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2017 U.S. Department of Energy Bioenergy Technologies Office Project Peer Review

Thermochemical Feedstock Interface

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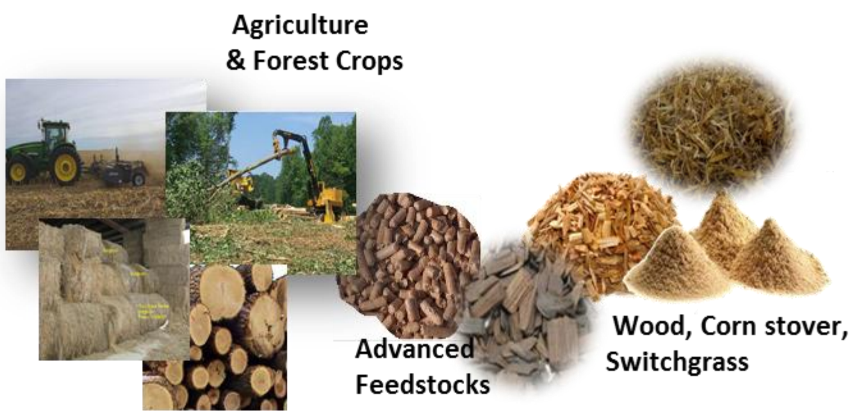
Goal Statement

GOAL: To enable a commercially viable biomass conversion value chain by evaluating the impacts of low-cost feedstocks, blends, and preprocessing approaches on the economics of **thermochemical** (TC) biofuels processes.

Outcomes:

- **Reduced risk** to biorefineries
- Biofuel **cost sensitivity** to feedstock composition
- In-feed **specifications**
- **Compatibility** of feedstocks with conversion technologies.



Relevance: This project provides insight to biorefineries regarding the financial viability of processing and conversion approaches with respect to feedstock choice, enabling the development of more flexible and market-responsive technologies.

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Project Quad Chart Overview

Timeline

- Start: October 2015
- End: September 2018
- 50% complete

Barriers:

- Ft-E. "Terrestrial Feedstock Quality, Monitoring and Impact on Conversion Performance"
- Ct-A. "Feedstock Variability."

This project quantifies the impacts of feedstock physical and chemical characteristics on conversion performance.

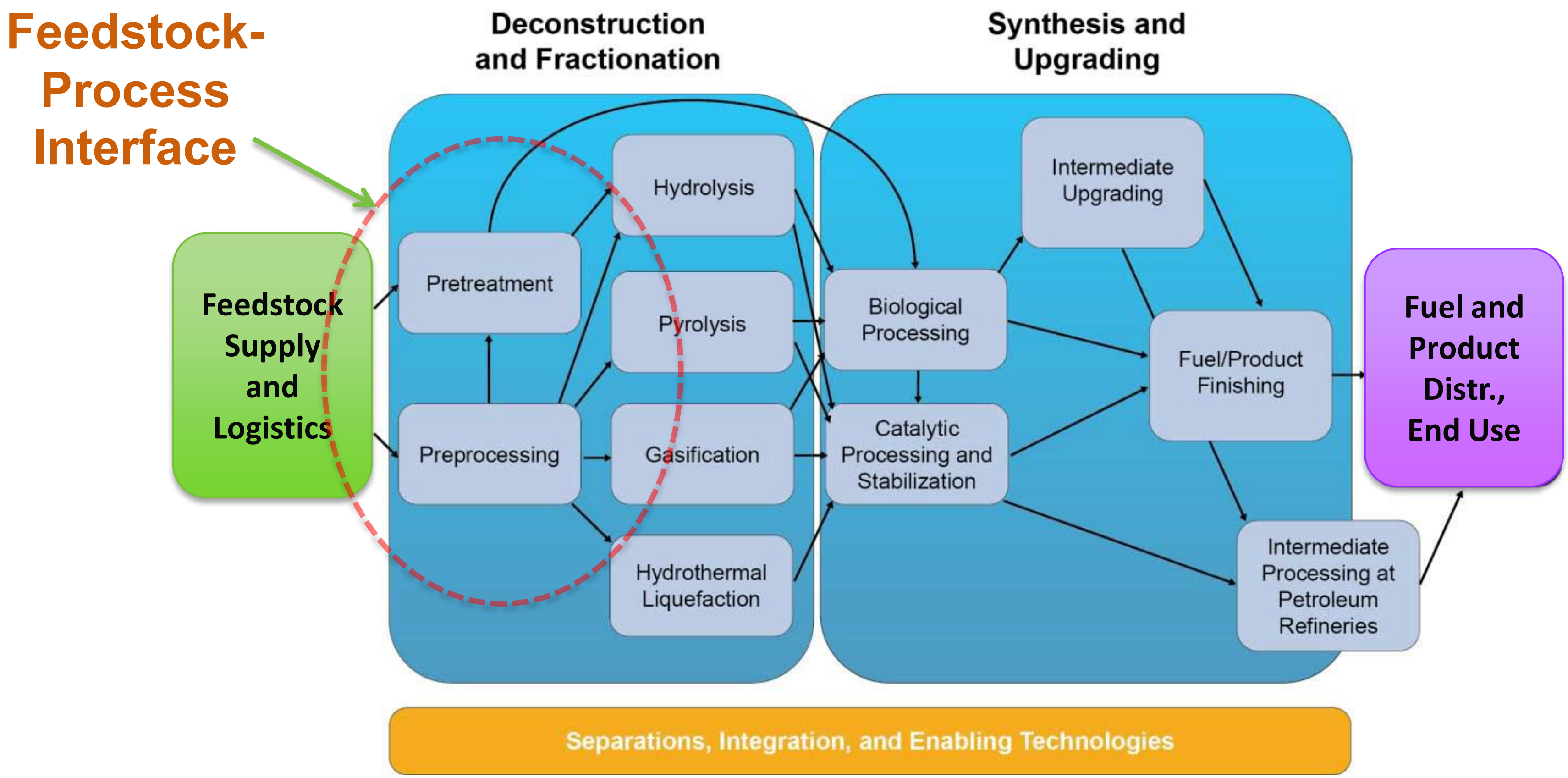
Budget

DOE Funded	FY 16 Costs	Total Planned Funding (FY 17-18)
NREL	$1,014K	$2,000K
INL	$983K	$1730K
PNNL	$600K	$1200K

Partners

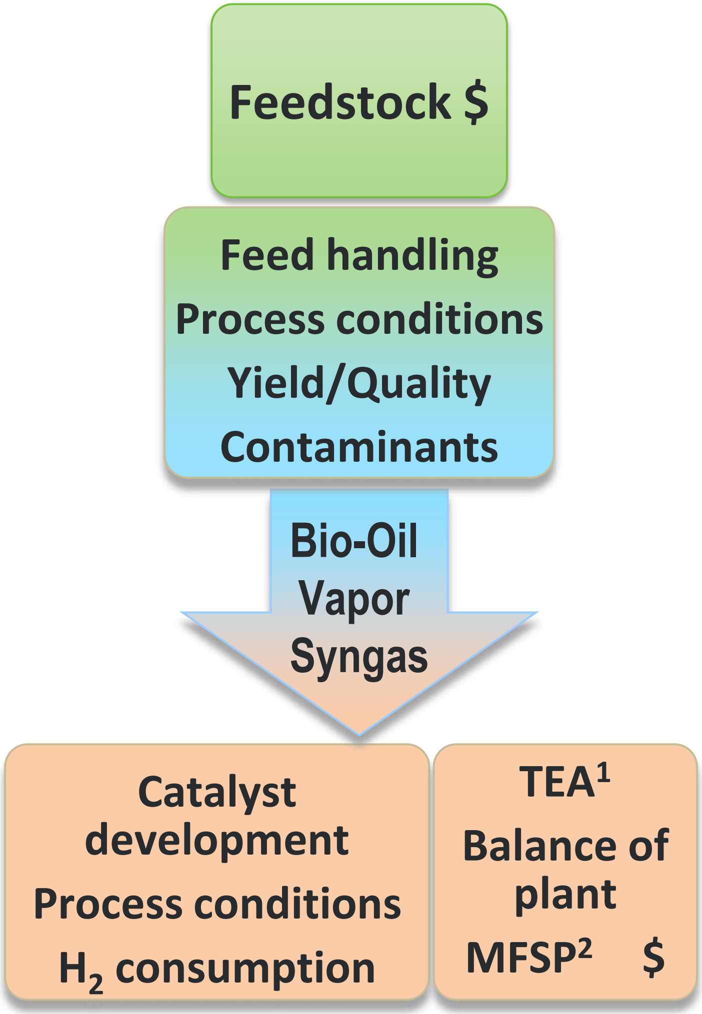
- **NREL** (40%)—Pyrolysis, catalytic pyrolysis, gasification/synthesis, feedstock screening, product analysis, modeling
- **INL** (35%)—Feedstock characterization, screening, handling, logistics, modeling
- **PNNL** (25%)—Bio-oil upgrading, fuel product analysis, modeling
- **CCPC**—Reactor modelling/optimization
- **C3Bio**—Lignin-modified poplars
- **MIT/BP**—Pyrolysis/Gasification modeling.

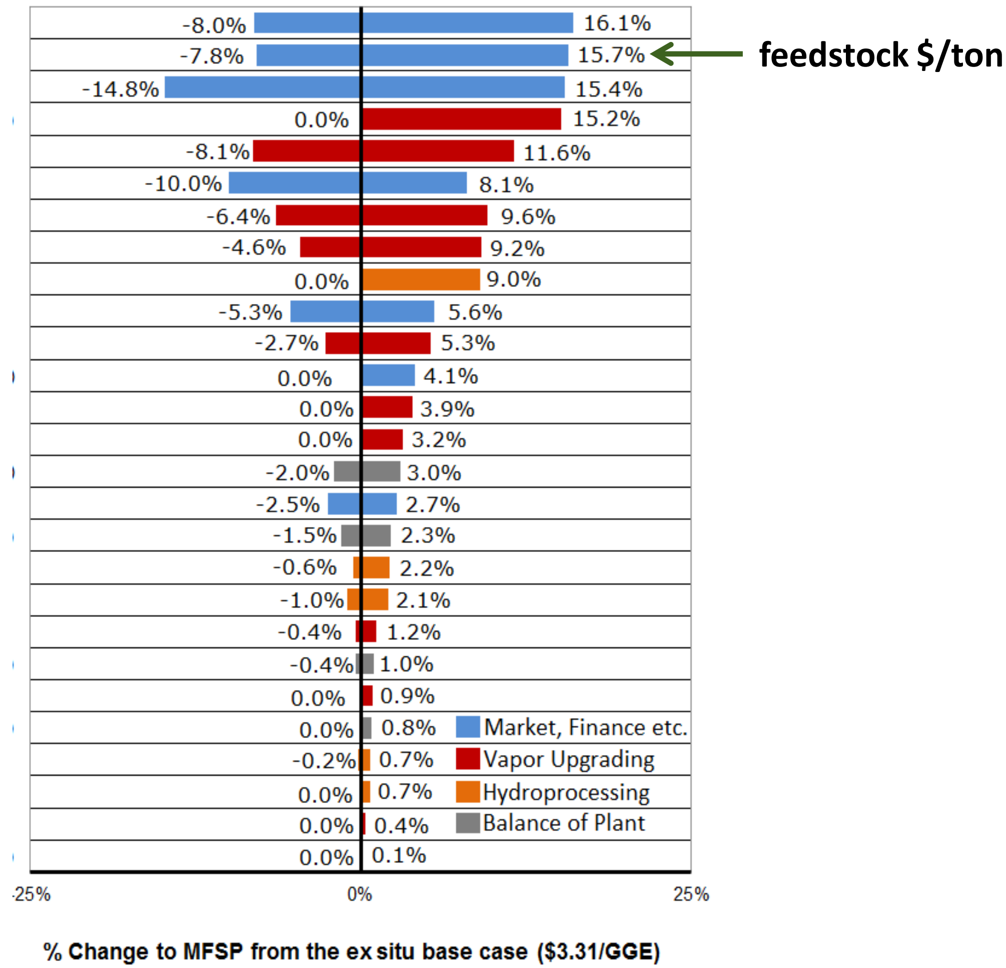
1 – Project Overview



1 – Project Overview

Feedstock is a dominant cost driver





[1]techno-economic analyses

[2]minimum fuel selling price

1 – Project Overview

- Joint NREL/INL/PNNL Project
- Feedstock variability = **risk** (cost, composition, format)
- Impacts of **blending** are largely unknown
- Need to test commercially-relevant feedstocks at a process-relevant scale for meaningful **models**

Near-Term Objective: Determine feedstock **blend properties** required to meet BETO cost targets – $84/dry ton, $2.53/gasoline gallon equivalent (GGE) for fast pyrolysis (FP) + hydrotreating (HT) (2017), $2.96/GGE for catalytic FP (2018).

Long-Term Objective: Develop a feedstock/process **co-optimization tool** for regional blends matched to specific TC conversion technologies (*feed composition + process conditions → fuel yields*).

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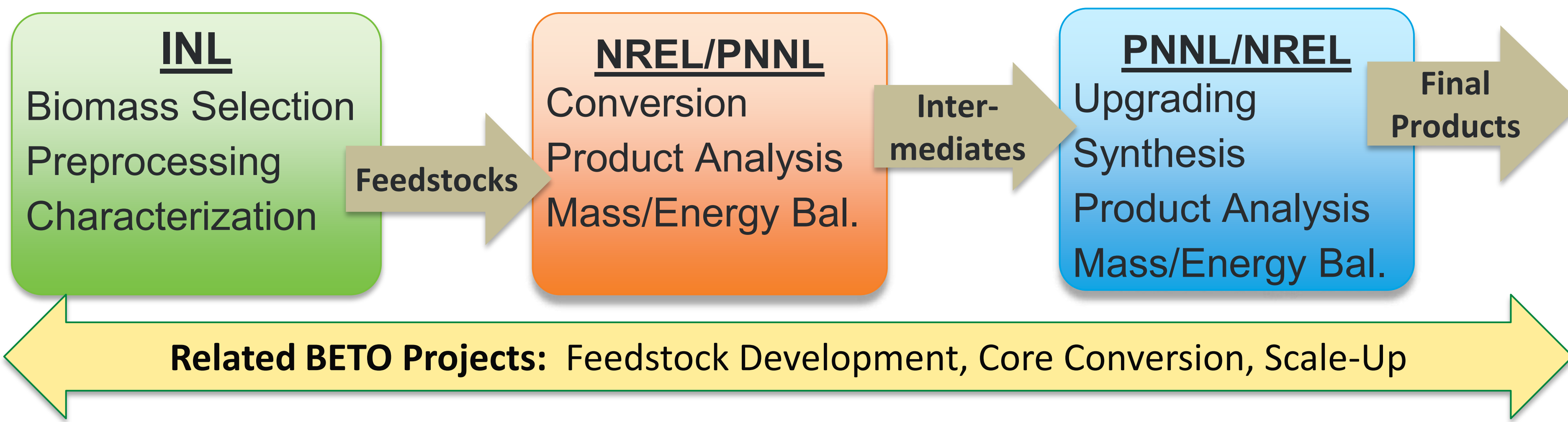
2 – Management Approach

Coordination, Communication, Feedback

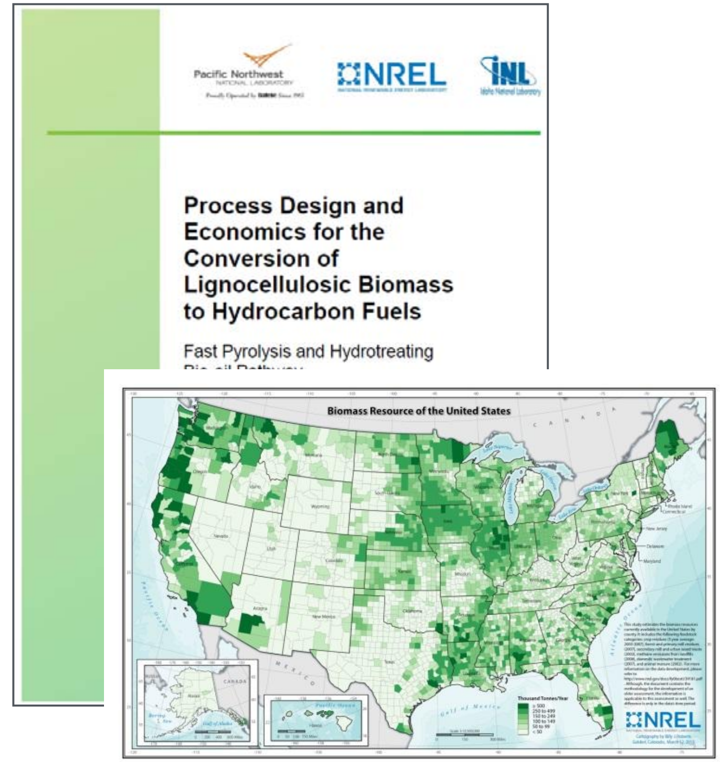
- Designated leads at each lab, technology area contacts
- Joint Merit Review, AOP's, Milestones, Go/No-Go's (GNG)
- Open sharing of feedstocks, products, characterization and conversion data (bar coded)
- Monthly team meetings, annual site visits
- Dissemination of results—annual joint publication, public Webinar (Apr. 2016), conferences



2 – Technical Approach

Technical and Economic Metrics

- Meet delivered feedstock cost target (<$84/dry ton for blend)
- Meet conversion yield/cost targets (0.27 $g_{fuel}/g_{biomass}$, $2.53/GGE for HT)
- Industrially-relevant (e.g. available at 800,000 tons/year)
- Meet sustainability targets (50% greenhouse gas reduction vs. fossil fuels)
- Variation in feedstock composition for robust predictive conversion models

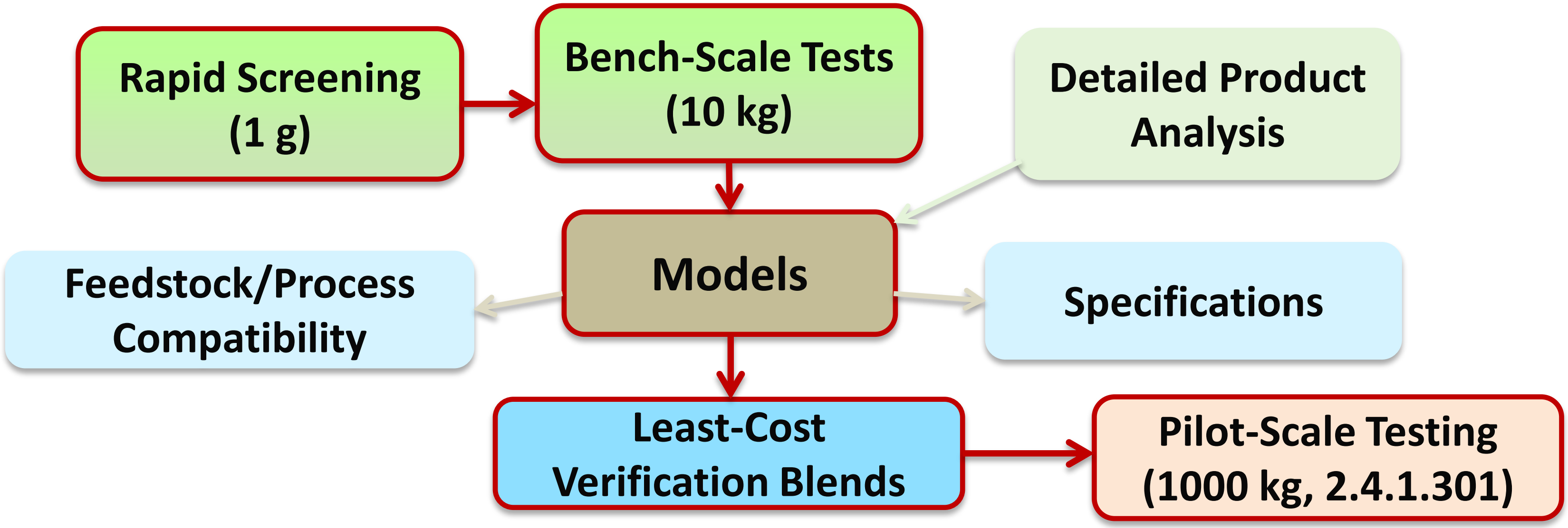


FY16 Mid-Project GNG:
Choose blend for FY17 FP+HT verification

FY17 Annual Milestone:
Develop composition-based model to predict FP+HT yields

FY18 Objective:
Validate model; determine acceptable feedstock properties

2 – Technical Approach



Challenges

- Many feedstocks and conversion technologies (variability, scaling)
- Extreme complexity of intermediates (e.g. bio-oil)

Critical Success Factors

- **Demonstrate** technical targets met with low-cost feedstocks (Go/No-Go)
- **Quantify** process and MFSP sensitivity to feedstock
- **Enable** industry use of low-cost feedstocks and blends

3 – Technical Accomplishment: Go/No-Go

Goal: Identify feedstock blend for the fast pyrolysis + hydrotreating **FY17 Verification** that meets all selection criteria.

BETO Performance Goal: "By 2017, validate at a pilot scale at least one technology pathway for hydrocarbon biofuel production…"

Bench-Scale "Field-to-Fleet" Tests:

INL: Feedstock recommendations, processing (1000 kg), delivery, characterization, model development

NREL: Bench-scale (10 kg) pyrolysis oil production, mass balances, product characterization

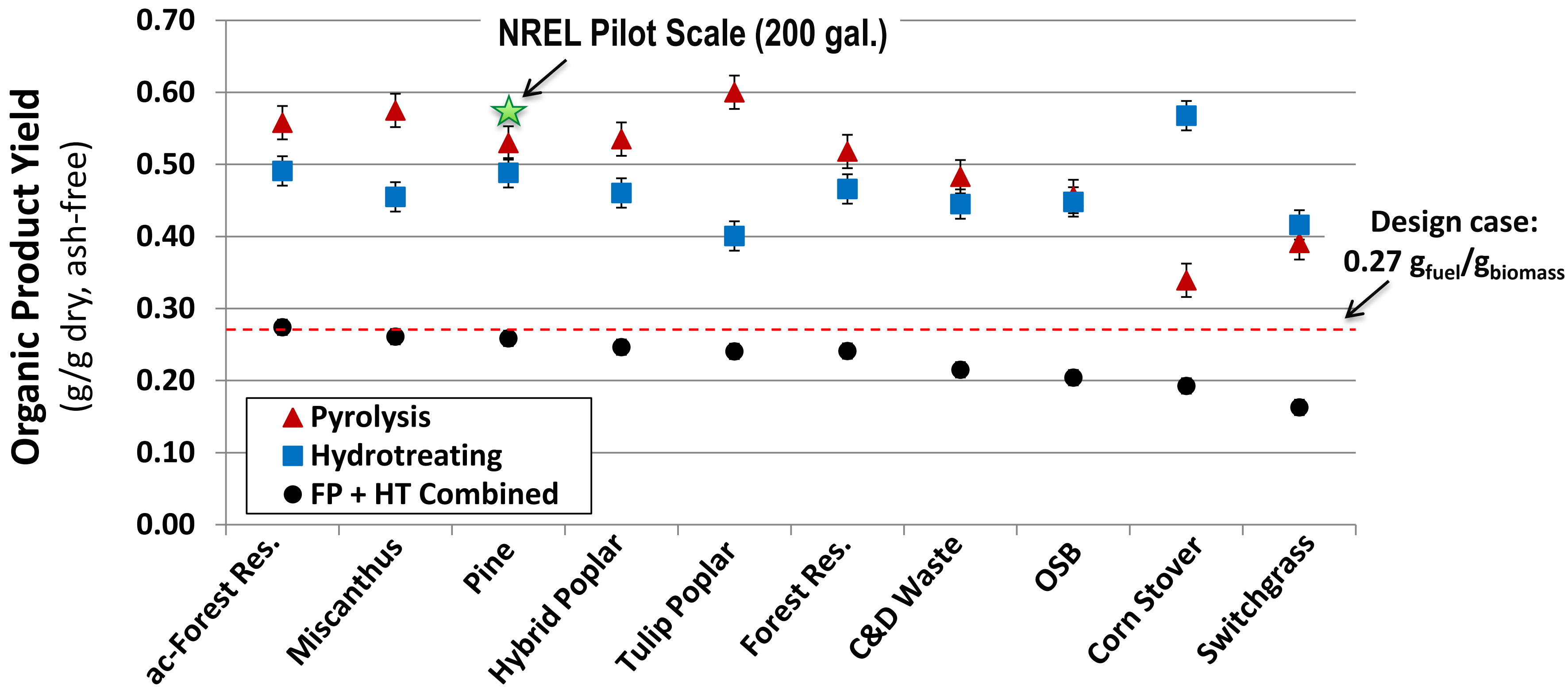
PNNL: Bench-scale (1 L) hydrotreating to fuel blendstock, mass balances, product characterization

- 2014: Baseline materials (pine, hybrid poplar, tulip poplar, switchgrass, corn stover, 2 blends)
- 2015: Blends, replicates, linearity, OSB, pinion/juniper
- 2016: Forest residues (FR), construction & demolition waste, air-classified FR, "least-cost" blends, miscanthus

Howe D, Westover TL, Carpenter D, Santosa D, Emerson R, Deutch S, Starace A, Kutnyakov I, Lukins C. (2015) Field-to-Fuel Performance Testing of Lignocellulosic Feedstocks: An Integrated Study of the Fast Pyrolysis/Hydrotreating Pathway, Energy&Fuels 29: 3188-3197.

3 – Technical Accomplishment: Feedstock Testing

Evaluation of Feedstock Options for Verification

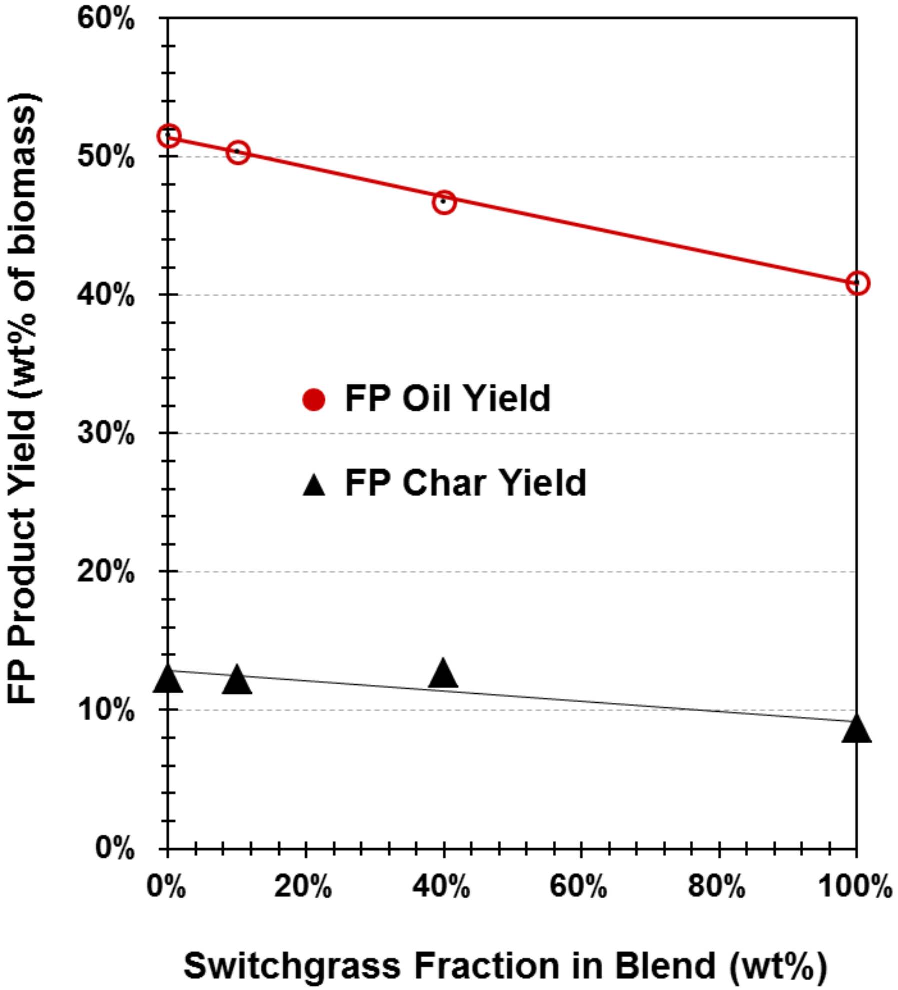


- Biomass-to-fuel yields range from 0.16-0.27 $g_{fuel}/g_{biomass}$
- Pine, ac-Forest Residues, and Miscanthus all close to design case
- **Need to evaluate *entire process* from feedstock to final products**

3 – Technical Accomplishment: Blending

Blends Behave Linearly

- Tested several blends (yield vs. % switchgrass shown)
- For FP+HT, blended feedstocks behave as the weighted sum of the components
- Conversion performance of new **blends can be predicted** based on yields of components



3 – Technical Accomplishment: GNG Met

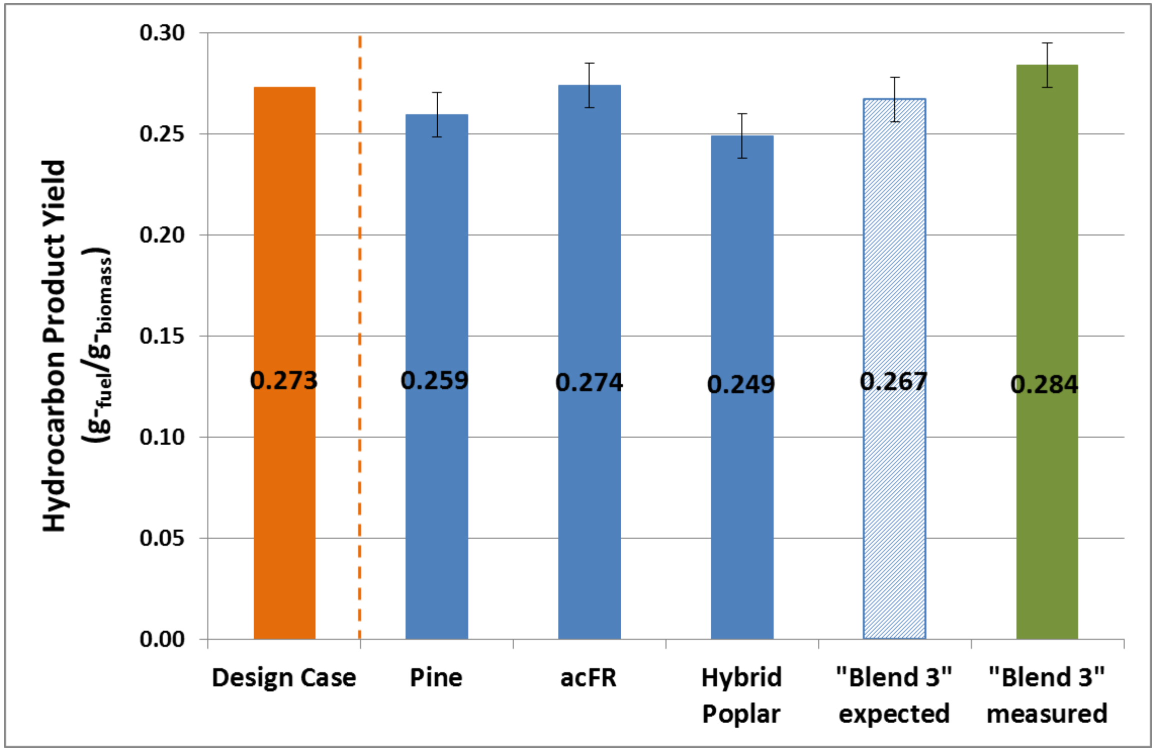
Blend Reduces Projected MFSP by $0.24/GGE

Feedstock **cost** + process **yield** data + **linearity** of blends → optimal blend

“Blend 3” = 60% air-classified forest residues, 30% clean pine, 10% hybrid poplar

- Yields similar to clean pine and 2013 Jones et al. design case (pulpwood)
- Represents MFSP **reduction of 7%** over clean pine ($0.24/GGE)

“Blend 3” meets all selection criteria



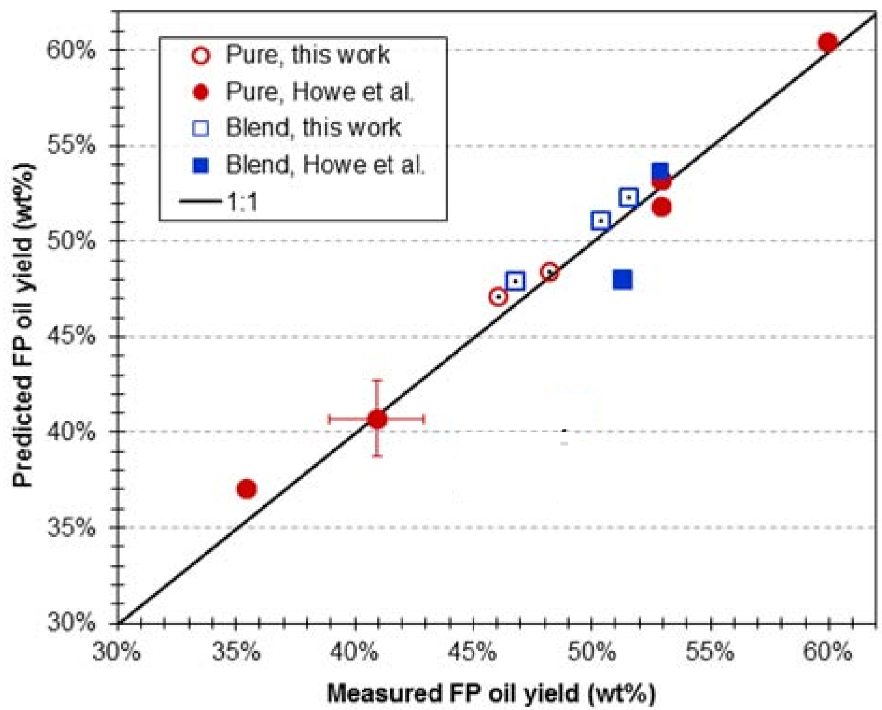
3 – Technical Accomplishment: Predictive Model

Developed Composition-Based Model

Goal: Model the impact of feedstock on thermochemical conversion processes

Enable predictive capabilities for biorefinery TEA with respect to feedstock composition to improve TEA projections (with Analysis Tasks, 2.1.0.301-2)

- Developed predictive **model** for fast pyrolysis oil yield
- Predictors are volatile matter, lignin, and K+Na (>90% correlation)
- Hydrotreating performance is *not* predicted
- Enables selection of **blends optimized** for cost and performance

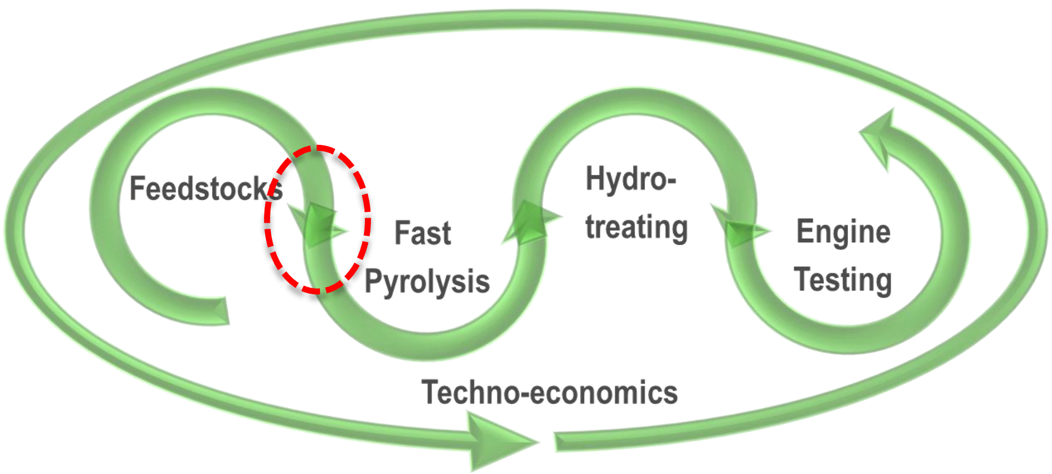


Carpenter D, Westover TL, Howe D, Deutch S, Starace A, Emerson R, Hernandez S, Santosa D, Kutnyakov I, Lukins C. Catalytic Hydroprocessing of Fast Pyrolysis Oils: Impact of Biomass Feedstock on Process Efficiency, 2016, accepted for publication in Biomass and Bioenergy.

4 – Relevance

Ensuring a robust biomass conversion value chain…

- **Provides the link** between feedstock and conversion research and development (R&D) that is critical to "ensuring a fully integrated supply chain from field to fuel"
- **Addresses the R&D need** to understand "how feedstock variability and characteristics affect overall conversion performance"



We are quantifying the impacts of feedstock physical and chemical characteristics on conversion performance

Supports **BETO FY17 Performance Goals:**

- "…supply and logistics systems that can deliver feedstock to the conversion reactor throat at required conversion process **in-feed specifications**, at or below $84/dry ton…"
- "…**deliver feedstocks** and complete **verification** operations at pilot scale…

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4 – Relevance

This project provides insight into the cost trade-offs of processing and conversion approaches with respect to feedstock choice, enabling the development of more flexible and market-responsive technologies.

Targeted industry outcomes:

- Feedstocks and conversion are **co-optimized** (matched) to maximize process robustness and minimize MFSP
- Market-responsive biorefineries are enabled with **flexibility** to meet shifting market conditions (feedstock price, end product value)

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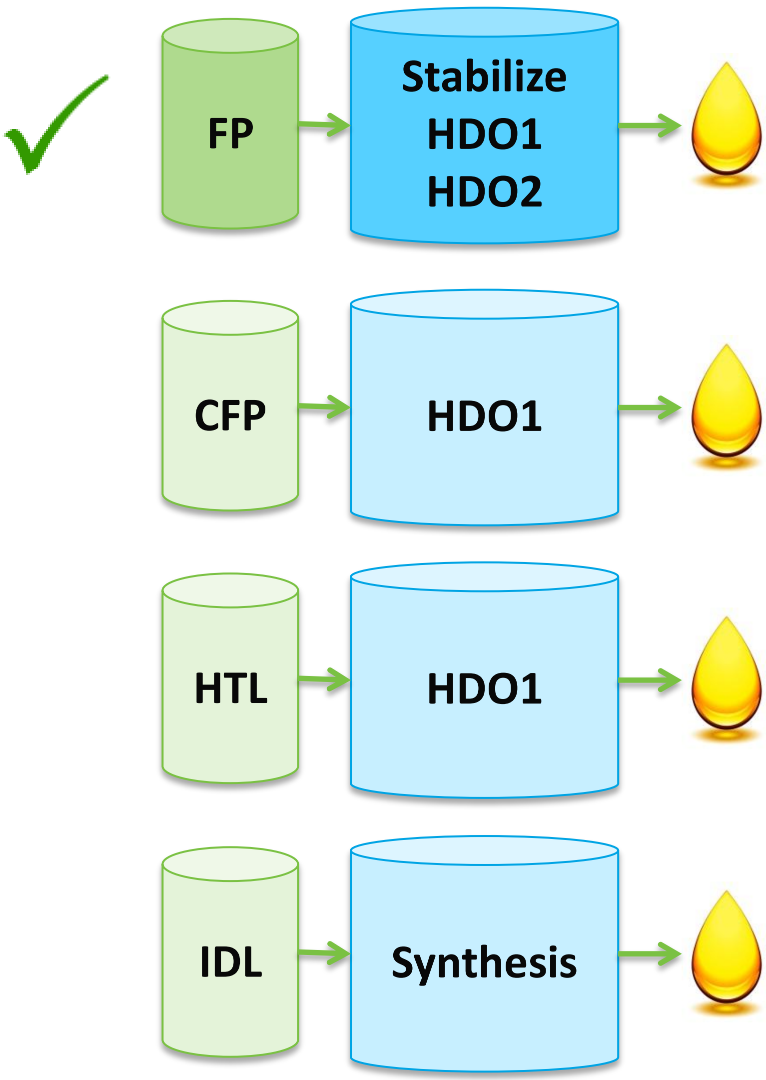
5 – Future Work

Shifting to other processes:

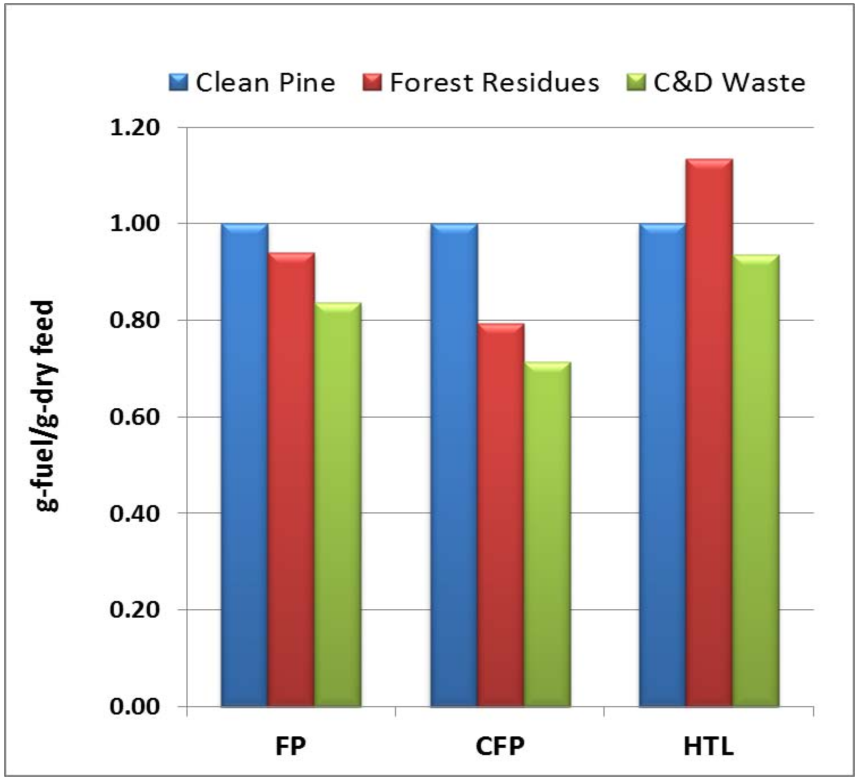
- **Catalytic fast pyrolysis (CFP)**
  - Product yields, catalyst lifetime vs. feedstock, aerosols, feed cleanup vs. hot filtration
  - **FY18 CFP verification blend**
- **Hydrothermal liquefaction (HTL)**
  - Field-to-fuel tests using same feedstocks
  - Product yields vs. feedstock
  - Potential 1-step upgrading
- **Gasification (IDL)**
  - Inorganic byproducts, bed interactions, loading on syngas cleanup systems/catalysts
  - **FY17 IDL verification blend**

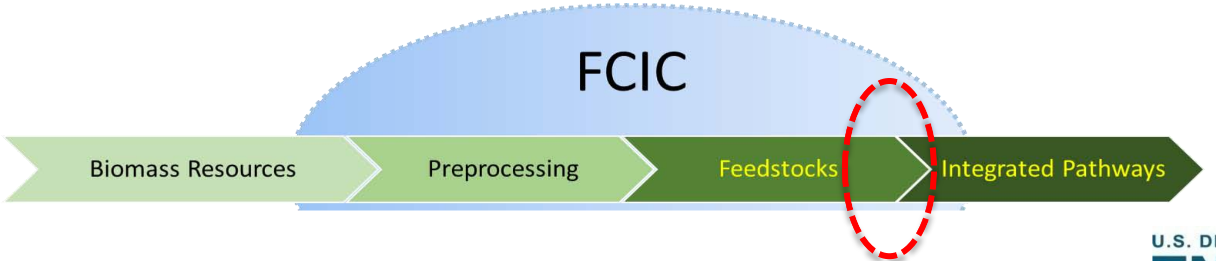


5 – Future Work

- Other predictive **models**
- **Scaling**
- Integrate into **TEA** and **Biomass Scenario** models
- Develop feedstock/process **optimization tool:**
    - (Feed Composition + Process Conditions → Fuel Yields)
- Support formation of **FCIC:**
    - Near-term industrial impact
    - Feeding, handling, “flowability”
    - Grading, specifications

Process Response to Feedstock:





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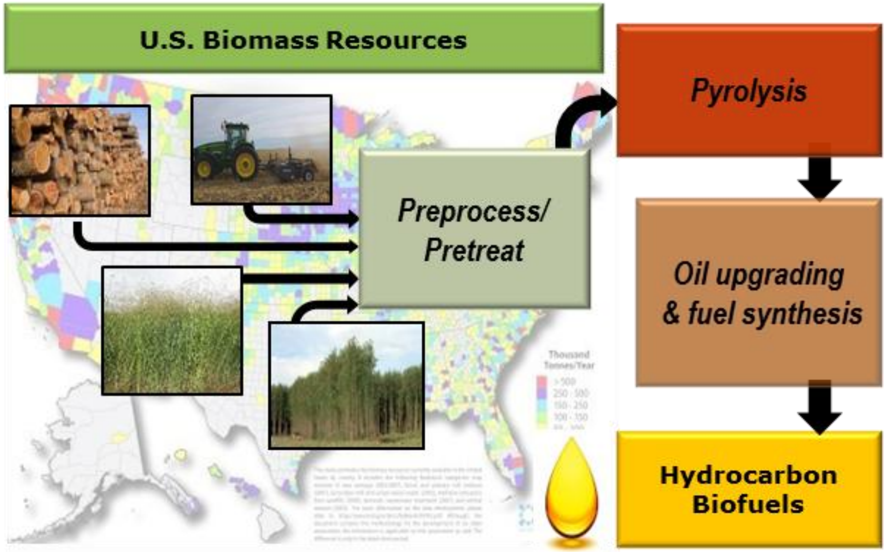
Summary

- Problem: Understanding how low-cost feedstocks and **blends** impact conversion is key to reducing biofuel costs and ensuring **compatibility**
- Approach: **Testing** commercially-relevant feedstocks, blends, preprocessing at relevant scales and developing feedstock/conversion predictive **models**
- Results:
  - Feedstock **impacts** almost every part of the process: bio-oil yield & composition, fuel blendstock yield & composition, and $/GGE (**40% variation** in conversion cost)



  - Go/No-Go: Selected blend for FP+HT **verification** that meets cost and yield criteria (ac-$FR_{60}CP_{30}HP_{10}$)
  - Developed composition-based **model** to predict fast pyrolysis oil yield
- Future: Yield models for **other processes** and a feedstock/process **optimization tool** for market-responsive biorefineries

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***Project leads at respective labs**

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***Idaho National Laboratory** is operated by Battelle under contract no. DE-AC07-05ID14517 with the Department of Energy Idaho Operations Office.*

Additional Peer Review Slides

Responses to 2015 Review Comments

1. Please evaluate the degree to which the project performers have communicated the projects history, the context in which the project fits into the portfolio, and its high level objectives.

Reviewer comments: (a) *There is not a clear delineation between what is being done in this project and what is being done in the INL Feedstock Interface project. (b)* The work in this project is closely related to the INL TC Feedstock Interface project. To avoid the perception of overlap and duplication of effort, DOE may want to combine these projects into a single, integrated project.

Response: Although reviewed separately this year, the Feedstock Interface projects at INL, NREL, and PNNL are very closely coordinated. Research plans are harmonized during each planning cycle, and results are shared between labs throughout the year and are used to develop the next year's plans. This ensures that we make effective use of each Lab's unique facilities and expertise while preventing duplication of efforts. Moving forward, the three projects will be formally reviewed as one for the purposes of the Merit Review process and likely for future Peer Reviews.

2. Please evaluate the degree to which (1) the project performers have made progress in reaching their objectives based on their project management plan, and (2) the project performers have described their most important accomplishments in achieving milestones, reaching technical targets, and overcoming technical barriers, (3) the project performers have clearly described the progress since the period of the last review.

Reviewer comments: *Starting to develop large data base of products and upgrading, and accelerate this by rapid screening. But need to make sure that upgrading data is of sufficiently high quality.*

Response: The current practice is to take samples from the "steady state" portion of each upgrading experiment (defined as the period when density of the oil is constant), analyze them separately, and then determine standard deviations within each run. Reported values are averages from these tests. Future upgrading experiments will include replicates of selected feedstocks to determine variability and the level of experimental error within the hydrotreatment process itself.

Reviewer comments: (a) Overall, the technical direction, results, and analysis make sense and were well presented. The ash influence, and means of at least quantifying it, really should be addressed - ash in switch grass is quite large and forms ash-oxides that "glass" onto the reactor walls and catalysts, but it's not as sever a problem from other biomass sources. (b) Suggest that future work highlight impact of the multitude of ash and ash-oxide constituents, and the type of ash glassing that occurs as a function of temperature in the 750-900 degC range.

Responses to 2015 Review Comments

Response: It is recognized that high-ash feedstocks can be problematic. In the case of gasification, we have observed this agglomeration/glassing with herbaceous feedstocks under certain process conditions. We will use this information to guide future experiments and to suggest feedstock formulations for the FY17 validation. Glass formation and bed slagging could certainly be an issue during gasification of high-ash feedstocks, especially those high in potassium. This, along with overall process efficiency, will likely limit the amount of herbaceous biomass in the blend proposed for the demonstration and the bed material used (e.g. olivine instead of silica sand to prevent bed agglomeration). In the proposed IDL design case, in addition to using olivine as a bed material, a small amount of MgO is added to sequester potassium and prevent glassing.

3. Please provide an overall assessment of the project based on the above criteria.

Reviewer comments: Relating feedstock properties to performance is a key and how to economically blend different feedstocks. Need to make final connection with producing a quality fuel. Quality data is key here--tightly material balanced results.

Response: Several quality indicators are assessed for the hydrocarbon fuel blendstocks produced in this project, such as simulated distillation, water content, total acid number, CHNS/O, viscosity, density, inorganic content, and heating value. Additionally, efforts are underway in Analysis projects to develop advanced biofuels blending models to estimate the value of biomass-derived blendstocks to refineries. We will coordinate with these projects to ensure the fuel quality data are relevant.

Publications

1. D. Howe, T. Westover, D. Carpenter, D. Santosa, R. Emerson, S. Deutch, A. Starace, I. Kutnyakov, C. Lukins. "*Field to Fuel Performance Testing of Lignocellulosic Feedstocks: An Integrated Study of the Fast Pyrolysis-Hydrotreating Pathway*", Energy Fuels, **2015**, 29 (5), pp 3188–3197, DOI: 10.1021/acs.energyfuels.5b00304.
2. J. Klinger, E. Bar-Ziv, D. Shonnard, T. Westover, R. Emerson. "*Predicting properties of gas and solid streams by intrinsic kinetics of fast pyrolysis of wood*," Energy & Fuels **2015**; 30 (1), 318-325.
3. A. Starace, R. Evans, D. Lee, D. Carpenter. "*Effect of torrefaction temperature on pyrolysis vapor products of woody and herbaceous feedstocks.*" Energy & Fuels, **2016**, 30 (7), pp 5677–5683, DOI: 10.1021/acs.energyfuels.6b00267.
4. S. Cheah, W. Jablonski, J. Olstad, D. Carpenter, K. Barthelemy, D. Robichaud, J. Hayter, S. Black, M. Oddo, T. Westover. "*Effects of thermal pretreatment and catalyst on biomass gasification efficiency and syngas composition*," Green Chem., **2016**, 18, 6291-6304, DOI: 10.1039/C6GC01661H.
5. P. Meyer, L. Snowden-Swan, K. Rappe, S. Jones, T. Westover, K. Cafferty. "*Field-to-fuel performance testing of lignocellulosic feedstocks for Fast Pyrolysis and upgrading: techno-economic analysis and greenhouse gas life cycle analysis*," Energy & Fuels **2016**; 30 (11), 9427-9439.
6. D. Carpenter, T. Westover, D. Howe, S. Deutch, A. Starace, R. Emerson, S. Hernandez, D. Santosa, I Kutnyakov, C. Lukins. "*Catalytic Hydroprocessing of Fast Pyrolysis Oils: Impact of Biomass Feedstock on Process Efficiency,*" Biomass & Bioenergy, **2017**, 96, 142-151, DOI: 10.1016/j.biombioe.2016.09.012.
7. E. Christensen, D. Carpenter, R. Evans. "*High-resolution mass spectrometric analysis of biomass pyrolysis vapors.*" J Analytical and Applied Pyrolysis, **2017**, Article in Press, DOI: 10.1016/j.jaap.2017.01.015.
8. G. Groenewold, K. Johnson, S. Fox, C. Rae, C. Zarzana, B. Kersten, S. Rowe, T. Westover, G. Gresham, R. Emerson, A. Hoover. "*Pyrolysis two-dimensional GC/MS of miscanthus biomass: quantitative measurement using an internal standard method*," Energy and Fuels, **2017**; Article ASAP.
9. R. Bates, W. Jablonski, D. Carpenter, C. Altantzis, A. Garg, J. Barton, R. Chen, R. Field, A. Ghoniem. "*Steam-air blown bubbling fluidized bed biomass gasification (BFBBG): Multi-scale models and experimental validation,*" AIChE Journal, **2017**, Accepted.

Presentations

1. Cheah, S.; Laroco, N.; Olstad, J. "*From plant materials to bio-chars: speciation and transformation of sulfur and potassium during biofuel production*." Oral presentation, 249th American Chemical Society National Meeting, Denver, CO, March **2015**.
2. R. French. "*Modeling of a bench-scale biomass pyrolyzer: an experimentalist's viewpoint,*" Poster presentation, 249th American Chemical Society National Meeting, Denver, CO, March **2015**.
3. W. Jablonski, S. Cheah, J. Olstad, S. Black, D. Carpenter. "*Parametric gasification study comparing traditional and blended feedstocks at varying conditions,*" Oral presentation, 249th ACS National Meeting, Denver, CO, March **2015**.
4. W. Jablonski, A. Garg, J. Barton, R. Chen, J. Olstad, S. Black, C. Field, D. Carpenter. "*Biomass Gasification Optimization: Feedstock blending and Air-steam Gasification for Better Product Yields*," 250th ACS National Meeting, Boston, MA, August **2015**.
5. Westover TL, Emerson RM, Carpenter D, Howe D. "*Feedstock rapid screening for fast pyrolysis using a focused microwave beam reactor,*" 37th Symposium on Biotechnology for Fuels and Chemicals, April 27-30, **2015**, San Diego CA.
6. W. Jablonski, A. Garg, J. Barton, R. Chen, J. Olstad, R. Field, D. Carpenter. "*Aspects of Biomass Gasification Optimization: Feedstock Blending and Air-Steam Gasification for Better Product Yields,*" NREL/CP-5100-65140, Preprints of Papers -- American Chemical Society, Division of Energy and Fuels Vol. 60 (2) August **2015** pp. 27-28.
7. T. Westover, R. Emerson. "*Fast pyrolysis parametric studies using a focused microwave beam reactor*," TCBiomass 2015. Nov. 2-5, **2015**, Chicago, IL.
8. D. Carpenter, C. Mukarakate, S. Budhi, D. Lee. "*The effect of feedstock on catalytic upgrading of biomass pyrolysis vapors*," TCBiomass 2015. Nov. 2-5, **2015**, Chicago, IL.
9. R. Emerson, T. Westover, A. Hoover, G. Gresham. "*Rapid screening processes for determining important quality attributes in biomass using spectroscopic techniques*," TCBiomass 2015. Nov. 2-5, **2015**, Chicago, IL.
10. E. Christensen, R. Evans, D. Carpenter. "*High-Resolution Mass Spectrometric Analysis of Biomass Pyrolysis Vapors*," TCBiomass 2015. Nov. 2-5, **2015**, Chicago, IL.
11. T. Westover, S. Hernandez, A. Matthews, J. Ryan. "*Flowability performance of pine chips as a function of particle size and moisture content*," AIChE Annual Meeting. Nov. 8-13, **2015**, Salt Lake City, UT.
12. D. Carpenter, D. Howe, T. Westover. "*Field-to-Fleet Webinar: How does Feedstock type affect biofuels conversion?*" Bioenergy Technologies Office Webinar Series, April 20, **2016**.
13. T. Westover. "*Selected emerging market opportunities for torrefied biomass*," presented by The World Bioenergy Association and the International Biomass Torrefaction Council in a webinar: Torrefied Biomass: New Markets, New Directions, New World. June 22, **2016**.

Presentations

14. (INVITED) T. Westover, "*Feedstock Considerations for Thermochemical Biofuels Production Including a Case Study of Fast Pyrolysis and Catalytic Hydrodeoxygenation*," Chemical and Biological Engineering Seminar Series, South Dakota School of Mines and Technology, Rapid City, SD Oct. 11, **2016**.
15. S. Cheah, A. Starace, D. Lee, R. Evans, D. Carpenter. "*Effect of inorganic elements on vapor phase upgrading of biomass pyrolysis products*," Symposium on Thermal and Catalytic Sciences for Biofuels and Biobased Products. Nov. 1-4, **2016**, Chapel Hill, NC.
16. T. Westover, R. Emerson, S. Hernandez, D. Carpenter, D. Howe. "*Determination of impact of feedstock composition on fast pyrolysis oil yield and quality using multiple linear regression modeling*," Symposium on Thermal and Catalytic Sciences for Biofuels and Biobased Products. Nov. 1-4, **2016**, Chapel Hill, NC.
17. S. Deutch, D. Howe, T. Westover, D. Carpenter, D. Santosa, R. Emerson, A. Starace, C. Lukins, I. Kutnyokov. "*Field-to-fuel performance testing of lignocellulosic feedstocks: production and catalytic upgrading of bio-oil to refinery blendstocks*," Symposium on Thermal and Catalytic Sciences for Biofuels and Biobased Products. Nov. 1-4, **2016**, Chapel Hill, NC.
18. T. Westover, R. Emerson, J. Ryan, L. Williams. "*Microwave-assisted fast pyrolysis (MW-FP) of several lignocellulosic feedstocks*," AIChE Annual Meeting. Nov. 14-17, **2016**, San Francisco, CA.
19. D. Howe, D. Carpenter, T. Westover. "*From Field to Fuel: The Effect of Biomass Feedstock Composition on Fast Pyrolysis, Vapor Phase Upgrading, and Hydrotreatment,"* AIChE Spring Meeting. March 26-30, **2017**, San Antonio, TX

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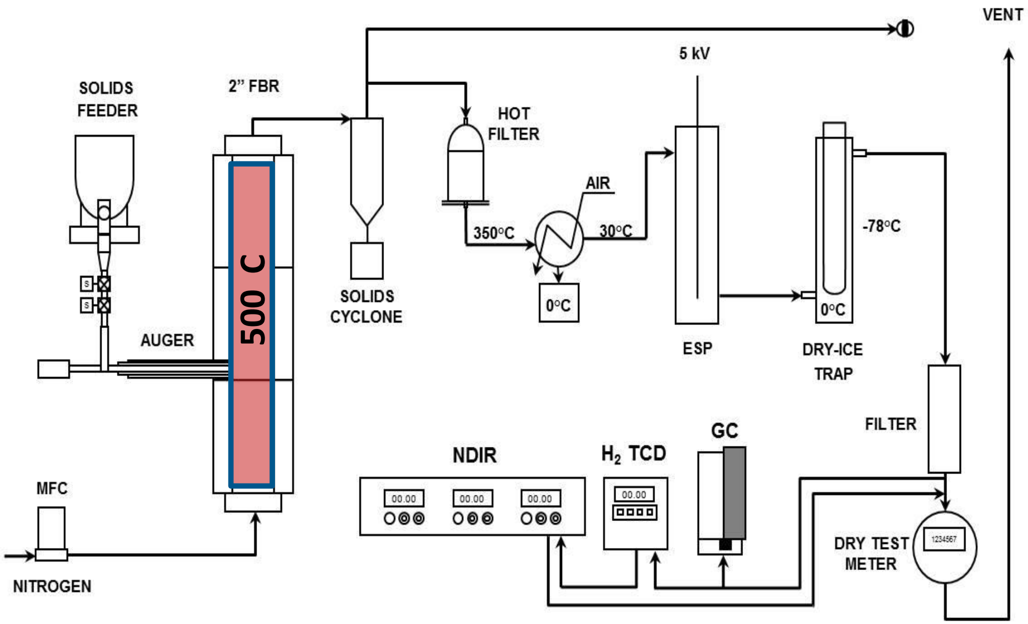
Backup Slides

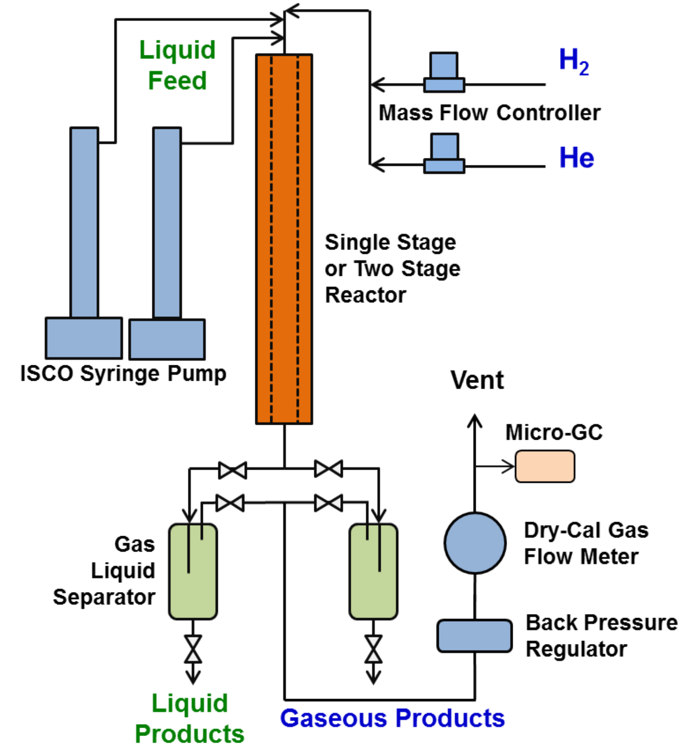
Bench-Scale Feedstock Testing

NREL 2FBR Fast Pyrolysis Reactor



Feed rate: 0.5 kg/h
Reactor: 5.0 cm ID
T = 500 C
P = 1 atm.

PNNL 40 mL Hydrotreating Reactor



Feed rate = 48 mL/h   T = 220 C/400 C
Reactor = 1.3 cm ID   P = 1550 psi

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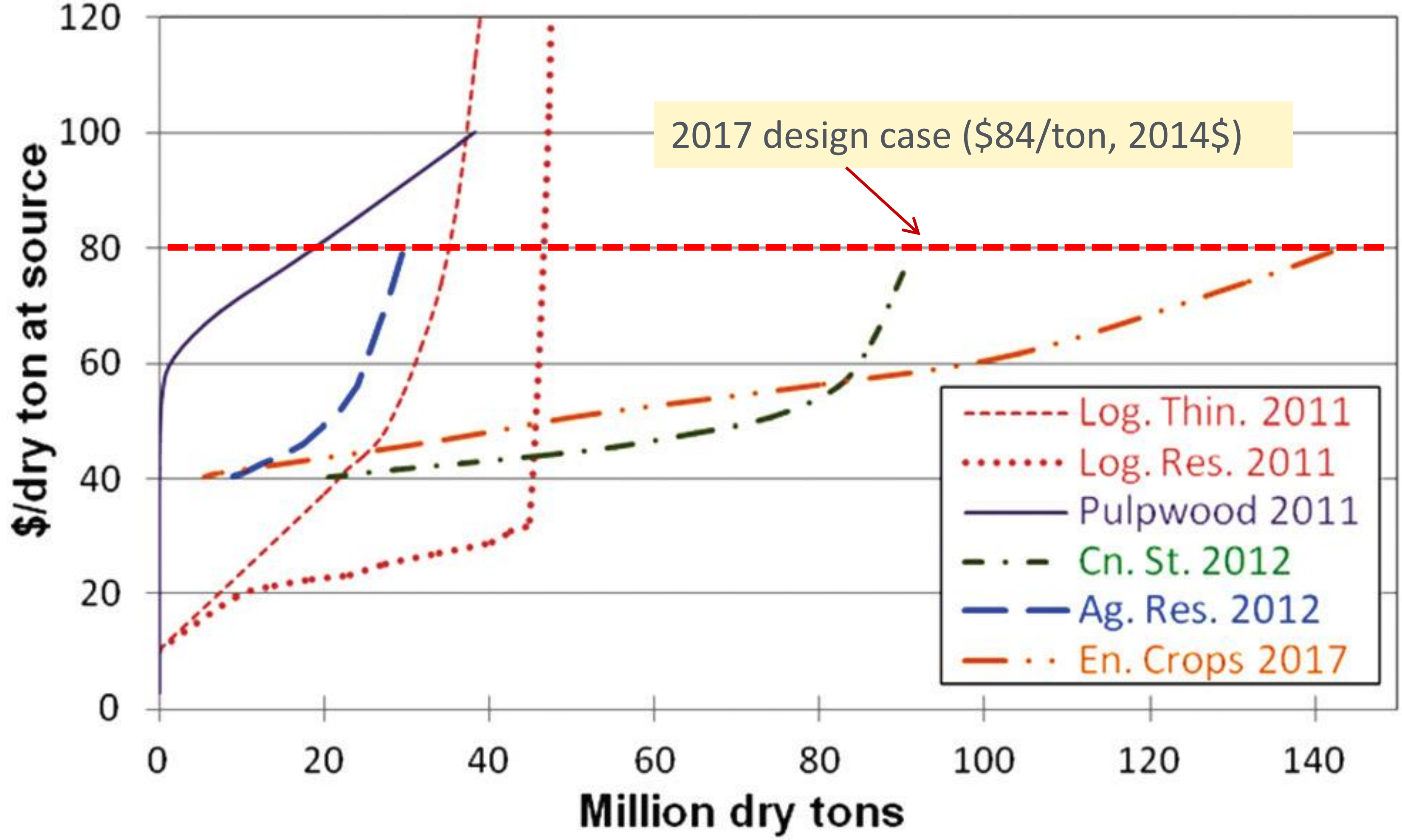
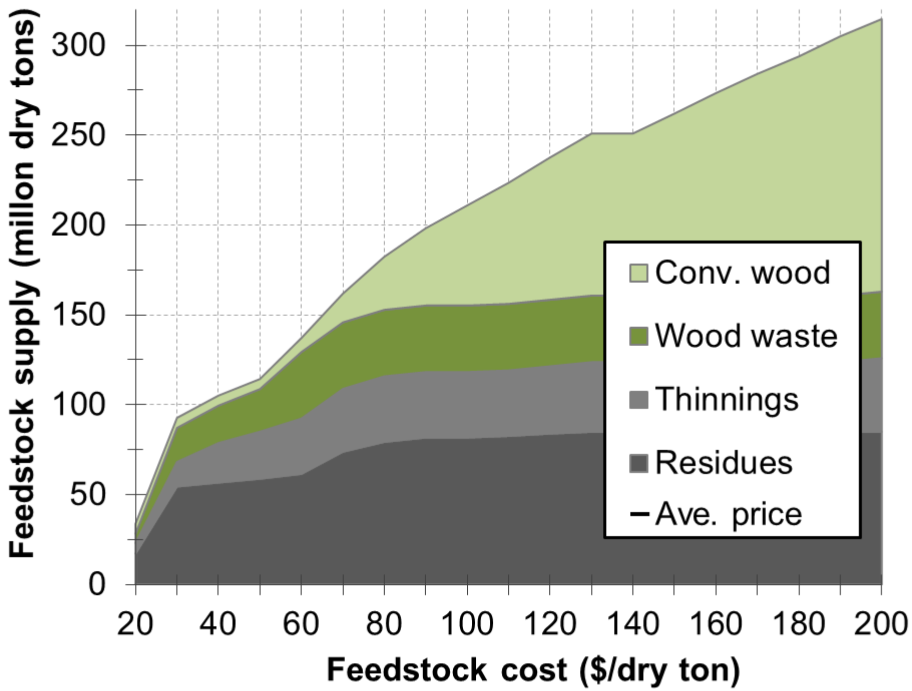
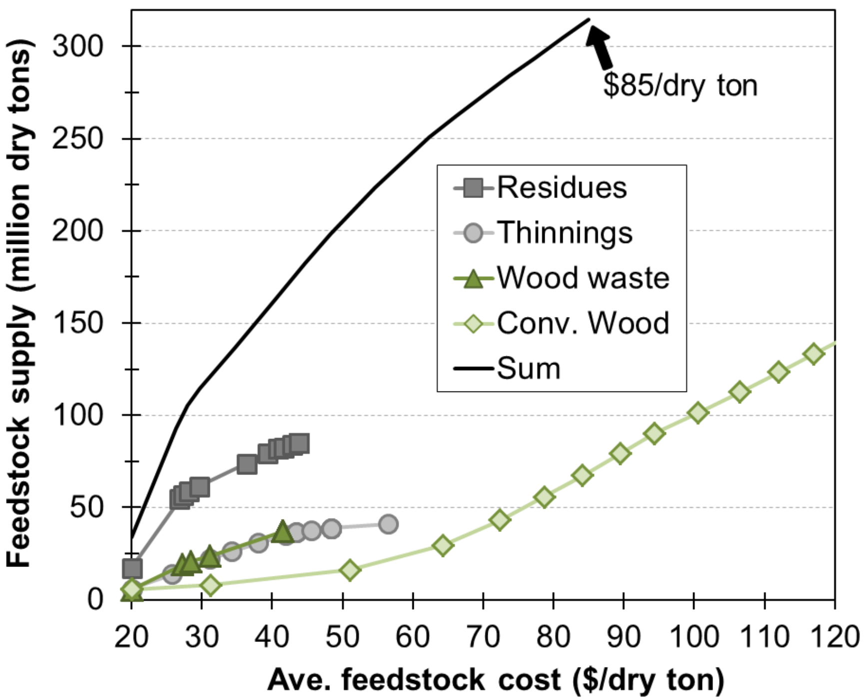
Supply-cost curves for some key feedstocks (BT2)



Carpenter, Westover, Jablonski, Czernik, Green Chem., 2014, 16, 384, adapted from BT2

Importance of blending (e.g. wood)





- ~315 million tons projected available in 2022
- Projections depend upon assumptions;
  - EPA estimated that 164 million tons of C&D waste were generated in the U.S. in 2003 (EPA, 2011; Paper in Support of Final Rulemaking: Identification of Nonhazardous Secondary Materials That Are Solid Waste)

Woody feedstock supply as functions of projected average cost

- Combining woody feedstocks in blend accesses all 315 million tons for average cost of $85/dry ton ($2011).
- Blending feedstocks increases supply while reducing costs and risks

Formulated feedstocks

Move toward formulated feedstocks…to mitigate variability, reduce/stabilize cost

- commoditize feedstocks for biofuels production
- establish composition-based specifications (precedence for this is coal and animal feed industries)

Example blend *(from Jones, et al design report):*

Feedstock	Reactor Throat Feedstock Cost ($/dry ton)[2]	Formulation Fraction (%)	% Ash Delivered to Throat of Conversion Reactor
Pulp	99.38	30	0.5
Logging Residues[1]	74.83	35	1.5
Switchgrass	80.54	10	2.8
C&D Wastes	63.77	25	0.5
Formulation Totals	**80.00**	**100**	**1.1**

[1] residues do not include costs for harvest and collection; they are moved to landing while attached to the merchantable portion of the tree (for example, timber or pulpwood)

[2] includes ash mitigation

How will the process tolerate different feedstocks? Biomass resource development and process optimization need to be closely-coupled!

Verification blend

Key feedstock compositional properties and preliminary availability and cost (2014$) of blend components near Piedmont, SC. (Note 1: all properties are similar, except K+Na content. Note 2: these estimates have changed based upon BY16 data

	VM	Ash	C	HHV	Lignin	K+Na	Grower pay	Harvest/ collection	Field prep	Transport etc.	In-plant receiving, prep, etc.	Total Cost
	(%)	(%)	(%)	(BTU/lb)	(%)	(ppm)						
Blend 3	82.0	0.65	51.1	8982	28.3	1703						**$84.77**
CP	83.7	0.65	51.4	9026	28.1	779	23.30	9.60	20.65	13.95	31.38	98.88
acFR	81.8	0.61	51.3	9020	29.5	3430	14.20	N/A[b]	10.75+1.5	13.95	31.38	70.78
HP	83.9	0.9	51.1	8638	~26.2	2053	35.45	14.41	N/A[a]	30.25	34.31	114.42

Production and Quality Assurance

- ≈ 4,000 kg of clean pine prepared at INL shipped to NREL (processed in NREL's TCPDU in Q1)
- 30 barrel bags of blend 3 prepared (≈104 kg each for 3,100 kg total)
- 5 bags selected at intervals for intra-bag variability sampling (2 kg sampled from top and bottom of each bag for analysis)
- 5 separate bags selected for inter-bag variability sampling (contents of entire bag uniformly split for analysis)
- 25 of the 30 bags shipped to NREL for processing with TCPDU (inter-bag variability testing still in progress).

Ash Removal: Air Classification Alone

Equipment: Model #16 Air Classifier by Key Technology (Walla Wall, WA)

Process costs for air classification at 22.68 dt/hr of wood chips. Assumptions match BETO fast pyrolysis design report (Jones, et al., PNNL-23053; November 2013).

Cost component	Usage	Unit cost	Cost ($/dt)
Other fixed costs	100%	$55,000/yr	0.34
Total capital investment	100%	$1,124,000	0.21
Salaries	62%	$52,700/yr	0.18
Electricity for blowers	2@15 HP	$0.10/kWh	0.10
TOTAL			0.83

Effectiveness and costs of air classifying logging residue wood chips at 22.68 dt/hr. Cost associated with yield loss is assumed to be $20/dt of lost organic material

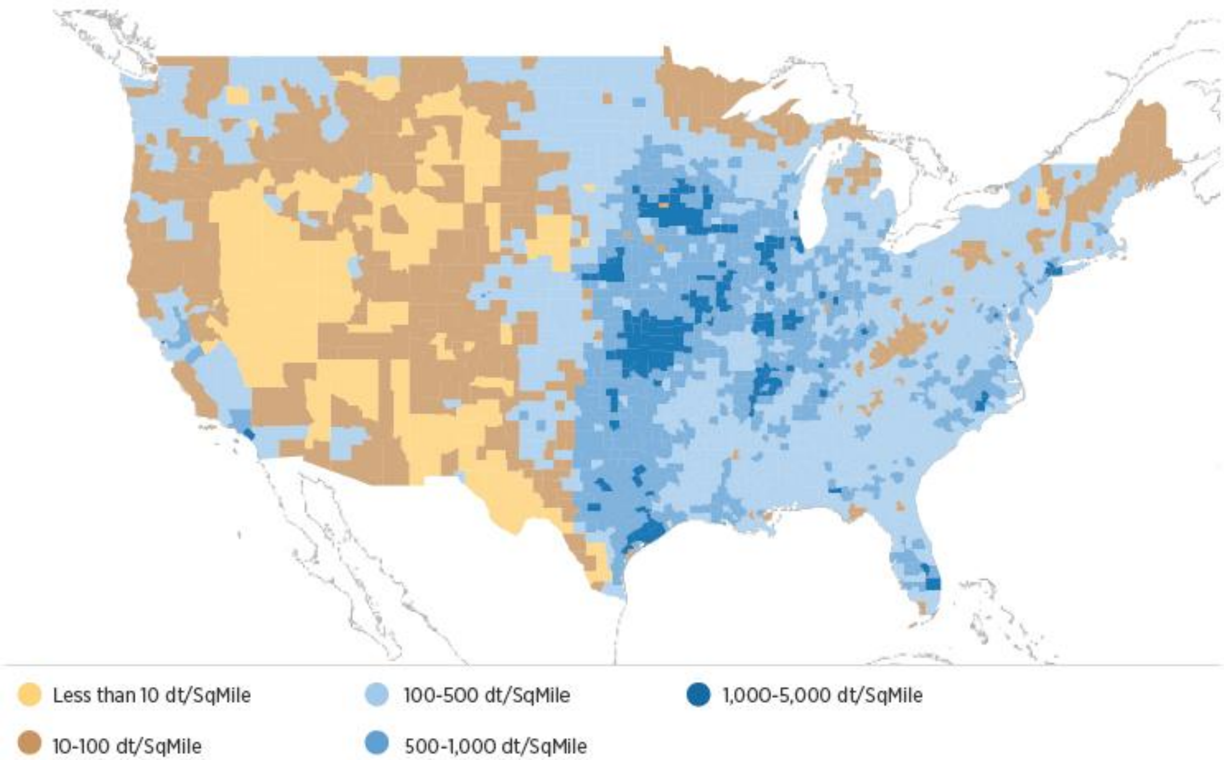
Fan VFD	Total mass (%)	Organic loss (%)	Organic loss (dt)	Yield loss cost ($/dt*)	Inorganic removal (%)	AAEMS+P removal	Total cost ($/dt*)
10 Hz	6.7%	6.3%	1.42	$1.34	42%	17%	$2.17
12Hz	9.1	8.7%	1.97	$1.90	49%	22%	$2.73

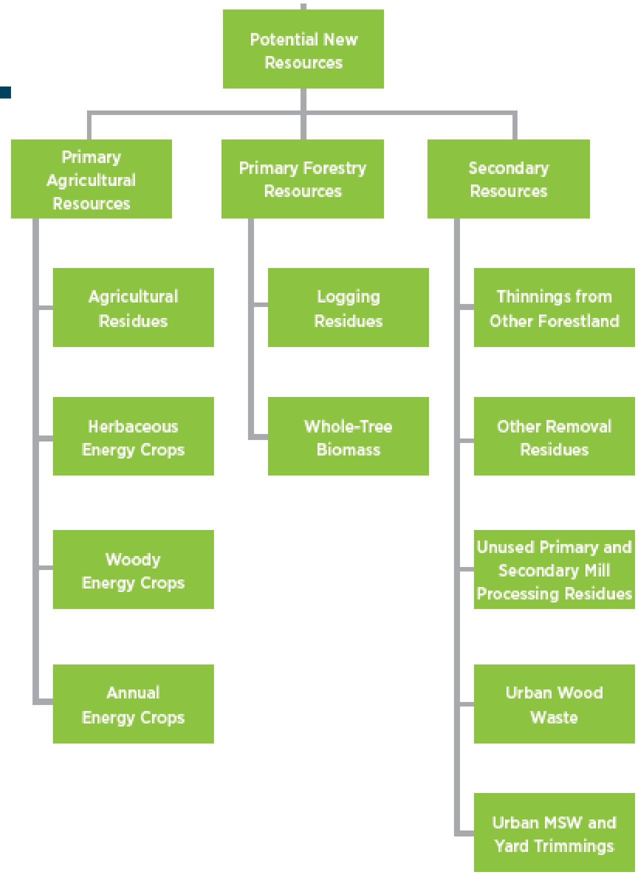
Sources: Lacey, Aston, Westover, Cherry, Thompson, Fuel 2015;16: 265-273; Hu, Westover, Aston, Lacey, Thompson, submitted for publication.

BT16

New Resources

Figure ES.4 | Combined potential supplies from forestry, wastes, and agricultural resources, base case, 2040[10]





U.S. Department of Energy. 2016. *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks.* M. H. Langholtz, B. J. Stokes, and L. M. Eaton (Leads), ORNL/TM-2016/160. Oak Ridge National Laboratory, Oak Ridge, TN. 448p.

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Model Development

Pure feedstocks (10)

1. Clean pine (CP) **(5x)**
2. Hybrid poplar (HP)
3. Tulip poplar (TP)
4. Piñon/juniper (PJ)
5. Oriented strand board (OSB)
6. Corn stover (CS)
7. Switchgrass (SG)
8. Construction & demolition waste (C&D-0.5mm)
9. Air classified forest residues (acFR-0.5mm)
10. Miscanthus (MS-0.5mm)

- CP-0.5mm
- SG-450 ^oC

Material were ground to 2 mm and temperature of pyrolysis reactor was 500 ^oC, except as noted

Blends (8)

1. CP_2HP_1
2. $CP_1TP_1SG_1$ **(2x)**
3. CP_8SOB_2
4. $CP_7OSB_2SG_1$
5. $CP_4OSB_2SG_4$
6. $CP_{30}acFR_{60}HP_{10}$-0.5mm
7. $CP_{45}FR_{25}C\&D_{30}$-0.5mm
8. $CP_{30}FR_{35}C\&D_{25}SG_{10}$-0.5mm

Response variables

- Dry, ash-free pyrolysis oil yield
- Ash-free pyrolysis char yield
- Dry hydrotreating oil yield

Independent tests (pure feedstocks): 10

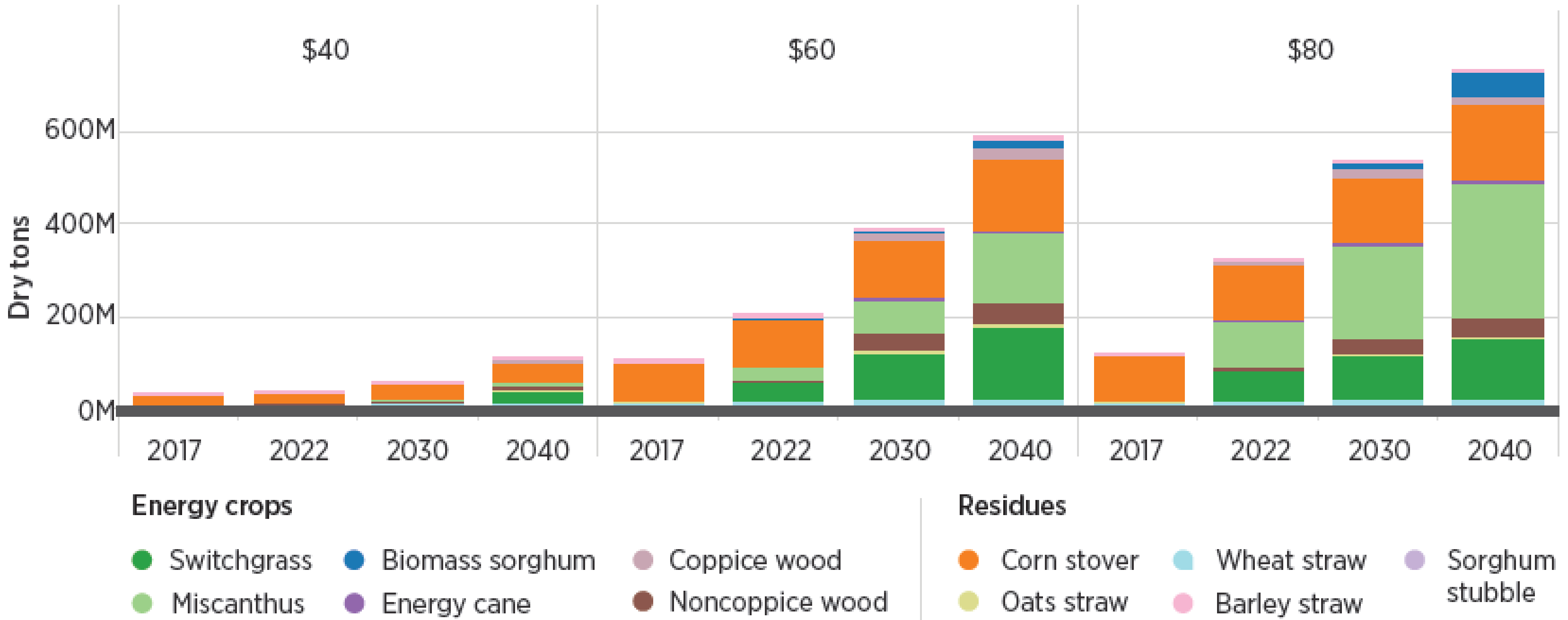
Effective replicates: 13

Predictor variables: 22

- Ultimate (C, H, N, S, O, HHV, LLV)
- Proximate (Volatiles, Fixed C, Ash)
- Ash speciation (Al, Ca, K, Mg, Na, S, Si)
- Composition ($H_2$0 Ext, Protein, Arabinan, Glucan, Lignin)

Herbaceous and woody energy

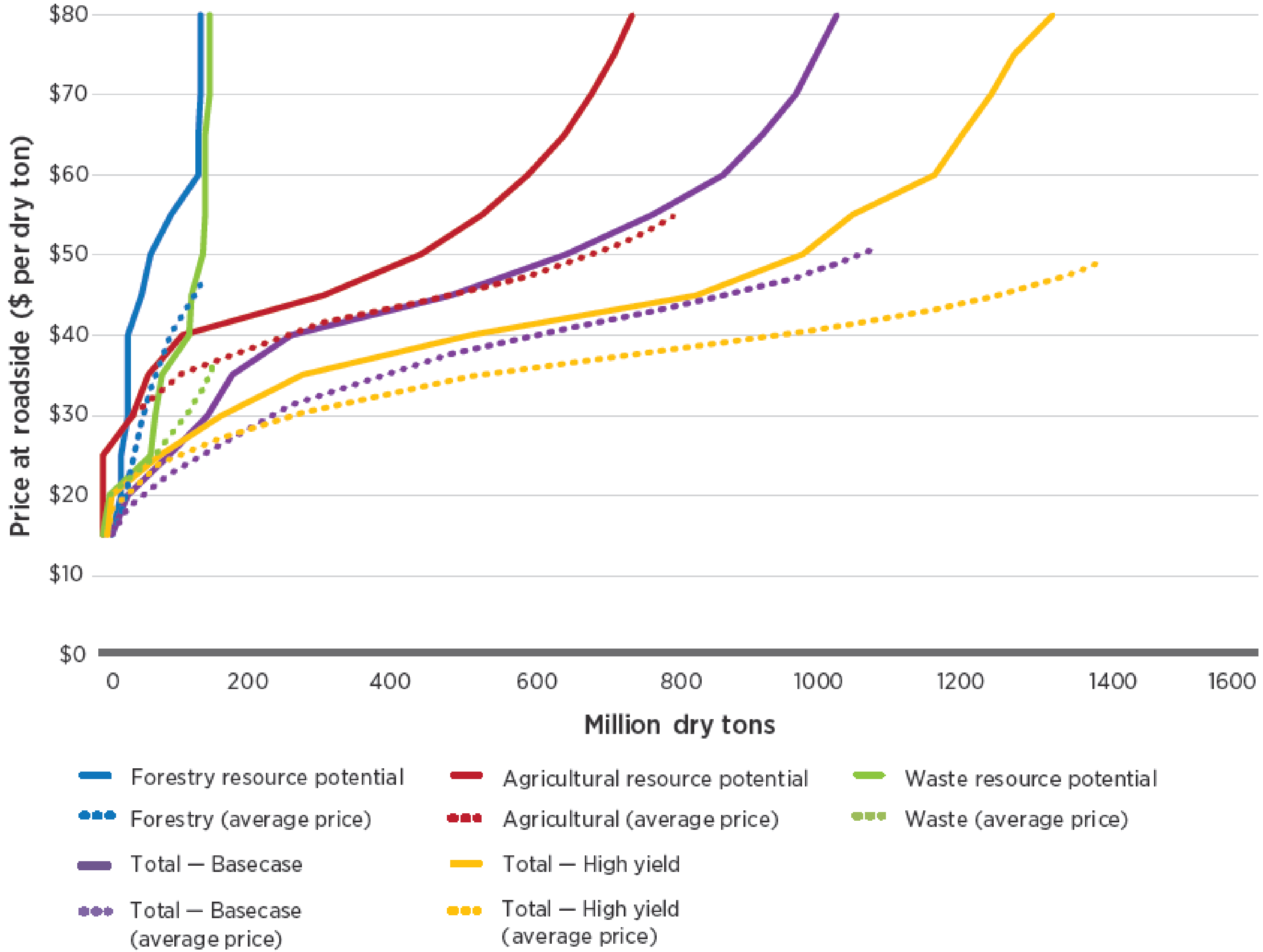
Figure 4.5 | Production of herbaceous and woody energy crops under ≤$40, ≤$60, and ≤$80 offered farmgate prices under a base-case (1%) scenario for select years[7]



U.S. Department of Energy. 2016. *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks.* M. H. Langholtz, B. J. Stokes, and L. M. Eaton (Leads), ORNL/TM-2016/160. Oak Ridge National Laboratory, Oak Ridge, TN. 448p.

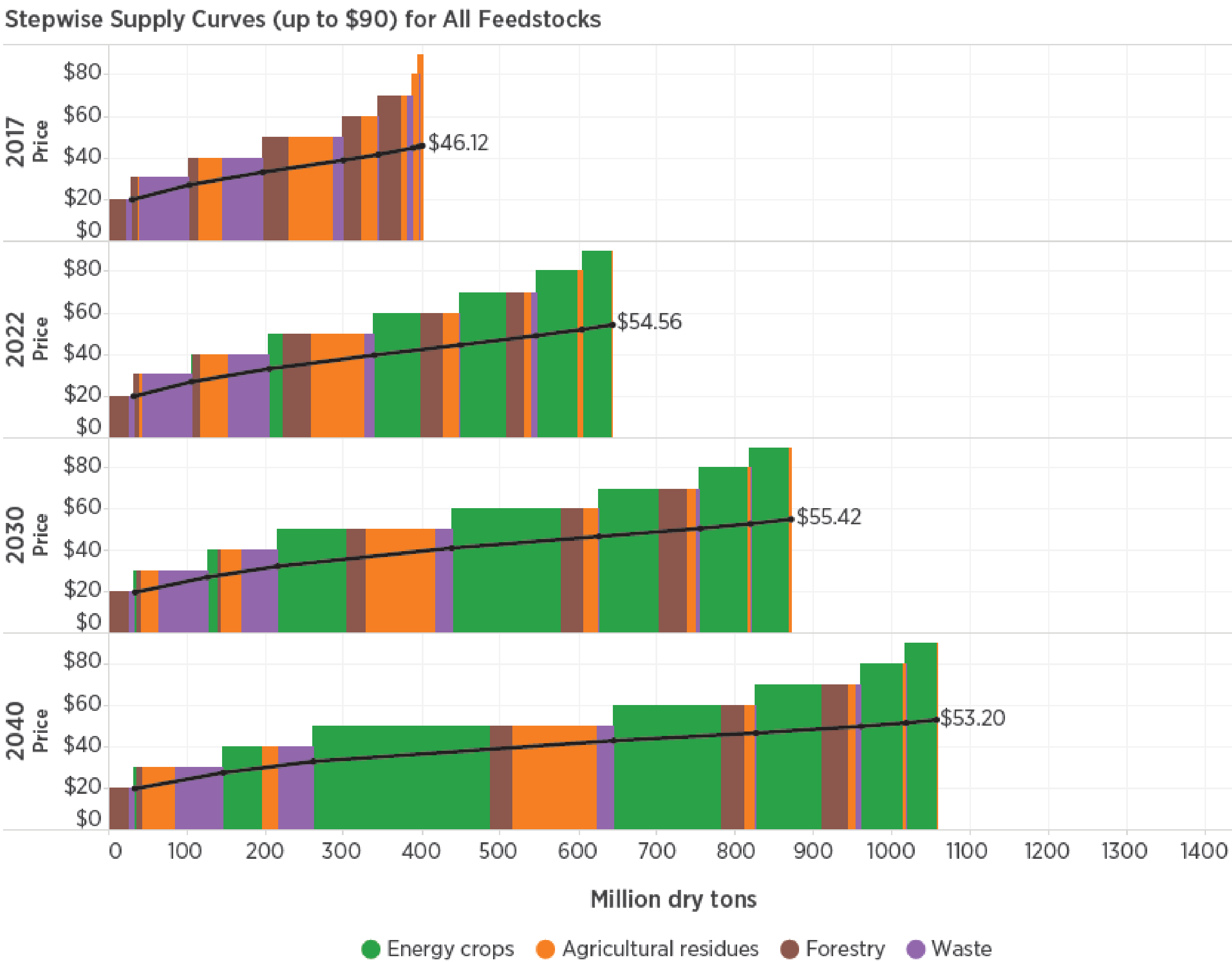
BT16

Figure ES.5 | Potential forestry, agricultural, and waste biomass resources shown as a function of marginal and average prices at the roadside In 2040 (base case)



BT16

Figure ES.6 | Combined potential forestry, agricultural, and waste biomass resources shown as a function of marginal and average prices at the roadside for select years (base case)[11]



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2016

Figure 2-23: Cost projection breakdown for the fast pyrolysis design case

Based on the 2013 design case for fast pyrolysis, Figure 2-23 shows that a total potential cost reduction of 75% can be achieved between 2009 and 2017 with improvements in all four R&D areas shown in the legend.

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5 – Future Work (cont.)

Project timeline:

SOT	FY14	FY15	FY16	FY17 Targets
Plan >	Test 8 *baseline feedstocks*, preliminary conversion model	Test 10 *blends*, propose 1-3 blends for demo, validate model	Validate yield model with 1-3 blends, optimize conversion	Demonstration with blended feedstock **($80/ton)**
Pulpwood **($120/ton)** Materials used >	Pine, poplar, corn stover, switchgrass, two blends	Combinations of pine, poplar, log. res., switchgrass, MSW	1-3 blends (per FY15 results)	1 blend for optimized conversion conditions
Carbon eff. (% feed carbon)	FP wood: **58-60%** HT wood: ?	→	→	FP blend: **69%** HT blend: **47%**
Example spec: Total ash < 1%	Propose > 1%, but limit specific elements (N, S, K, P, etc.)	Set initial chemical and physical specifications	Finalize specifications for demonstration	Update specifications as needed

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