costs. This suggests that both whole tree thinnings and pine residues may be viable feedstock options for CFP conversion. Life cycle inventories (LCIs) were also generated for each case, enabling a field-to-fuel quantification of the cost and carbon cycle associated with each feedstock.

Table of Contents

List of Figures

List of Tables

Introduction

Underutilized, low-cost feedstocks are ideal candidates for enabling the production of cost-competitive biofuels in the near term. These feedstocks can be diverted from an existing commercial industry and add value without any significant interruption to normal operations. In CFP, woody biomass is a preferred feedstock due to its low ash content and propensity to produce high-quality bio-oil suitable for upgrading to biofuel (Carpenter et al. 2014). It follows that logical feedstocks for enabling cost-competitive, high-temperature conversion processes are underutilized streams from the existing commercial pine industry. Two potential sources for these feedstocks are whole precommercial thinning trees (removed prior to full maturity for the purpose of preventing growth stagnation in adjacent trees) and residues of mature trees used for commercial purposes such as lumber or pulp and paper. We also considered a blend of these two feedstocks in the ratio that would be available from a single harvest area. To quantify the economic and life cycle impacts of utilizing these feedstocks, rigorous modeling should be done at each step of the supply chain. Here, we focus on predicting the impacts of each feedstock on the CFP conversion step.

The most recent analyses for CFP have sought to advance the state of technology toward underutilized feedstocks while still demonstrating competitive performance parameters. In the fiscal year 2019 state-of-technology report (Dutta et al. 2020), this is achieved by using a 50/50 blend of clean pine and pine residues, with future target cases envisioning increasingly higher proportions of residues. In this study, we build on previous work to investigate the cost impacts of utilizing waste streams from the commercial pine industry on CFP conversion. Specifically, we focus on (1) precommercial thinning trees, represented by whole 13-year-old trees, and (2) pine residues from mature trees used in existing industries, represented by 23-year-old residues (Figure 1). A combination of these two feedstocks is also considered as a third case. In addition to an analysis of cost impacts within conversion, we also generate an LCI to enable the field-to-fuel life cycle assessment of a CFP process utilizing these waste feedstocks.

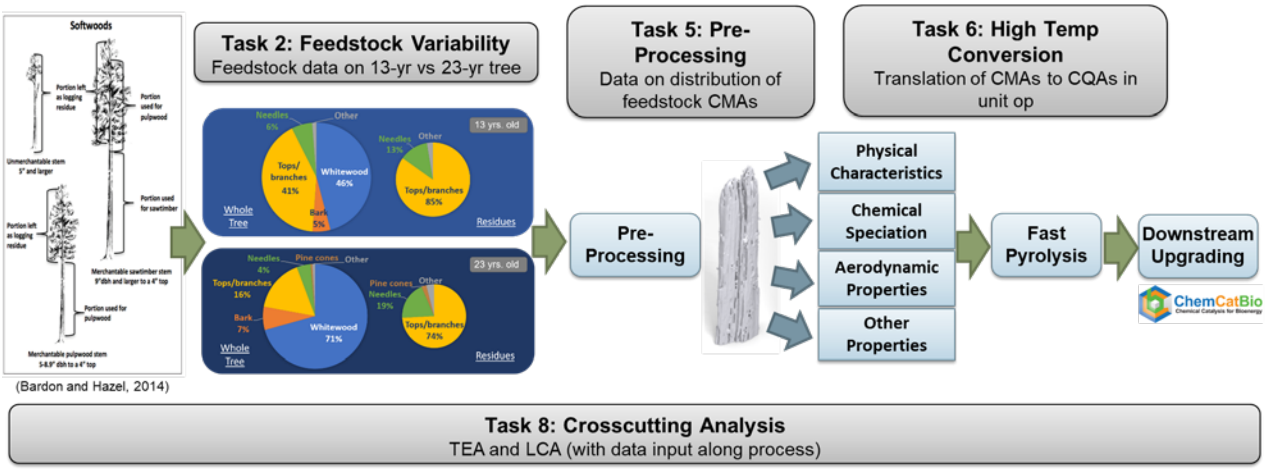


Figure 1. High-level flowchart of field-to-fuel 13- and 23-year-old tree study.
Figure courtesy of Daniel Carpenter, National Renewable Energy Laboratory.

Methods

To quantify the impact of each feedstock on the MFSP of the conversion process, experimental FP data generated from the FCIC were leveraged, which included carbon yields of oil, gas, and char yields through the pyrolyzer for each feedstock. These data were then adjusted to a CFP basis by comparing the FP yields of a known feedstock (a 50/50 blend of clean pine and residues) to the CFP fuel yields of a similar feedstock from the 2019 CFP state of technology (Dutta et al. 2020), run on a 0.5% Pt/TiO_2 catalyst. An adjustment factor of 1.72 was applied to the FP yields for each feedstock to estimate the resulting modeled CFP fuel carbon yields (Table 2). This adjustment factor is a reasonable approximation for the purpose of applying to multiple scenarios and approximating MFSP for comparison; however, it should be noted that it is less appropriate for providing an exact MFSP in isolation. For validation, the adjustment factor was applied to an unrelated feedstock (clean pine) for which both FP and CFP data were available. When applied to the experimental FP yield of 59.3%, the adjustment factor predicted a CFP yield of 34.6%, which can be compared to an actual CFP yield of 35.9% (Dutta et al. 2018) over the same 0.5% Pt/TiO_2 catalyst. This difference shows both the suitability of the adjustment factor as an approximation for comparison and the limitations of using it to predict accurate fuel yields for a feedstock in isolation.

Following this adjustment, the CFP yields for each feedstock were used in conjunction with correlations developed from a previous techno-economic assessment (TEA) to predict the MFSP of each feedstock (Wiatrowski et al. 2021). This published correlation (Wiatrowski et al. 2021) was developed by exercising a rigorous TEA model over varying levels of fuel and char yields. Additional details on the TEA model from which the correlation was developed can be found in Dutta et al. (2020). Finally, MFSPs were then adjusted according to the supply and preprocessing costs, obtained from colleagues within the FCIC at Oak Ridge National Laboratory and Idaho National Laboratory, respectively (Table 1).

Table 1. Feedstock costs for each feedstock considered, broken down into supply and preprocessing. Supply cost represents the delivered feedstock cost prior to preprocessing; preprocessing cost represents the cost specifically incurred during preprocessing; total feedstock cost represents the feedstock cost at the reactor throat.

	Whole Thinnings	Residues	Thinnings & Residues
Total feedstock cost ($/ton)	$90.13	$73.75	$85.74
Supply ($/ton)	$64.00	$46.41	$59.17
Preprocessing ($/ton)	$26.13	$27.34	$26.57

In addition to the cost impacts of the various feedstocks considered, an LCI was generated for each of the two primary feedstocks of interest (13-year-old whole trees and 23-year-old residues). LCIs were generated by linear interpolation of fuel yield between two established CFP cases: the 2019 state-of-technology case, upon which the modeling framework is based, and the

2020 projection case, which considers increased fuel yields (Dutta et al. 2020). This approach allows for high-throughput generation of LCI data.

Results and Discussion

It was found that the field-to-fuel processing costs for each feedstock within the conversion process were similar, with MFSPs spanning \$0.27/GGE (\$4.34–\$4.61/GGE) for all the feedstocks considered. A cost breakdown of each case by supply stage chain (i.e., supply, preprocessing, and conversion) is shown in Figure 2. Twenty-three-year-old residues were the most economical option, despite higher conversion costs. This is primarily driven by lower supply costs, since the harvesting costs of residues are allocated to merchantable wood products.

It should be noted that the *conversion* of 13-year-old whole tree thinnings was actually more economical than residues (assuming equivalent feedstock costs) due to higher char yields for the pine residues (18.6% for residues vs. 14.6% for thinnings) and comparable fuel yields (45.4% for residues vs. 43.5% for thinnings). However, any economic benefit from this is outweighed by the higher harvesting costs for the whole tree thinnings.

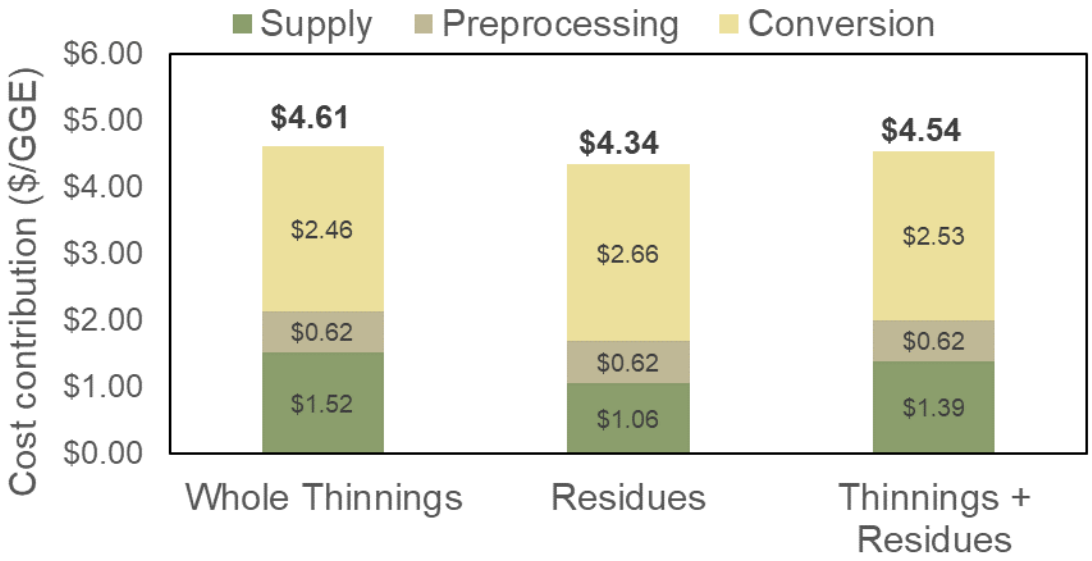


Figure 2. Cost contribution of each supply chain stage to the MFSP for each feedstock. “Thinnings + Residues” represents a case considering the harvesting, preprocessing, and conversion of both feedstocks (36% residues and 64% thinnings, based on supply availability from a single harvest area).

Table 2. Experimental and modeled pyrolysis oil yields for each feedstock. Modeled CFP char yield was assumed to be equal to the experimental FP char yield. "50/50 Clean Pine and Residues" represents the basis for the CFP adjustment and is relevant for the 2019 state-of-technology case (Dutta et al. 2020). Clean pine is shown for comparison only (Dutta et al. 2018).

	Residues	Thinnings	Thinnings + Residues	50/50 Clean Pine and Residues	Clean Pine
Experimental FP Yield (wt % of dry biomass)	45.4%	43.5%	44.2%	56.7%	59.3%
Modeled CFP Fuel C Yield	26.4%	25.3%	25.7%	33.0%	34.6% (vs. actual value of 35.9%) (Dutta et al. 2018)
CFP Fuel Carbon Yield: Experimental FP Yield	0.583	0.583	0.583	0.583	0.605
Char Yield	18.6%	14.6%	16.1%	11.7%	11.7%

Similarly, the conversion process LCI for each feedstock (Table 3) was found to be comparable for each feedstock of interest. Higher fuel yields for the 13-year-old whole trees resulted in lower char yields, consequently leading to a higher amount of required natural gas to supplement char burning to meet process heating demands. This also resulted in a higher amount of excess electricity produced.

Table 3. LCI for each feedstock considered. "Thinnings + Residues" represents a case considering the harvesting, preprocessing, and conversion of both feedstocks (36% residues and 64% thinnings, based on supply availability from a shared area of land).

	Flow rate (lb/h)		
	Residues	Thinnings	Residues + Thinnings
Products			
Gasoline fuel	15,602	15,125	15,298
Diesel fuel	12,307	11,612	11,865
Total	27,909	26,737	27,163
Byproducts			
Excess electricity	12,682	14,457	13,813
MEK (2-butanone)	1,165	1,165	1,165
Acetone	4,912	4,897	4,902
Resource Consumption			
Blended woody biomass (wet)	204,131	204,131	204,131
Blended woody biomass (dry)	183,718	183,718	183,718
Sand makeup	155	155	155
Natural gas [a]	158	177	170
Zeolite catalyst	0.00E+00	0.00E+00	0.00E+00
Fixed-bed VPU catalyst (0.5% Pt/TiO_2)	7	7	7

Hydrotreating catalyst (sulfided CoMo)	11	11	11
Hydrocracking catalyst (crystalline Si-Al with rare-earth metals)	2	2	2
ZnO (reforming cleanup)	4.01E-02	4.49E-02	4.32E-02
HDS (reforming cleanup)	1.72E-02	1.92E-02	1.85E-02
Steam reforming catalyst	8.87E-02	9.92E-02	9.54E-02
Shift catalyst	1.21E-01	1.36E-01	1.30E-01
PSA adsorbent	3.04E+00	3.40E+00	3.27E+00
50 wt % caustic	289	289	289
Net water makeup	73,713	73,526	73,594
Boiler feed water chemicals	2	2	2
Cooling tower chemicals	1	1	1
No. 2 diesel fuel	71	71	71
Waste Streams			
Solids purge from fluidized bed reactors	5,345	5,541	5,470
Wastewater	23,221	22,921	23,030
Air Emissions			
CO_2 (fossil)	433	484	466
CO_2 (biogenic)	217,319	220,833	219,558
CH_4	0.00E+00	0.00E+00	0.00E+00
CO	0.00E+00	0.00E+00	0.00E+00
NO_2	11	12	12
SO_2	105	105	105
H_2O	144,287	145,995	145,375
H_2S	0.00E+00	0.00E+00	0.00E+00

[a] Natural gas stream was negligible. This was included to maintain model flexibility to allow natural gas use as an option (Dutta et al. 2020).

Conclusion and Next Steps

The field-to-fuel economics for several industrially relevant low-cost feedstocks were defined, including whole tree thinnings, mature residues, and a combination of the two. This effort leveraged data from several tasks of the FCIC, including experimental data from high-temperature conversion and feedstock supply and preprocessing costs from crosscutting analysis (which in turn leveraged data from the preprocessing and feedstock variability tasks). The economics of each feedstock were not dramatically different, suggesting both residues and whole tree thinnings, or some combination of the two, can be viable feedstocks for a CFP biorefinery. Residues were shown to be the most economical option of those considered here, primarily due to lower supply costs.

LCIs generated from this exercise also showed limited differences between the cases. The case considering the 13-year-old whole trees demonstrated slightly lower fuel yields, accompanied by slightly higher excess generated electricity compared to the 23-year-old residues. These data, in combination with similar LCI data from the supply and preprocessing steps, enable a rigorous quantification of the field-to-fuel greenhouse gas emissions for each feedstock through the supply chain.

Citations and References

Carpenter, Daniel, Tyler L. Westover, Stefan Czernik, and Whitney Jablonski. 2014. "Biomass Feedstocks for Renewable Fuel Production: A Review of the Impacts of Feedstock and Pretreatment on the Yield and Product Distribution of Fast Pyrolysis Bio-Oils and Vapors." *Green Chemistry* 16 (2): 384–406. https://doi.org/10.1039/C3GC41631C.

Dutta, Abhijit, Kristiina Iisa, Calvin Mukarakate, Mike Griffin, Eric Tan, Josh Schaidle, David Humbird, et al. 2018. *Ex Situ Catalytic Fast Pyrolysis of Lignocellulosic Biomass to Hydrocarbon Fuels: 2018 State of Technology and Future Research*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5100-71954.

Dutta, Abhijit, Maarit K. Iisa, Michael Talmadge, Calvin Mukarakate, Michael B. Griffin, Eric C. Tan, Nolan Wilson, et al. 2020. *Ex Situ Catalytic Fast Pyrolysis of Lignocellulosic Biomass to Hydrocarbon Fuels: 2019 State of Technology and Future Research*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5100-76269. https://doi.org/10.2172/1605092.

Wiatrowski, Matthew R., Abhijit Dutta, M. Brennan Pecha, Meagan Crowley, Peter N. Ciesielski, and Daniel Carpenter. 2021. "A Simplified Integrated Framework for Predicting the Economic Impacts of Feedstock Variations in a Catalytic Fast Pyrolysis Conversion Process." *Biofuels, Bioproducts & Biorefining* 16 (2). https://doi.org/10.1002/bbb.2319.

Acknowledgments

This work was performed as part of the Feedstock-Conversion Interface Consortium (FCIC) with funding graciously provided by the U.S. Department of Energy (DOE) Bioenergy Technologies Office. This article was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, under Contract No. DE-AC36-08GO28308. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

The author would like to thank the following researchers for their contributions to this work: Erin Webb (Oak Ridge National Laboratory) for contributions regarding the supply costs of the feedstocks considered here; David Thompson and Damon Hartley (Idaho National Laboratory) for contributions regarding the preprocessing costs of the feedstocks considered here; and Steven Phillips (Pacific Northwest National Laboratory), Abhijit Dutta, and Anne Starace (National Renewable Energy Laboratory) for revisions and comments on the content of this report.

U.S. DEPARTMENT OF
ENERGY
Office of ENERGY EFFICIENCY
& RENEWABLE ENERGY

BIOENERGY TECHNOLOGIES OFFICE

For more information, visit: energy.gov/eere/bioenergy