DOE Bioenergy Technologies Office (BETO) 2019 Project Peer Review

2.2.2.301 PNNL Hydrothermal Processing of Biomass

Date: March 6, 2019

Technology Session Area Review: ADO: Integration and Scale-Up

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Goal Statement

Commercialization of Hydrothermal Processing for Conversion of Wet Feedstocks to Fuels Requires R&D to Overcome Process Integration and Scale-up Challenges

Goal

Adapt and apply PNNL hydrothermal PDU capabilities* to enable the production of biofuels and co-products from wet waste feedstocks

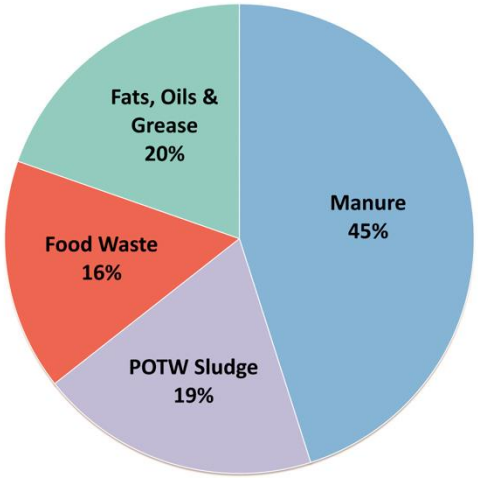
** Hydrothermal Liquefaction (HTL), Hydrotreating (HT), Catalytic Hydrothermal Gasification (CHG)*

Outcome

- The project will enable ***technology innovation, process integration*** and ***partnership projects*** to demonstrate ***scalable hydrothermal processing methods*** for the conversion of wet waste feedstocks into biofuel and co-products

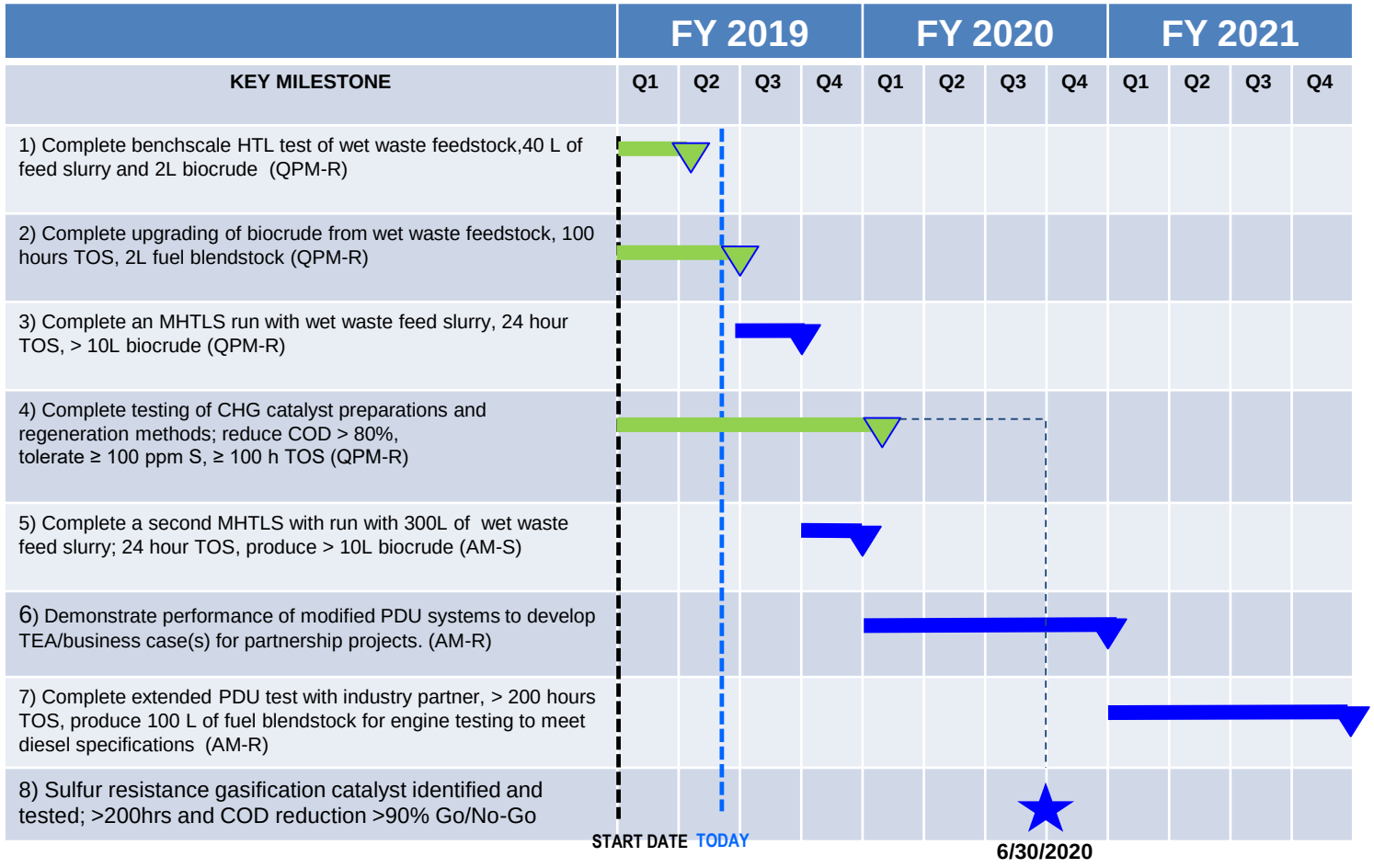
Relevance

- 69.4 Million dry metric tons/year of wet waste feedstocks available[1]
- 5.6 Billion gallons/year of renewable diesel blendstocks produced[2]
- Huge benefits in waste management and environmental protection



[1]Milbrandt A., Seiple T., Heimiller D., Skaggs R., Coleman A., Wet waste-to-energy resources in the United States, Resources, Conservation and Recycling, 2018, v.137, Pages 32-47, Doi:10.1016/j.resconrec.2018.05.023.
[2]Skaggs R., Coleman A., Seiple T., Milbrandt A., Waste-to-Energy biofuel production potential for selected feedstocks in the conterminous United States, Renewable and Sustainable Energy Reviews, Volume 82, Part 3, 2018, Pages 2640-2651, doi:10.1016/j.rser.2017.09.107.

AOP Project Milestones



Legend: Green is active and Blue is planned

AOP Project Budget Table

	Original Project Cost (Estimated)			Project Spending and Balance		Final Project Costs
Budget Periods	**DOE Funding[1]** **Budget[2]**	**Project Team Cost Shared Funding**	**Contingency**	**Spending to Date**	**Remaining Balance**	**What funding is needed to complete the project. (FY19)**
Project	**2,473,804[1]** **3,900,000[2]**			**505,000**	**3,395,000**	**1,426,196**
Task 1. PDU Enabling R&D				**333,000**	**572,000**	
Task 2. System Performance Testing and Scale-up				**45,000**	**505,000**	
Task 3. PDU Business Models and Outreach				**17,000**	**143,000**	
Task 4. PDU Modification, Testing, Maintenance, and Management				**110,000**	**450,000**	
Task 5. CRADA Partnership Projects				**0**	**1,000,000**	
FY19 Planned Carryover					**725,000**	

Quad Chart Overview

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Timeline

- Project start date: October 1, 2018
- Project end date: September 30, 2021
- Percent complete: 12%

	Total Costs Pre FY 17	FY 17 Costs	FY 18 Costs	Total Planned Funding (FY 19-Project End Date
DOE Funded AOP	$0	$0	$0	$8,900,000
DOE CRADA-light Funds	$0	$0	$0	$1,000,000

Barriers

- Barriers addressed
  - ADO-A. Process Integration
  - ADO-D. Technology Uncertainty of Integration and Scaling
  - ADO-F. First-of-a-Kind Technology Development

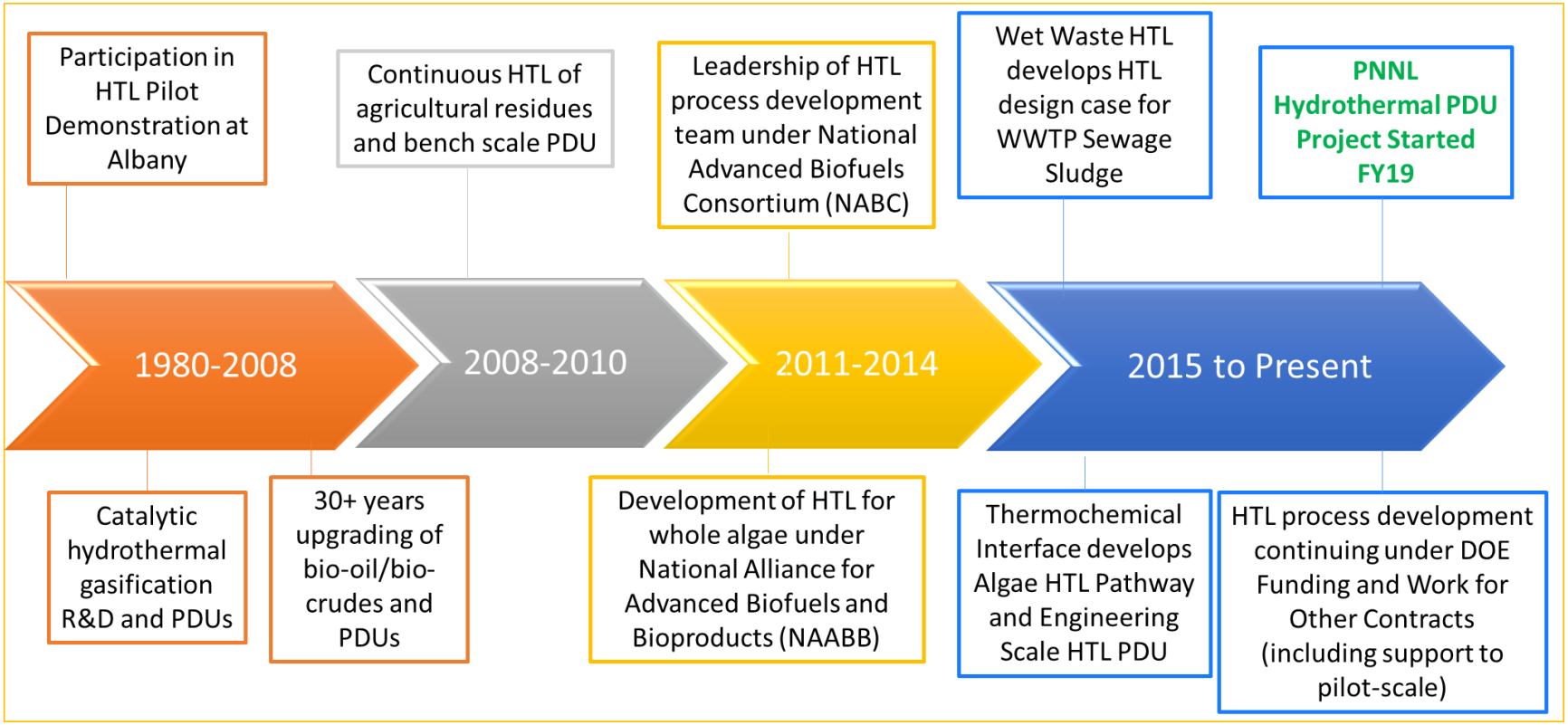
Other Interactions

- PDU Collaborations (NREL, LBL, INL)
- Related Projects

Bench Scale HTL of Wet Wastes	2.2.2.302
Strategies for Co-processing in Refineries – PNNL	2.4.2.305
HTL Model Development	1.3.5.202
Analysis and Sustainability Interface - PNNL	2.1.0.301
Thermochemical Interface	1.3.4.101
Waste-to-Energy: Feedstock Evaluation and Biofuels Production	2.1.0.113
Separations Consortium - ORNL	2.5.5.507
Recovering and Upgrading Biogenic Carbon in Biomass-Derived Aqueous Streams	2.3.1.310
HYPOWERS HTP Pilot WWTP	3.4.1.23

1 - Project Overview

How Was the PDU Capability Developed?



Leverages >$3M BETO Capital Investments

1 - Project Overview

What Will the PDU Project Do?

- Conduct process development research to evaluate impacts of different feedstocks on;
  - HTL yields and upgraded fuel blendstock quality
  - Valorization of process waste streams
  - PDU unit operations and process parameters
  - Engineering scale-up challenges that are required prior to conducting later stage integrated pilot testing
- Produce meaningful quantities (>5 gallons) of drop-in fuel blendstocks for supporting BETO R&D and consortia work as well as industrial partnerships
- Establish partnerships to conduct testing of multiple feedstocks to make fuel blendstocks and or biocrude suitable for co-processing in a refinery and support business case development
- Provide process data to update models, TEA, LCA, SOT, and for business case input

2 – Approach (Technical)

Technical Approach Structured Around Key Challenges and Defined Objectives

Tasks	Challenges	Objectives
1. PDU Enabling R&D	Feedstock Impacts	Evaluate Biosolids in Benchscale HTL Testing
		Evaluate Manure Benchscale HTL Testing
	Advanced Characterization	Complete Fate Report on HTL Destruction of Hazardous Compounds from WWTP
		Biocrude Pre-treatment Characterization to Determine Process Effectiveness
	Process R&D Unit Operations	Conduct Rheology Evaluations of Feedstocks and Products
		Update HTL Large Scale Pumping Review
		Complete Heat Exchanger Evaluation for HTL Processing
		Conduct Oil/Water Separation Studies Using Enhanced Processing Methods
		Develop Methods to Improve CHG Catalyst Life for HTL Aqueous Treatment
		Develop and Test New Pretreatment and Upgrading Methods for HTL Biocrude
2. Feedstock and System Performance Testing & Scale-up	HTL Testing & Scale-up	Conduct Bench HTL Testing of New Wet Waste Feed and Blends
		Conduct HTL PDU Processing of New Wet Waste Feed and Blends
	Upgrading Testing & Scale-up	Conduct Pretreatment Testing for Clean-up of Biocrude and Process Scale-up
		Conduct HT PDU Processing of Biocrudes From Wet Waste Feed and Blends
3. PDU Business Models & Outreach	PDU Awareness & Utilization	Develop PDU Website, Business Models, and Strategies for Partnership Projects
		Collaborate with other BETO PDUs on Best Practices and Lessons Learned
4. PDU Modification, Testing, Maintenance and Management	PDU System Modifications	Plan and Complete Needed Modifications to MHTLS PDU
		Plan and Complete Needed Modifications to HT PDUs
		Plan and Complete Needed Modifications to Mobile CHG PDU
	Capability Management and Maintenance	Manage PDU and Maintain PDU Equipment and Facilities
		Provide QA for Configeration Control of Systems, SOPs, Operator Training,etc.
5. CRADA Light Partnership Projects**	Partnership Projects	Establish Competitive PDU Partnership Projects Working Through BETO
		Conduct PDU Partnership Projects

2 – Approach (Technical)

Hydrothermal Liquefaction PDU Systems

Modular Hydrothermal Liquefaction System

- Engineering-scale system
  - support HTL scale up
  - generate large quantities of products for testing
- Feed rate 12 to 18 L/h
- Skid for slurry feed preparation
- Skid for product separations and storage
- HTL Skid
  - PFR configuration w/ heat integration
  - Hybrid CSTR/PFR configuration
- Designed for typical 100 h test campaign

Scale	Systems	Reactor Configurations	Rxt Volume	Feed Rate
Bench Scale	2	Multiple PFRs and CSTRs options	0.3 to 2 L	1 to 4 L/h
Engineering Scale	1	PFR with heat integration and hybrid PFR with CSTR	3 to 5 L	12 L/h

Critical Success Factors

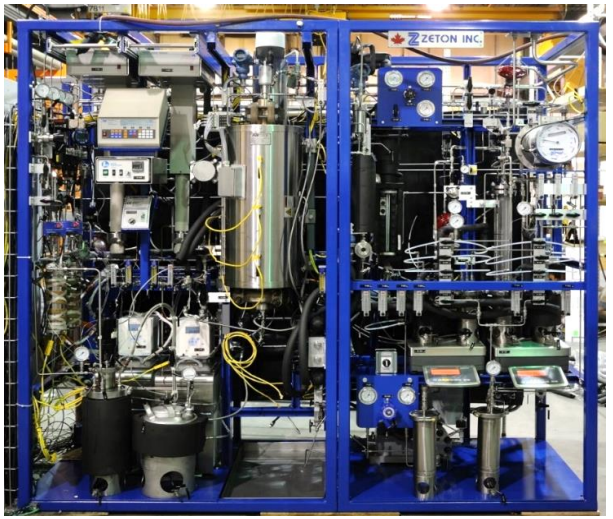
- *HTL Throughput*
- *Operational Reliability*

2 – Approach (Technical)

Upgrading PDU Systems

- HTL biocrude upgrading requires
  - Pretreatment to remove trace metals
  - Hydrotreating to remove hetero atoms (O, N, S) to produce fuel blend stocks
  - Demonstration of long TOS
- PDU capability
  - biocrude pretreatment systems
  - several scales and modes of continuous flow hydrotreaters
- Adapting moving bed technology
  - to increase the catalyst life by better distribution of trace metal impurities

Moving Bed HT



Scale	Systems	Reactor Configurations	Rxt Volume	Feed Rate
Lab-scale	4	Down-flow trickle bed. Unattended operation for long duration tests	50 ml	3 to 25 ml/h
Bench Scale	2	Fixed bed and moving bed	0.4 to 1 L	40 to 250 ml/h

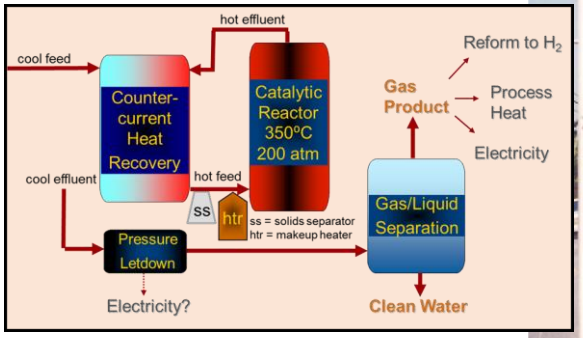
Critical Success Factors

- *Pre-treatment and Upgrading Methods*
- *Refinery Integration Strategies*

2 – Approach (Technical)

Catalytic Hydrothermal Gasification PDU Systems

- Aqueous waste stream treatment
- Provides COD reduction > 95%
- Produces methane fuel gas
  - 60:40% CH_4:CO_2
- Heterogeneous catalyst



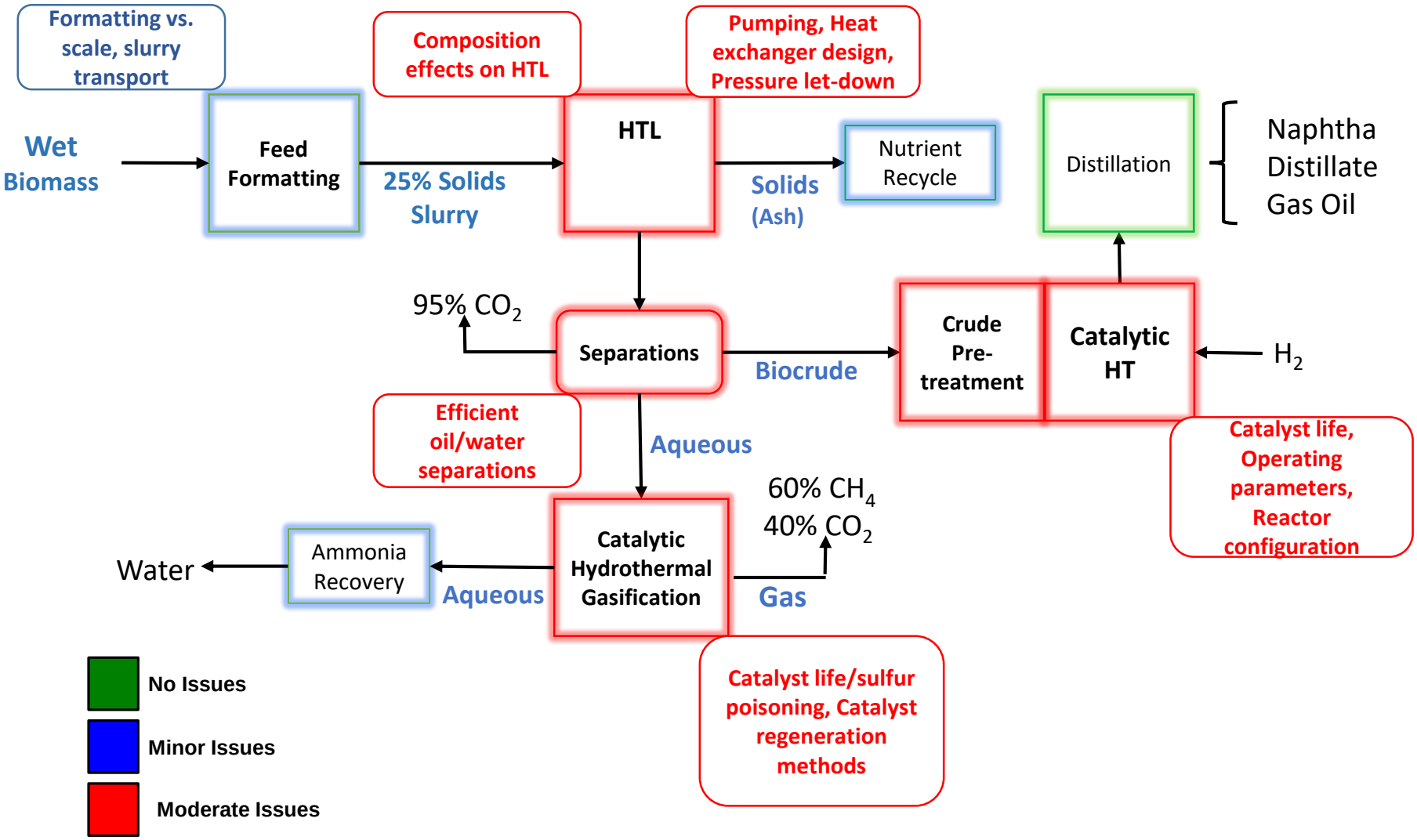
Mobile CHG Trailer

Scale	Systems	Reactor Configurations	Rxt Volume	Feed Rate
Bench scale	2	Unattended, fixed bed, up-flow	25 ml	20 to 200 ml/h
Engineering Scale	1	Mobile unit in trailer, 4 fixed bed reactors in series, with heat integration	4-L	8 to 16 L/h

Critical Success Factor

- *Catalyst Life for CHG Processing*

Process Operations Block Diagram



2 – Approach (Management)

Project Structured to Support Internal and External Work

- **PNNL's ongoing hydrothermal R&D program**
- **Extend and integrate with other BETO R&D**
- **Establish and conduct partnership projects**

- Detailed WBS with experienced task leads
  - Well defined scope/deliverables
  - Funding authorizations
- Monthly project team meetings
  - Review progress, schedule and budget
  - Discuss issues and integration
- Defined AOP Milestones (1/Quarter) and Deliverables
  - Quarterly Reports
- Regular Meetings with BETO
- Coordination and Integration with Other PDUs
- Management and Integration of Supporting Projects and Partners

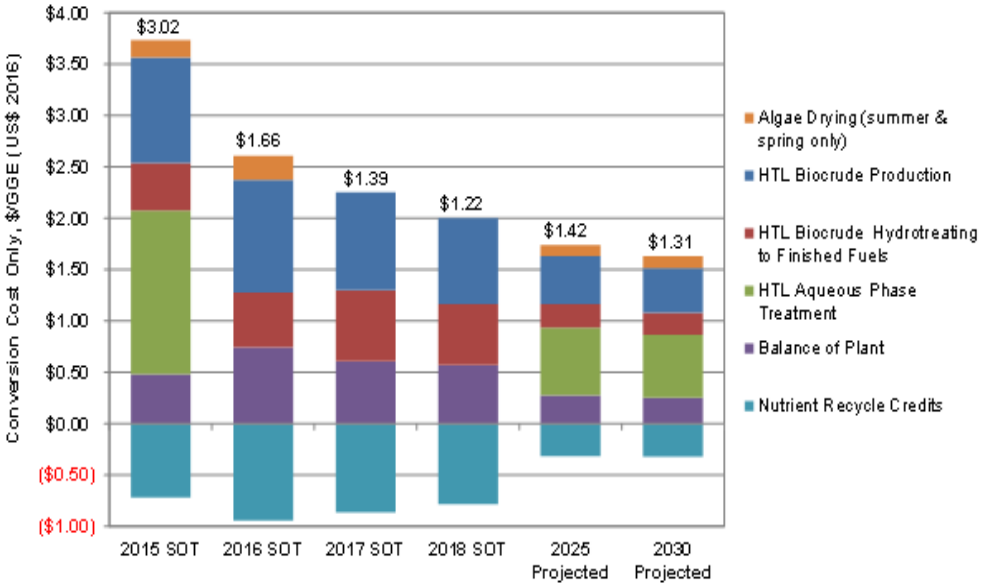
3 – Technical Accomplishments/ Progress/Results

PNNL Hydrothermal Processing R&D Progress

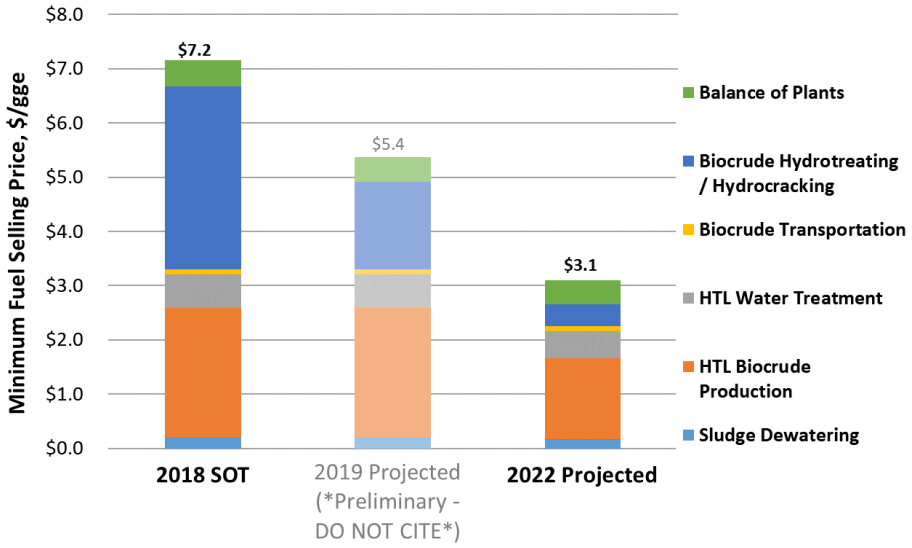
- Design Cases Developed with TEA/LCA Models
- R&D and Cost Targets Driven by SOTs
- Significant Progress Made in Driving Down Conversion Cost

(HTL yield, throughput, separations, nutrient recycle, blended feedstocks)
(HT upgrading pretreatment, process methods, catalysts / LHSV)

Algae HTL Processing SOT



WWTP Sludge HTL Processing SOT



4 – Relevance

Enables the Production of Biofuels and Co-products from Wet Waste Feedstocks

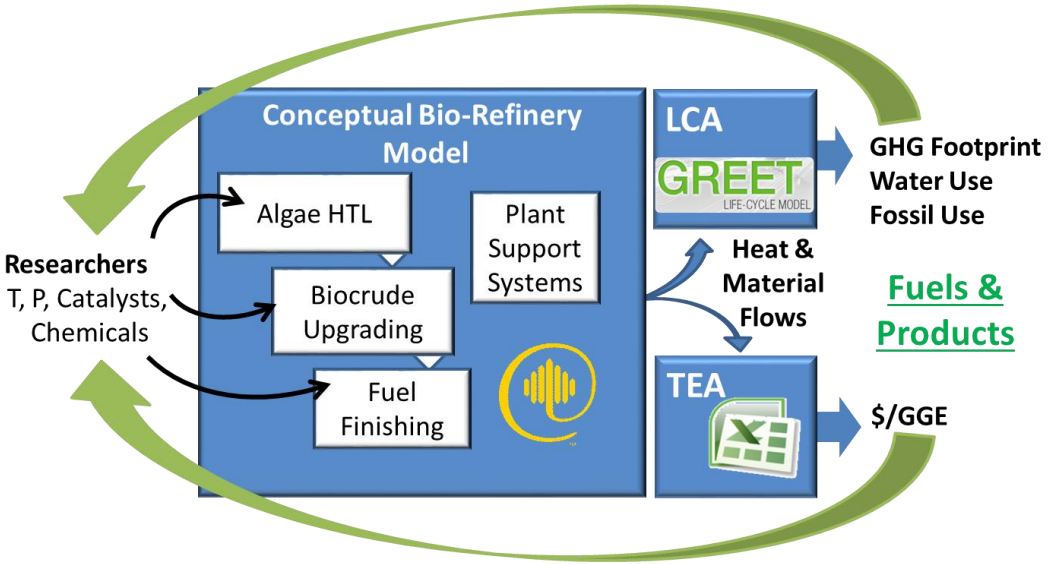
Directly supports BETO's ADO strategic goals: By 2022, verify integrated systems research at engineering scale for hydrocarbon biofuel technologies that achieve a mature modeled MFSP of $3/GGE with a minimum 50% reduction in emissions relative to petroleum-derived fuels.
By 2030, verify integrated systems research at engineering scale for hydrocarbon biofuel technologies that achieve a mature modeled MFSP of $2.5/GGE with a minimum 50% reduction in emissions

- **Hydrothermal processing of wet waste feedstocks has the potential to produce 5.6 Billion gallons/year of renewable diesel blendstocks**
- **Huge benefits in waste management and environmental protection**

4 – Relevance

R&D Focus and Cost Targets Identified and Driven by SOT

- **Develop data-driven process models (AspenPlus) and cost models (Excel)**
- **Developing enabling technology for critical elements (HTL, Upgrading and HTL waste streams)**
- **Project structured to drive down conversion costs and meet MFSP cost targets**



4 – Relevance

Project Structured to Support Internal and External Work

- **Project will support technology transfer**
  - *Access to engineering scale PDU capabilities*
  - *Promotes multiple collaborations with industrial partners*
  - *Provides a process and funding for partnership projects*

- **Project will leverage synergies and support to BETO projects**
  - *Waste to Energy, Conversion, Co-processing, Separations, Materials of Construction, Feedstock Logistics*

- **Project will contribute to multiple publications and invited presentations and is closely aligned with national organizations representing technology adopters e.g. Water Research Foundation (WRF)**

5 – Future Work
Project Scope

PDU Enabling R&D

- Focused on essential R&D to address technical gaps
    - New feedstock testing in benchscale HTL
    - Advanced characterization to mitigate bad actors from feed and products
    - Processing R&D
        - feedstock conditioning, pumping, heating, pressure letdown, oil/water separation, aqueous byproduct treatment/valorization, biocrude pretreatment, and biocrude upgrading

Feedstock and System Performance Testing & Scale-up

- Focus on performance of individual PDU unit operations using various feedstocks to make fuel blendstocks
    - MHTLS processing campaigns
    - Pre-treament and HT campaigns
    - Distillation of upgraded fuels
    - CHG testing of aqueous streams
    - Biofuel characterization and engine testing

5 – Future Work
Project Scope (cont.)

PDU Business Models & Outreach

- Focused on developing business models for PDU utilization and out reach for partnership projects
    - Coordination and collaboration with BETO and other BETO PDUs
    - Outreach with potential PDU partners
        - WWTP utilities, refineries and fuel producers, equipment manufacturers, potential industrial owner/operators for HTL processing wet wastes

PDU Modification, Testing, Maintenance and Management

- Focused on updating PDU unit operations and maintaining the systems operational capability
    - System mods and maintenance
    - Configuration control of systems and SOPs
    - Operator training
    - Management of PDUs systems

CRADA Light Partnership Projects

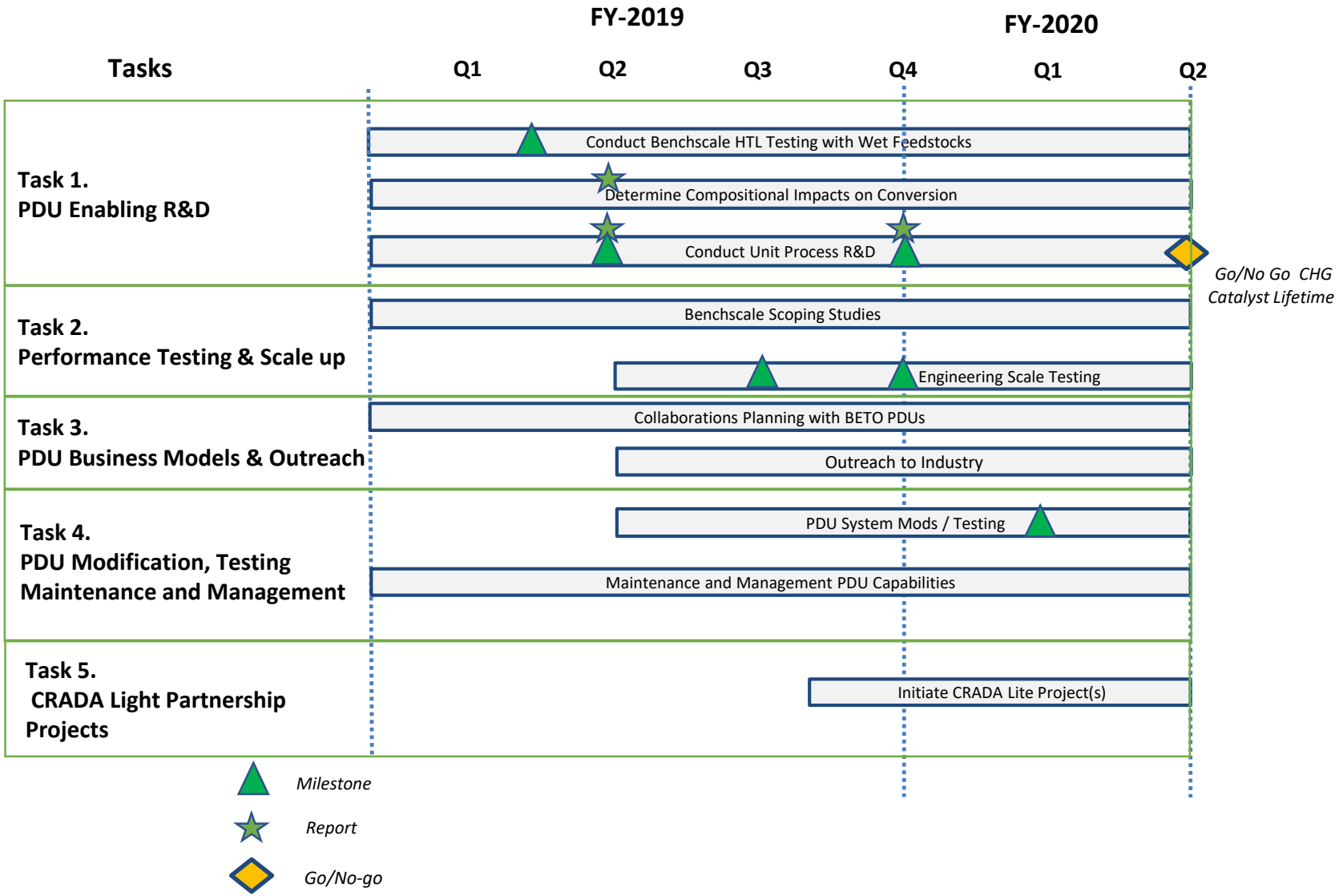
- PNNL will support BETO competitive partnership projects utilizing the PDU

5 – Future Work

Detailed WBS

WBS	Task/Subtask Description	Task Lead
Task 1	**PDU Enabling R&D**	
1.1	***Feedstock R&D***	
	Biosolids Benchscale Testing	AJ Schmidt
	Dairy Manure Benchscale Testing	AJ Schmidt
1.2	***Advanced characterization***	
	Fate Report HTL WWTP	J Billings
	Biocrude Pre-treatment characterization	RT Hallen
1.3	***Processing R&D***	
	Rheology Evaluations	AJ Schmidt
	HTL Large Scale Pumping Review	M Thorson
	Heat Exchanger Evaluation	L Snowden-Swan
	Oil/Water Separation Studies	J Billings
	CHG Catalyst Life Testing	MV Olarte
	Pretreatment and Upgrading	RT Hallen
Task 2	**Feedstock and System Performance Testing**	
2.1	***Bench HTL Wet Waste Feed***	AJ Schmidt
2.2	***MHTLS Wet Waste Feed***	AJ Schmidt
2.3	***Upgrading Wet Waste Biocrude***	DM Santosa
2.4	***Subcontracts*** *(Analytical, Detail Characterization, Fuel EngineTesting)*	
Task 3	**PDU Business Models, Outreach for Partnerships Projects**	DB Anderson
Task 4	**PDU Modification, Testing, Maintenance and Management**	
4.1	***MHTLS System Mods***	AJ Schmidt
4.2	***Upgrading System Mods***	RT Hallen
4.3	***CHG System Mods***	T Hart
4.4	***MHTLS Manager Pilot Plant Operations***	MJ Gray
4.5	***QA Support PDUs***	L Middleton-Smith
Task 5	***CRADA Lite Partnership Projects***	DB Anderson
	Project Management and Integration	DB Anderson

5 – Future Work Schedule FY 19-20



Summary

Overview:

Adapting and applying PNNL hydrothermal PDU capabilities to enable the production of biofuels and co-products from wet waste feedstocks

Approach:

Conduct analysis driven process R&D for scale-up and partnership projects for biofuels production

Technical Accomplishments/Progress/Results:

Building on a legacy of prior research leading to new conversion pathways for biofuel and co-products from wet feedstocks

Relevance:

Directly supports meeting BETO's 2030 cost target goals for biofuels

Future work:

- PDU Enabling R&D
- Feedstock and System Performance Testing & Scale-up
- PDU Business Models & Outreach
- PDU Modification, Testing, Maintenance and Management
- CRADA Light Partnership Projects

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Thank you

Acknowledgements

- Liz Moore– BETO Technology Manager
- Hydrothermal PDU Team
  - Dan Anderson
  - Andy Schmidt
  - Rich Hallen
  - Justin Billing
  - Todd Hart
  - Mariefel Olarte
  - Miki Santosa
  - Michel Gray
  - Mike Thorson
  - Lisa Middleton-Smith

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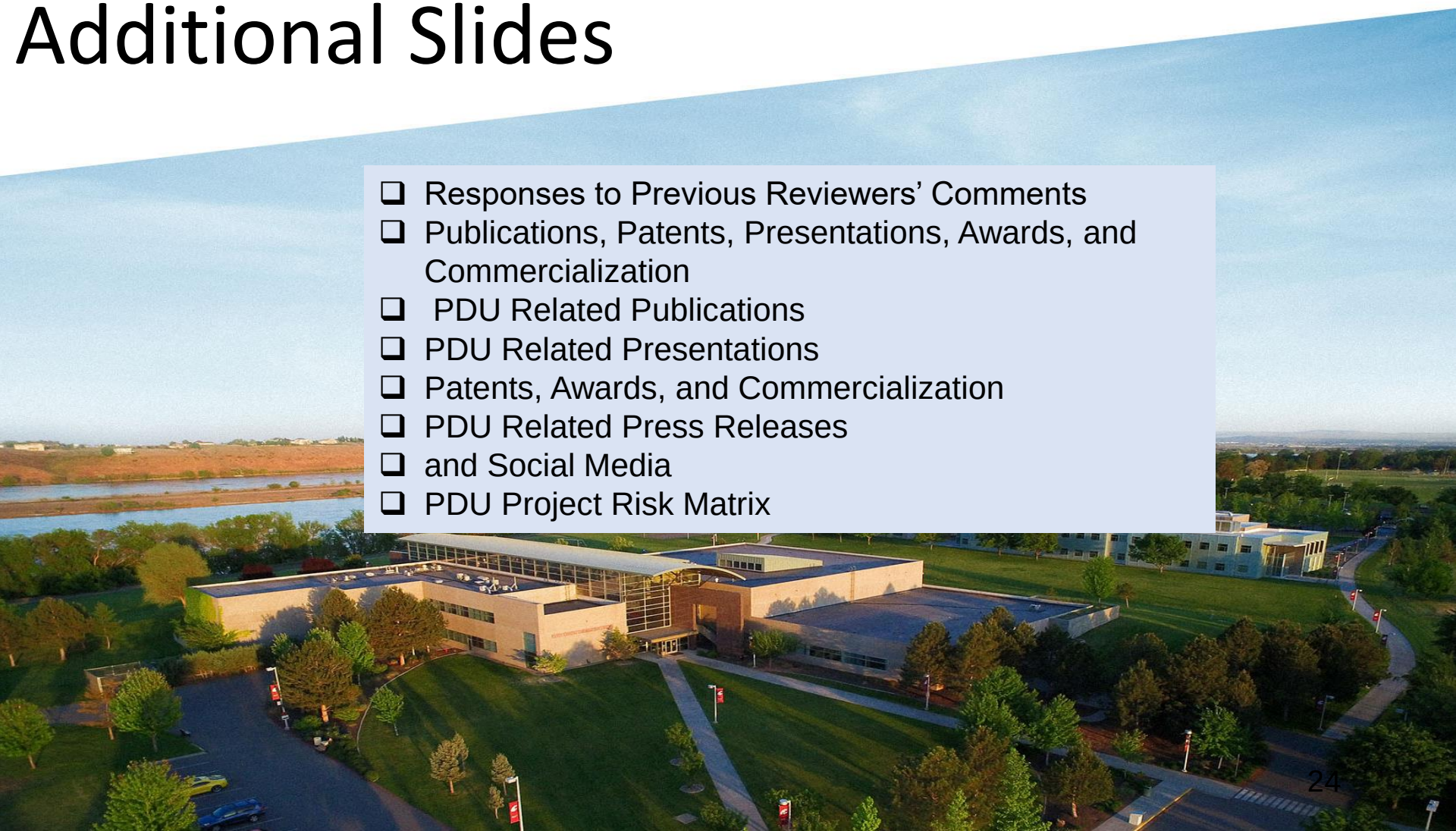
Additional Slides

- Responses to Previous Reviewers' Comments
- Publications, Patents, Presentations, Awards, and Commercialization
- PDU Related Publications
- PDU Related Presentations
- Patents, Awards, and Commercialization
- PDU Related Press Releases
- and Social Media
- PDU Project Risk Matrix



Responses to Previous Reviewers' Comments

Project is new start

Publications, Patents, Presentations, Awards, and Commercialization

Project is new start

PDU Related Publications

- Pegallapati, AK, J Dunn, E. Frank, S. Jones, Y Zhu, L Snowden-Swan, R Davis, C Kinchin. April 2015. Supply Chain Sustainability Analysis of Whole Algae Hydrothermal Liquefaction and Upgrading. ANL/ESD—13/8 https://www.osti.gov/src/details.jsp?query_id=1&Page=0&osti_id=1183770

- Jiang Y., S.B. Jones, Y. Zhu, L.J. Snowden-Swan, A.J. Schmidt, J.M. Billing, and D.B. Anderson. 2018. "Techno-Economic Uncertainty Quantification of Algal-derived Biocrude via Hydrothermal Liquefaction." *Algal Research*. PNNL-SA-138139. [submitted]

- Zhu Y., S.B. Jones, A.J. Schmidt, K.O. Albrecht, S.J. Edmundson, and D.B. Anderson. 2018. "Techno-Economic Analysis of Alternative Aqueous Phase Treatment Methods for Microalgae Hydrothermal Liquefaction and Biocrude Upgrading System." *Algal Research*. PNNL-SA-137970. [submitted]

- Jiang Y., S.B. Jones, Y. Zhu, L.J. Snowden-Swan, A.J. Schmidt, J.M. Billing, and D.B. Anderson. 10/29/2018. "Techno-Economic Uncertainty Quantification of Algal-derived Biocrude via Hydrothermal Liquefaction." Pittsburgh, Pennsylvania. PNNL-SA-139100.

- Zhu Y., S.B. Jones, A.J. Schmidt, J.M. Billing, K.O. Albrecht, R.T. Hallen, and D.B. Anderson. 06/12/2018. "Co-feeding of algae/wood blend feedstock for hydrothermal liquefaction (HTL) and upgrading – a techno-economic analysis." Presented by Yunhua Zhu at The 8th International Conference on Algal Biomass, Biofuels and Bioproducts, Seattle, Washington. PNNL-SA-135398.

- Anderson D.B., J.M. Billing, S.J. Edmundson, A.J. Schmidt, and Y. Zhu. 04/29/2019. "Demonstration of the Hydrothermal Liquefaction Pathway for Conversion of Microalgae to Biofuels with Integrated Recycle of Nutrients." Abstract submitted to Biofuels and Bioenergy Conferences, San Francisco, California. PNNL-SA-139499

- "Performance of a Compression Ignition Engine Fueled with Renewable Diesel Blends Produced from Hydrothermal Liquefaction, Fast Pyrolysis, and Conversion of Ethanol to Diesel." Jessica Tryner, Karl Albrecht, Justin Billing, Richard T. Hallen, and Anthony J. Marchese. Paper accepted for presentation and publication in Conference Proceedings of the Western States Section of the Combustion Institute Meeting at the University of Wyoming, October 3, 2017

- "FT-ICR MS analysis of blended pine-microalgae feedstock HTL biocrudes." Jacqueline M Jarvis; Justin M Billing; Yuri E Corilo; Andrew J Schmidt; Richard T Hallen; Tanner Schaub, Ph.D. **Fuel**, Volume 216, 15March 2018, Pages 341-348. (https://doi.org/10.1016/j.fuel.2017.12.016)

PDU Related Publications (cont.)

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- He Y, X Li, X Xue, MS Swita, AJ Schmidt, and B Yang. 2017. "Biological Conversion of the Aqueous Wastes from Hydrothermal Liquefaction of Algae and Pine Wood by Rhodococci." Bioresource Technology 224:457-464. doi:10.1016/j.biortech.2016.10.059
- Elliott, D.C. 2016. “Review of Recent Reports on Process Technology for Thermochemical Conversion of Whole Algae to Liquid Fuels.” Algal Research 13, 255-263, web published: December 17, 2015, DOI: 10.1016/j.algal.2015.12.002
- Albrecht, K.O. 2016 “Impact of Heterotrophically Stressed Algae for Biofuel Production via Hydrothermal Liquefaction and Catalytic Hydrotreating in Continuous-Flow Reactors” Algal Research 14, 17-27, web published: January 8, 2016, DOI: 10.1016/j.algal.2015.12.008.
- Maddi, B.; Panisko, E.; Wietsma, T.; Lemmon, T.; Swita, M.; Albrecht, K.; Howe, D., Quantitative characterization of the aqueous fraction from hydrothermal liquefaction of algae. Biomass and Bioenergy 2016, 93, 122-130.
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- He Y, X Li, X Xue, MS Swita, AJ Schmidt, and B Yang. 2017. "Biological Conversion of the Aqueous Wastes from Hydrothermal Liquefaction of Algae and Pine Wood by Rhodococci." Bioresource Technology 224:457-464. doi:10.1016/j.biortech.2016.10.059
- Maddi B, EA Panisko, TW Wietsma, TL Lemmon, MS Swita, KO Albrecht, and DT Howe. 2017. “Quantitative Characterization of Aqueous Byproducts from Hydrothermal Liquefaction of Municipal Wastes, Food Industry Wastes, and Biomass Grown on Waste, ACS Sustainable Chemistry & Engineering.” Accepted, in press. doi: 10.1021/acssuschemeng.6b02367
- Panisko EA, TW Wietsma, TL Lemmon, KO Albrecht, and DT Howe. 2015. "Characterization of the Aqueous Fractions from Hydrotreatment and Hydrothermal Liquefaction of Lignocellulosic Feedstocks." Biomass & Bioenergy 74:162-171. doi:10.1016/j.biombioe.2015.01.011

PDU Related Presentations

- Albrecht KO, RT Hallen, AJ Schmidt, JM Billing, MA Lilga, AR Cooper, JE Holladay, and DB Anderson. 2016. "Waste Streams as Economic Feedstocks for the Production of Sustainable Liquid Fuels." Presented by Karl O Albrecht at 2nd CRC Advanced Fuel and Engine Efficiency Workshop, Livermore, CA on November 2, 2016.
- Billing JM, AJ Schmidt, TR Hart, GD Maupin, RT Hallen, and DC Elliott. 2015. "Continuous Hydrothermal Liquefaction of Cellulosic and Lignocellulosic Biomass." Presented by Justin M. Billing at ACS 249th National Meeting, Denver, CO on March 25, 2015.
- Billing JM, AJ Schmidt, TR Hart, GD Maupin, KO Albrecht, H Wang, DB Anderson, RT Hallen, and DC Elliott. 2015. "Continuous Flow Hydrothermal Liquefaction of Biomass Feedstock." Presented by Justin Billing at tcbiomass 2015, Chicago, IL on November 4, 2015.
- Billing JM, DB Anderson, RT Hallen, TR Hart, GD Maupin, AJ Schmidt, and DC Elliott. 2016. "Design, Fabrication, and Testing of the Modular Hydrothermal Liquefaction System (MHTLS)." Presented by Justin M Billing at TCS 2016, Chapel Hill, NC on November 3, 2016.
- “Performance of a Compression Ignition Engine Fueled with Renewable Diesel Blends Produced from Hydrothermal Liquefaction, Fast Pyrolysis, and Conversion of Ethanol to Diesel.” Jessica Tryner, Karl Albrecht, Justin Billing, Richard T. Hallen, and Anthony J. Marchese. Paper presented and publication in Conference Proceedings of the Western States Section of the Combustion Institute Meeting at the University of Wyoming, October 3, 2017.
- “Characterization of Fuel Properties and Engine Performance of Renewable Diesel Produced from Hydrothermal Liquefaction of Microalgae and Wood Feedstocks.” Jessica Tryner, Karl Albrecht, Justin Billing, Richard T. Hallen, and Anthony J. Marchese. Algal Biomass Summit, Salt Lake City UT, October 30, 2017. PNNL-SA-126131.
- Albrecht KO, RT Hallen, AJ Schmidt, JM Billing, MA Lilga, AR Cooper, JE Holladay, and DB Anderson. 2016. "Waste Streams as Economic Feedstocks for the Production of Sustainable Liquid Fuels." Presented by Karl O Albrecht at 2nd CRC Advanced Fuel and Engine Efficiency Workshop, Livermore, CA on November 2, 2016.
- Billing JM, AJ Schmidt, TR Hart, GD Maupin, KO Albrecht, H Wang, DB Anderson, RT Hallen, and DC Elliott. 2015. "Continuous Flow Hydrothermal Liquefaction of Biomass Feedstock." Presented by Justin Billing at tcbiomass 2015, Chicago, IL on November 4, 2015.

PDU Related Presentations (cont.)

- Billing JM, DB Anderson, RT Hallen, TR Hart, GD Maupin, AJ Schmidt, and DC Elliott. 2016. "Design, Fabrication, and Testing of the Modular Hydrothermal Liquefaction System (MHTLS)." Presented by Justin M Billing at TCS 2016, Chapel Hill, NC on November 3, 2016.
- Elliott DC, DB Anderson, RT Hallen, AJ Schmidt, and JM Billing. 2016. "Recent Developments in Hydrothermal Processing of Wet Biomass." Presented by Douglas C. Elliott (Invited Speaker) at South Dakota School of Mines and Technology, Rapid City, SD on March 22, 2016.
- Drennan C. 2016. "Hydrothermal Liquefaction - a new paradigm for sustainable bioenergy." Presented by Corinne Drennan at Bioenery Australia 2016, Brisbane, Australia on November 14, 2016.
- Jones SB, Y Zhu, LJ Snowden-Swan, and DB Anderson. 2015. "HTL Model Development." Presented by Susanne B. Jones (Invited Speaker) at DOE Bioenergy Technologies Office (BETO) 2015 Project Peer Review, Washington DC, DC on March 24, 2015. PNNL-SA-108674.
- Zhu Y, SB Jones, DB Anderson, RT Hallen, AJ Schmidt, KO Albrecht, and DC Elliott. 2015. "Techno-Economic Analysis of Whole Algae Hydrothermal Liquefaction (HTL) and Upgrading System." Presented by Zhu, Yunhua (Invited Speaker) at Algae Biomass Summit, Washington, D.C., DC on October 2, 2015. PNNL-SA-112790.
- Billing JM, DC Elliott, RT Hallen, TR Hart, AJ Schmidt, PA Marrone, JC Moeller, and P Kadota. 2017. "Bench-Scale Evaluation of the Genifuel Hydrothermal Processing Technology for Wastewater Solids." Presented by Philip A Marrone at WEFTEC 17 Conference, Chicago, IL on September 30, 2017.
- Drennan C. 2016. "Hydrothermal Liquefaction - a new paradigm for sustainable bioenergy." Presented by Corinne Drennan at Bioenery Australia 2016, Brisbane, Australia on November 14, 2016.
- Elliott DC, DB Anderson, RT Hallen, AJ Schmidt, and JM Billing. 2016. "Recent Developments in Hydrothermal Processing of Wet Biomass." Presented by Douglas C. Elliott (Invited Speaker) at South Dakota School of Mines and Technology, Rapid City, SD on March 22, 2016.
- Holladay JE, and C Drennan. 2015. "Waste to Energy." Presented by John Holladay at Mass Production of Biomass Refineries Workshop, Broomsfield, CO on May 11, 2015.
- Maddi B, EA Panisko, TW Wietsma, TL Lemmon, MS Swita, KO Albrecht, and DT Howe. 2016. "Quantitative Characterization of Aqueous Byproducts from Hydrothermal Liquefaction of Municipal Wastes, Food Industry Wastes, and Biomass Grown on Waste." Presented by Balakrishna Maddi at TCS 2016, Chapel Hill, NC on November 1, 2016.

Patents, Awards, and Commercialization

Awards

- 2015 FLC technology transfer excellence award
- 2015 R&D 100 Award “Hydrothermal Processing to Convert Wet Biomass into Biofuels”

Patents

- Elliott, D.C.; Oyler, J.R. "Methods for Sulfate Removal in Liquid-Phase Catalytic Hydrothermal Gasification of Biomass." U.S. Patent #8,877,098, issued on November 4, 2014.

PDU Related Press Releases and Social Media

- Reddit Ask Me Anything (AMA) live event with Justin Billing. “Human Waste to Biofuels” in r/Science category. Archived questions and responses at The Winnower. doi: 10.15200/winn.148060.00259. Stats: Most popular biofuels AMA, 10,031 user click-throughs, 7,576 up-votes, estimated 16.2M people who saw the link on Reddit or other social media.
- “From the Toilet to the Tank,” YouTube video. 2016. https://youtu.be/ER4C6EapZQ4, accessed 03 February 2017. Currently 97K views.
- “Fuel from sewage is the future – and it's closer than you think.” PNNL News Center. November 2, 2016. Story adapted by dozens of national and international media outlets including Popular Science and the Huffington Post UK. http://www.pnnl.gov/news/release.aspx?id=4317, accessed 03 February 2017.

PDU Project Risk Matrix

Name	Status	Target Completion Date	Severity	Response	Description
Pressure Let-down	Ongoing	9/30/19	Moderate	Risk Management Response: mitigate Plan: Work with larger scale units, accept deficiency in PDU operations	MHTLS scale too small to allow demonstration of robust pressure letdown Impact of Risk: moderate Probability of Risk: moderate
Oil/Water separation	Ongoing	9/30/19	High	Risk Management Response: mitigate Plan: Investigate continuous centrifugal separator on bench scale. If successful, deploy on MHTLS	First 3 MHTLS runs hampered/shut down due to oil/water separation challenges Impact of Risk: major Probability of Risk: moderate,
Heat Exchanger (HX) Design/Cost	Ongoing	9/30/20	Moderate	Risk Management Response: mitigate Plan: Conceptualize and test novel heat exchange approaches to reduce CapEx.	HX is the most expensive unit op in the process. Impact of Risk: moderate Probability of Risk: moderate
Hydrotreater Modifications	Ongoing	9/30/20	Moderate	Risk Management Response: mitigate Plan: Develop detailed plan for system modifications integrated with testing	Hydrotreater system modifications to solve process challenges delayed Impact of Risk: moderate Probability of Risk: moderate
Lack of Feedstock	Ongoing	9/30/19	High	Risk Management Response: avoid, Plan: Proactive engagement with industry and feedstock program	Lack of availability of strategic feedstocks to support R&D studies Impact of Risk: major Probability of Risk: moderate
Feedstock Properties	Ongoing	9/30/21	Moderate	Risk Management Response: mitigate Plan: Issue topical report on rheological properties of feedstock. Eliminate issue with feed or system modification, find an alternative feedstock	Feedstock properties not well characterized and/or not suited for processing in MHTLS Impact of Risk: moderate Probability of Risk: moderate
Fuel Blendstock Testing	Ongoing	9/30/19	Moderate	Risk Management Response: avoid Plan: Develop detailed plan for minimum fuel blendstock production and associated fuel testing	Fuel blendstock testing constrained by availability of blendstocks produced or subcontractor schedule Impact of Risk: moderate Probability of Risk: moderate

PDU Project Risk Matrix (cont.)

Name	Status	Target Completion Date	Severity	Response	Description
Upgrading Catalyst Lifetime	Ongoing	9/30/21	Moderate	Risk Management Response: mitigate Plan: Determine cause and find new catalysts or pretreatment processes	Insufficient catalyst longevity/activity for biocrude upgrading Impact of Risk: moderate Probability of Risk: moderate
CHG Catalyst Lifetime	Ongoing	6/30/20	High	Risk Management Response: mitigate Plan: Find and/or develop new sulfur resistant catalyst Find other means to recycle or valorize HTL aqueous waste stream	High sulfur levels in wet waste feedstocks poison current gasification catalyst Impact of Risk: major Probability of Risk: highly likely
Fuel Blendstock Testing	Ongoing	9/30/19	Moderate	Risk Management Response: avoid Plan: Develop detailed plan for minimum fuel blendstock production and associated fuel testing	Fuel blendstock testing constrained by availability of blendstocks produced or subcontractor schedule Impact of Risk: moderate Probability of Risk: moderate