

PNNL-39453

Algae Hydrothermal Liquefaction

End-of-Project Report

June 2026

Peter Valdez



U.S. DEPARTMENT
of **ENERGY**

Prepared for the U.S. Department of Energy
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Pacific Northwest National Laboratory
Richland, Washington 99354

Summary

This document is a close-out report for two Pacific Northwest National Laboratory (PNNL) projects funded by the Alternative Fuels and Feedstocks Office (formerly the Bioenergy Technologies Office) of the Department of Energy (DOE).

The two projects are:

- Thermochemical Interface (DOE ref. no. 1.3.4.101, PNNL ref. no. 64490)
- HTL Model Development (DOE ref. no. 1.3.5.202, PNNL ref. no. 71612)

At the end of fiscal year 2025, both projects ended. Additional activities related to the topics of algae, hydrothermal liquefaction (HTL), and the techno-economic assessment of HTL of algal feedstocks will be studied in other projects.

Key technical findings of the projects were published in early 2025 [1] and highlights will be summarized in this document. A summary of recent technical findings from 2025 are also included herein. This close-out report summarizes key outcomes from both projects highlighting the value and technical impact achieved.

Acknowledgments

Numerous contributors supported research for both the Thermochemical Interface and HTL Model Development projects. Their contributions over several years resulted in many meaningful outcomes and measured research progress. Contributors are from Pacific Northwest National Laboratory unless otherwise noted (Idaho National Laboratory [INL]).

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Acronyms and Abbreviations

DOE	Department of Energy
ERDC	Engineer Research and Development Center
FLC	Federal Laboratory Consortium
FTICR-MS	Fourier-transform ion cyclotron resonance mass spectrometry
GGE	gasoline gallon equivalent
HTL	hydrothermal liquefaction
MFSP	minimum fuel selling price
MHTLS	modular hydrothermal liquefaction system
PNNL	Pacific Northwest National Laboratory
SAF	synthetic aviation fuel
SCM	supplemental cementitious material
SOT	state-of-technology
TEA	techno-economic assessment

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1.0 Introduction

In September 2025, researchers at Pacific Northwest National Laboratory (PNNL) completed two key projects related to the hydrothermal liquefaction (HTL) of algae to produce biofuels. The first project, initiated in 2013 as “Thermochemical Interface,” focused on the technology development for HTL processing of algal slurries. The overall objective of the project was to address scale-up barriers and further advance the commercialization of HTL processing and the subsequent upgrading of the HTL products. Throughout the project, several improvements were discovered to improve the technical feasibility and economic viability of HTL with algae as a feedstock. A large variety of micro- and macro-algal feedstocks were also tested to prove their viability.

The second project, “HTL Model Development” was started in 2017 and complemented the Thermochemical Interface project by providing focused techno-economic assessments that guided and tracked the technological developments through economic metrics. For several years, both projects contributed to the publication of state-of-technology (SOT) reports. Six consecutive reports were published, starting in 2020, with each report summarizing key technology and/or process improvements to HTL. The improvement in breakeven selling price (minimum fuel selling price [MFSP]) was reported to quantify the value of the technical improvements for a conceptualized industrial-scale process.

The purpose of this document is to highlight the value and technical impact of the project achieved through publications, patents, and licenses.

2.0 Key Research Outcomes

Through both projects, key innovations and research outcomes were produced. The following paragraphs highlight key findings and the relevant publications that detail each finding.

Minimizing Costs

One of the objectives of the annual SOT reports was to quantify the technical improvements as a reduction in MFSP for the finished fuel product from algal HTL. The SOT reports highlighted how cost of equipment and materials influenced the final fuel cost. Ultimately, the cost of the feedstock was determined to be the most significant contributor to the cost of the fuel. The cost contribution of pond-cultivated microalgae was at least \$5.54/gasoline gallon equivalent (GGE) (2025\$). Developing cost-advantaged or zero-cost algae improved cost calculations, resulting in MFSP values as low as \$3.73/GGE (2025\$). Wastewater-grown algae provided the best cost outcomes, achieving low MFSP values while maintaining a reasonable yield of biocrude and scalability comparable to pond-cultivated algae. Figure 1 summarizes MFSP calculations from several SOT reports, showing the relationship between scale of the HTL system and feedstock type with respect to the MFSP (2020\$) [1]. The figure shows two categories of feedstocks, zero-cost feedstocks, shown in the gray-shaded region, and purchased feedstocks (pond-cultivated), shown in the blue-shaded region. Because of the higher cost of farm-grown feedstock, a facility with a larger production capacity is needed to achieve the benefits of economies of scale.

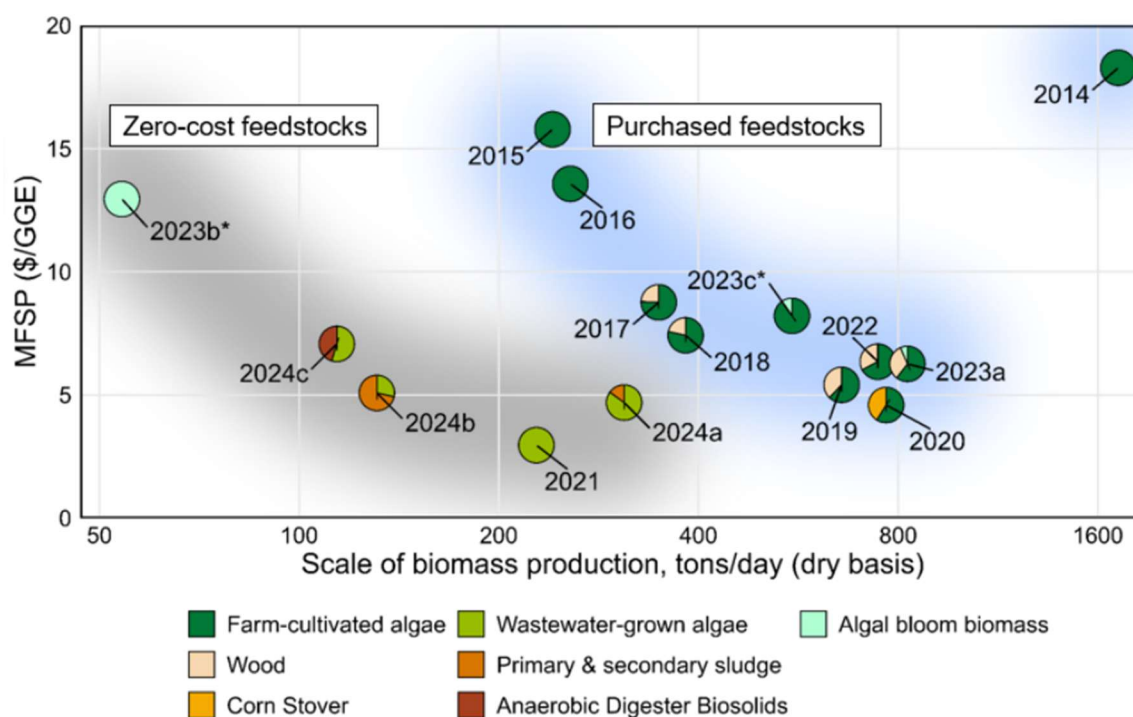


Figure 1. Biomass conversion scale, minimum product selling price, and feedstock source for HTL scenarios modeled between 2014 and 2024. Scenarios marked with an asterisk (*) exclude the cost of hydrotreating biocrude to finished fuel products. Costs shown are in 2020\$; additional details about the figure are published previously [1].

Storage and Pretreatment

Research in the project demonstrated the stability of the algal biomass for HTL processing after >100 days of anaerobic storage with the addition of *Lactobacillus plantarum* [2]. Demonstrating storage stability ensures that seasonally produced algae can be later processed with comparable performance to fresh feedstocks. HTL biocrude from the stored and fresh algae showed negligible differences in yield and composition.

As feedstocks shifted toward low-cost but high-ash biomass, such as wastewater-grown algae and algal bloom biomass, pretreatment methods were examined to remove ash precipitates prior to HTL processing. Brown et al. successfully demonstrated a 21 wt. % reduction in ash content, with minimal loss (8 wt. %) of organic content, using pH adjustment (9.5) and hydrocyclone processing [3]. The reduced ash content is expected to facilitate HTL processing, reducing the total volume of material to be processed and enabling higher carbon retention in the biocrude.

Scale-up

Experimental data and process expertise significantly contributed to the design and operation of the engineering-scale HTL system at PNNL. The process knowledge for HTL, which was gained mostly from processing algal feedstocks, was used to inform scale-up of the bench-scale HTL equipment (up to 5 liters per hour) to the modular hydrothermal liquefaction system ([MHTLS] up to 16 liters per hour) [4]. The MHTLS is part of the process development unit capability at PNNL for hydrothermal conversion, shown in Figure 2. The MHTLS is a focal point for HTL research at PNNL, enabling scaled-up, large-volume demonstrations of HTL conversion across a variety of biomass feedstocks.



Figure 2. Photo of the MHTLS at PNNL.

Jet Fuel

The project reported the first ever production of synthetic aviation fuel (SAF) from algae via HTL [5]. *Picochlorum celeri* was hydrothermally processed and the resulting biocrude was hydroprocessed to finished fuels. The jet fuel cut was isolated and assessed for jet fuel properties, showing that many of the properties were within specification; Figure 3 shows the results of the jet fuel testing. In later research, SAF was also produced from wastewater-grown algae, producing a similar quality of fuel products [6].

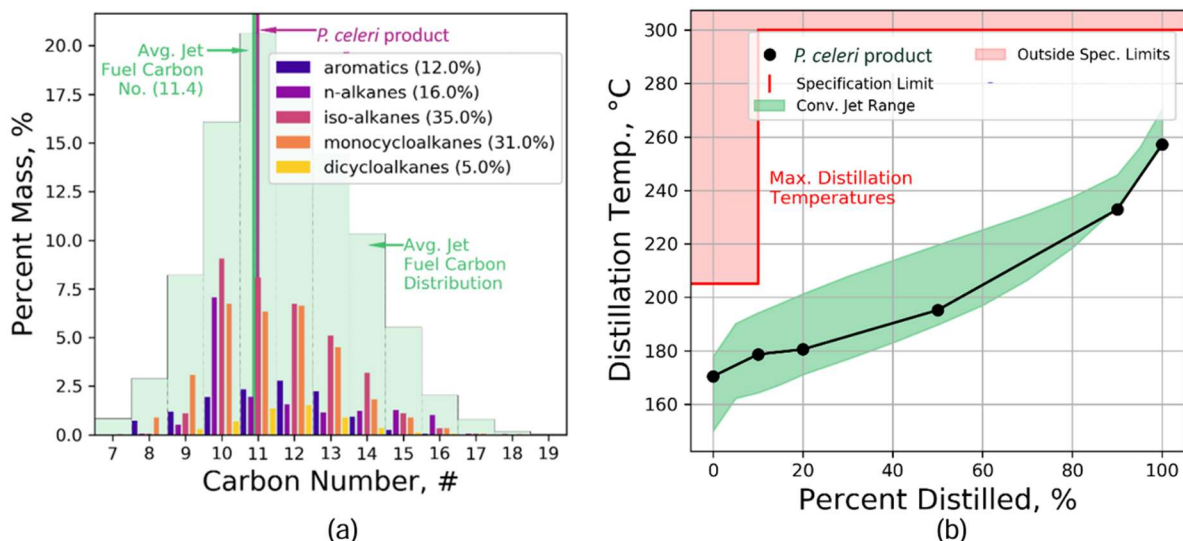


Figure 3. Characterization results from the SAF sample derived from *P. celeri* showing (a) the distribution of carbon number and hydrocarbon type and (b) distillation profile [5].

Co-Products

Although the production of biocrude as a fuel intermediate was the primary goal for HTL research, several valuable and scalable co-products were also considered to improve the overall value of HTL processing. Extractable sugars for fermentation [7] or even precipitated fertilizer products (e.g., struvite) were examined in the project [8]. Seed germination studies proved the viability of the direct usage of HTL solids as a fertilizer substitute. Figure 4 shows results of the seed germination study as seeds were planted with different concentrations of HTL solids, up to 100 wt. %. All the seeds at lower concentrations (5, 10, 25 wt. %) successfully germinated, and only the seeds in 100 wt. % solids were unable to germinate.

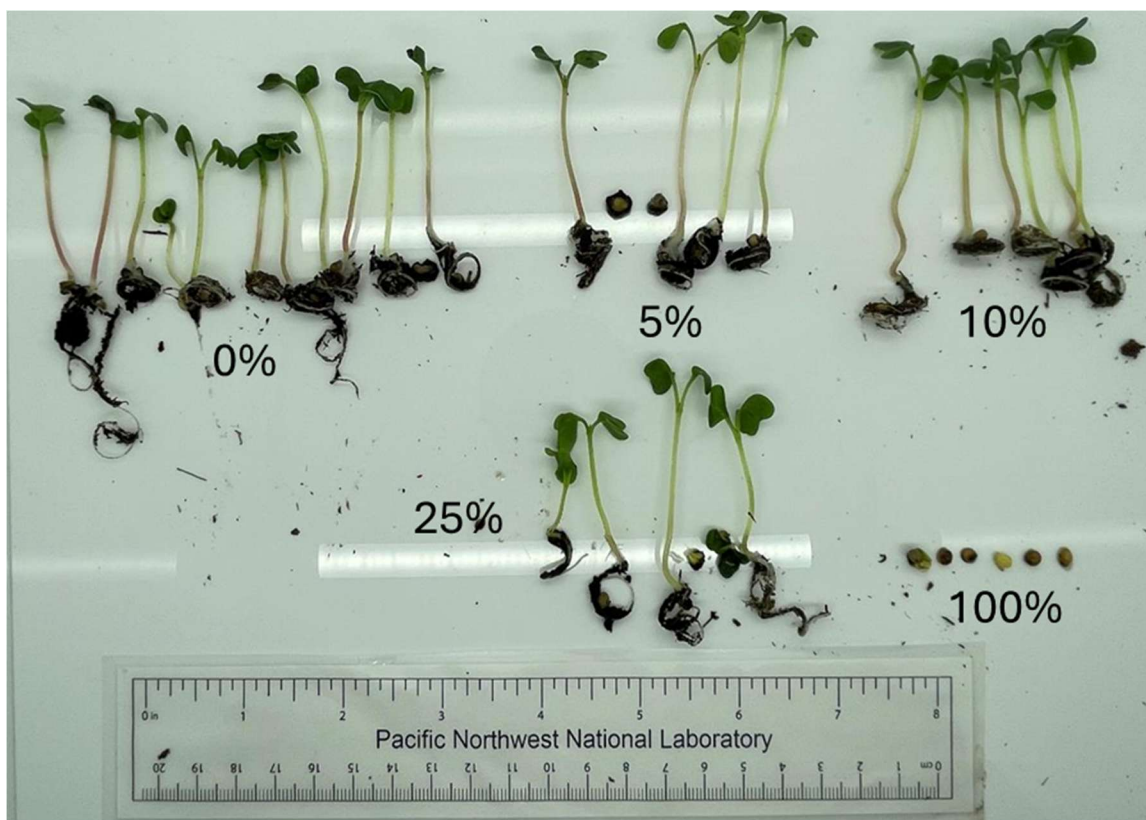


Figure 4. Seedlings fertilized with HTL solids increasing up to 100 wt. % concentration.

Alternatively, the HTL solids from high-ash algae, such as wastewater-grown algae or algal bloom biomass, produced a material suitable for use as a cement additive [9]. Specifically, HTL solids were blended into cement formulations as a supplemental cementitious material (SCM). The HTL solids from algal bloom biomass were particularly high in concentration for aluminum, silicon, and calcium, which help improve pozzolanic activity. The use of HTL solids would supplement other SCM materials, such as coal fly ash. This was the first published use of HTL solids as an SCM.

The biocrude was examined as an asphalt binder for pavement applications [10-13]. The novel use of biocrude in this way eliminated the need for additional refinement or hydrotreatment after HTL. In fact, the blending of algal biocrudes into bitumen formulations improved the moisture resistance, self-healing capability, and thermal cracking (at low temperatures). The improved characteristics have been attributed to the fatty acids and amides from the algae. Analysis and Modeling

Fourier-transform ion cyclotron resonance mass spectrometry (FTICR-MS) was utilized to understand the transformation of biomass into crude-like molecules. Using the precision of FTICR-MS assisted in understanding how porphyrins from algae decomposed during HTL [14]. Porphyrins are specific to chlorophyll-rich biomass, such as blue-green microalgae, and it was important to understand how the release of iron from the porphyrin complex could impact downstream catalytic upgrading of the biocrude to finished fuels. The removal of iron before hydrotreatment was highlighted as a priority to limit catalyst deactivation in hydrotreatment processes.

HTL biocrudes from pine wood and algae were assessed via FTICR-MS. The analysis revealed synergistic reactions that occur during HTL when feedstocks are blended together, producing new compounds that are not present from single feedstocks [15]. The addition of algae to pine wood during HTL was found to be beneficial in moderating the pH and preventing certain polymerization reactions that would ultimately produce more solids than biocrude.

The data generated from several algae-HTL experiments were used to develop a predictive model for the yield and elemental composition of the HTL products from algae [16]. Creating a simple model to predict HTL outcomes enabled the use of Monte Carlo simulation to examine thousands of possible processing scenarios and estimate uncertainty in the predicted values for MFSP. Uncertainty in the MFSP was $\pm 12\%$, which equates to variations of up to $\pm \$0.50/\text{GGE}$ for predicted values.

3.0 Scientific and Commercial Impact

Overall, the two projects provided scientific products, external awards, and commercial patents.

Between the two projects, numerous publications, reports, and presentations were produced, providing contributions toward the technical knowledge of HTL within the scientific community. A listing of the peer-reviewed publications (18), technical reports (11), and conference presentations and invited talks (24) are provided in Appendix A.

In addition to the published technical content, two patents were issued for technology developments that were generated by the project team. Both patents have been successfully licensed for commercial utilization.

1. Elliott, D., J. Oyler. Issued on November 4, 2014. "Methods for Sulfate Removal in Liquid-Phase Catalytic Hydrothermal Gasification of Biomass." U.S. Patent #8,877,098.
2. Thorson, M., L. Snowden-Swan, A. Schmidt, T. Hart, J. Billing, D. Anderson, and R. Hallen. Issued March 2022. "Hydrothermal liquefaction system." U.S. Patent #11,279,882.

The issued patents and subsequent licensing were recognized by two external organizations. In 2015, PNNL was recognized with an R&D100 award for "Hydrothermal Processing to Convert Wet Biomass into Biofuels" [17]. The R&D100 awards recognize the innovation and significance of new technologies available for licensing.

Also in 2015, the Federal Laboratory Consortium for Technology Transfer (FLC) awarded the project team for "Excellence in Technology Transfer." The FLC was created by Congress in 1974 to recognize the work accomplished by federal laboratories and research centers. The Excellence in Technology Transfer Award recognizes outstanding work in transferring federally developed technology into the commercial sector. The award specifically recognized the successful licensing of PNNL-developed HTL technology to Genifuel [18].

The foundational research for algae HTL led to collaborations with research consortia, national laboratories, universities, and commercial organizations throughout the project's lifetime. Additional parallel projects continued to develop the topic in novel and valuable research directions. One example is from PNNL's contributions to the National Alliance for Advanced Biofuels and Bio-products. Early research examined coupling HTL of algae biomass with lipid extraction or catalytic hydrothermal gasification to boost the total yield of energy products [19]. Another example is a parallel project funded by the U.S. Army Engineer Research and Development Center (ERDC) to examine the HTL of algal bloom biomass harvested from freshwater lakes. The project with ERDC led to a separate FLC award, in 2023, in the category of impact, recognizing tangible and lasting impact from successful technology transfer [20].

4.0 Conclusions and Recommendations

Research at PNNL has contributed to the advancement and technology development for algal fuels and products produced via HTL. Innovations and findings in storage stability, preprocessing, fertilizer and cement co-products, and the first demonstrated production of algae-derived SAF have expanded the technical feasibility of algae HTL while strengthening its economic viability. Advanced analytical studies and modeling have improved understanding of product compositions, uncertainty quantification, and predictive modeling.

The projects have delivered impactful scientific contributions through high-quality publications, patents, and awards for technology transfer. The accomplishments at PNNL highlight the substantial technical value and broad impact from the projects. The research for algae HTL at PNNL was fundamental for developing additional research topics and projects in HTL.

In the 2024 report, three key recommendations were proposed for continued improvements for the technical and economic feasibility of algae HTL [1].

1. Reducing capital intensity

There are still opportunities to innovate the commercial-scale design for HTL, maximizing biocrude yield and quality (low nitrogen and oxygen content) while minimizing equipment cost and complexity. Reducing operating temperature and pressure, maximizing resource (carbon and energy) utilization, or catalyzing HTL reactions will reduce costs at any process scale (pilot to commercial).

2. Other co-products or alternatives

The HTL biorefinery will benefit from a broad variety of co-products to achieve economic viability. Initial investigations for fertilizers and SCMs are promising, but additional research is needed to fully validate their potential. Other co-products should be considered for technical and economic viability.

3. Scaling cost-advantaged feedstocks via blending opportunities

The cost of algal feedstock is a limiting factor for utilization. Continued investigation of alternative, cost-advantaged algae or other feedstocks will reduce the MFSP. However, as low-cost feedstocks are considered, the trade-offs with respect to quality and availability will also need consideration.

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Appendix A – Technical Products

A.1 Peer-Reviewed Publications

18. Kazemi, M., S. Parikhah-Zarmehr, F. Pahlavan, A. Hung, A. Rahimi, A. Lamanna, P. Valdez, P. Lammers, and E. Fini. (2026). "Conserving Asphalt Resources: Rethinking Rejuvenator Performance Evaluation Through Peptizing Efficiency." *Resources, Conservation & Recycling* 229, 108847. <https://doi.org/10.1016/j.resconrec.2026.108847>
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2. Albrecht, K. (2015). "Impact of Heterotrophically Stressed Algae for Biofuel Production via Hydrothermal Liquefaction and Catalytic Hydrotreating in Continuous-Flow Reactors." *Algal Research* 14, 17–27. <https://doi.org/10.1016/j.algal.2015.12.008>
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A.2 Technical Reports (not peer-reviewed)

11. Watkins, J., A. Kumar, and P. Valdez. (2025). "Whole Algae Hydrothermal Liquefaction and Upgrading." PNNL-37209. <https://doi.org/10.2172/2500903>
10. Kumar, A., D. Cronin, S. Fox, A. Schmidt, and P. Valdez. (2025). "2024 Case Study: Hydrothermal Liquefaction of Biomass Sources at a Wastewater Treatment Facility." PNNL-37230. <https://doi.org/10.2172/2499474>
9. Xu, Y., S. Edmundson, Y. Zhu, T. Hart, D. Cronin, S. Fox, A. Schmidt, and P. Valdez. (2024). "2023 Business Case Study: Hydrothermal Liquefaction of Algal Bloom Biomass." PNNL-35507. <https://doi.org/10.2172/2482043>
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7. Zhu, Y., A. Schmidt, P. Valdez, L. J. Snowden-Swan, and S. Edmundson. (2022). "Hydrothermal Liquefaction and Upgrading of Wastewater-Grown Microalgae: 2021 State of Technology." PNNL-32695. <https://doi.org/10.2172/1855835>
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5. Zhu, Y., S. Jones, A. Schmidt, J. Billing, M. Thorson, D. Santosa, R. Hallen, and D. Anderson. (2020). "Algae/Wood Blends Hydrothermal Liquefaction and Upgrading: 2019 State of Technology." PNNL-29861. <https://doi.org/10.2172/1616287>
4. Davis, R., A. Coleman, M. Wigmosta, J. Markham, Y. Zhu, S. Jones, J. Han. (2018). "2017 Algae Harmonization Study: Evaluating the Potential for Future Algal Biofuel Costs, Sustainability, and Resource Assessment from Harmonized Modeling." PNNL-27547. <https://doi.org/10.2172/1468333>
3. Zhu, Y., S. Jones, and D. Anderson. (2018). "Algae Farm Cost Model: Considerations for Photobioreactors." PNNL-28201. <https://doi.org/10.2172/1485133>
2. Frank, E., A. Pegallapati, R. Davis, J. Markham, A. Coleman, S. Jones, M. Wigmosta, and Y. Zhu. (2016). "Life-Cycle Analysis of Energy Use, Greenhouse Gas Emissions, and Water Consumption in the 2016 MYPP Algal Biofuel Scenarios." <https://www.osti.gov/biblio/1352505>
1. Pegallapati, A., J. Dunn, E. Frank, S. Jones, Y. Zhu, L. Snowden-Swan, R. Davis, and C. Kinchin. (2015). "Supply Chain Sustainability Analysis of Whole Algae Hydrothermal Liquefaction and Upgrading." <https://www.osti.gov/biblio/1352732>

A.3 Presentations

24. Kumar, A., and P. Valdez. (2025). "Synthetic Aviation Fuel from Co-HTL of Anaerobic Digestion-Derived Biosolids and Wastewater-Grown Algae: A Combined Experimental Study and Techno-Economic Assessment." AIChE Annual Meeting, Boston, MA.
23. Kumar, A., and P. Valdez. (2024). "Comparative Study of Sustainable Aviation Fuel Produced from Wastewater-Grown Algae vs. Farmed Algae." AIChE Annual Meeting, San Diego, CA.
22. Valdez, P. (2024). "Converting algal resources into materials for the bioeconomy." INFEWS and Circular Bioeconomy Systems Workshop, Urbana-Champaign, IL. Invited Talk.
21. Valdez, P., M. Thorson, and A. Schmidt. (2023). "Advancing Towards Scale-Up: Developments in Hydrothermal Liquefaction of Biomass at Pacific Northwest National Laboratory." AIChE Annual Meeting, Orlando, FL. Invited Talk.
20. Valdez, P. (2023). "Converting algal blooms into a resource for fuels, fertilizers, and fill-ins." Algae Biomass Summit, Madison, WI. Invited Talk.
19. Valdez, P., A. Schmidt, S. Edmundson, T. Hart, D. Cronin, and S. Fox. (2022). "Overcoming Engineering Challenges for the Hydrothermal Liquefaction of Cost-Advantaged Algal Feedstocks." AIChE Annual Meeting, Phoenix, AZ.
18. Zhu, Y., S. Jones, A. Schmidt, J. Billing, J. Collett, L. Snowden-Swan, and D. Anderson. (2021). "Preliminary Economic Analysis of Microalgae Conversion to Biofuels and Biochemicals via Sequential Hydrothermal Liquefaction (SEQHTL) and Bioprocessing." International Conference on Algal Biomass, Biofuels and Bioproducts, Online.
17. Anderson, D., J. Billing, S. Edmundson, A. Schmidt, and Y. Zhu. (2019). "Demonstration of the Hydrothermal Liquefaction Pathway for Conversion of Microalgae to Biofuels with Integrated Recycle of Nutrients." Biofuels and Bioenergy Conferences, San Francisco, CA.
16. Jiang, Y., S. Jones, Y. Zhu, L. Snowden-Swan, A. Schmidt, and J. Billing. (2018). "Techno-Economic Uncertainty Quantification of Algal-Derived Biocrude via Hydrothermal Liquefaction." AIChE Annual Meeting, Pittsburgh, PA.
15. Zhu, Y., S. Jones, A. Schmidt, J. Billing, K. Albrecht, R. Hallen, and D. Anderson. (2018). "Co-Feeding of Algae/Wood Blend Feedstock for Hydrothermal Liquefaction (HTL) and Upgrading – A Techno-Economic Analysis." International Conference on Algal Biomass, Biofuels and Bioproducts, Seattle, WA.
14. Edmundson, S., R. Kruk, K. Pittman, M. Huesemann, A. Schmidt, and D. Anderson. (2018). "Sustained Algal Biomass Productivities in Continuously Reused Cultivation Water with Nutrients Derived from the Waste Products of Algal Biocrude Production by Hydrothermal Liquefaction." International Conference on Algal Biomass, Biofuels, and Bioproducts, Seattle, WA.

13. Edmundson, S., R. Kruk, K. Pittman, M. Huesemann, A. Schmidt, T. Lemmon, N. Schlafer, J. Wood, and D. Anderson. (2018). "Water and Nutrient Recycling in Algal Biomass Production for Biofuels." Algal Biomass Summit, Houston, TX.
12. Tryner, J., K. Albrecht, J. Billing, R. Hallen, and A. Marchese. (2017). "Performance of a Compression Ignition Engine Fueled with Renewable Diesel Blends Produced from Hydrothermal Liquefaction, Fast Pyrolysis, and Conversion of Ethanol to Diesel." Western States Section of the Combustion Institute Meeting, University of Wyoming, Laramie, WY.
11. Tryner, J., K. Albrecht, J. Billing, R. Hallen, and A. Marchese. (2017). "Characterization of Fuel Properties and Engine Performance of Renewable Diesel Produced from Hydrothermal Liquefaction of Microalgae and Wood Feedstocks." Algal Biomass Summit, Salt Lake City, UT.
10. Kruk, R., S. Edmundson, and M. Huesemann. (2017). "Climate-Simulated Biomass Productivities of *Chlorella sorokiniana* Using Recycled Nutrients Derived from Hydrothermal Liquefaction Processing." Algal Biomass, Biofuels and Bioproducts, Miami, FL.
9. Edmundson, S., R. Kruk, M. Huesemann, T. Lemmon, J. Billing, A. Schmidt, and D. Anderson. (2017). "Complete NPK Recycle in Algal Cultivation After Hydrothermal Liquefaction of Algal Biomass." Algal Biomass, Biofuels and Bioproducts, Miami, FL.
8. Kruk, R. (2016). "Completing the Nutrient Cycle in Algae Biomass Production." Northwest Algae and Seagrass Symposium, Whidbey Island, WA.
7. Edmundson, S. (2016). "Phosphorus Recycle Following Algal Biocrude Production via Hydrothermal Liquefaction." International Conference on Algal Biomass, Biofuels and Bioproducts, San Diego, CA.
6. Albrecht, K., R. Hallen, A. Schmidt, J. Billing, M. Lilga, A. Cooper, J. Holladay, and D. Anderson. (2016). "Waste Streams as Economic Feedstocks for the Production of Sustainable Liquid Fuels." CRC Advanced Fuel Workshop, Livermore, CA.
5. Billing, J., D. Anderson, R. Hallen, T. Hart, G. Maupin, A. Schmidt, and D. Elliott. (2016). "Design, Fabrication, and Testing of the Modular Hydrothermal Liquefaction System (MHTLS)." TC Biomass 2016, Chapel Hill, NC.
4. Elliott, D., D. Anderson, R. Hallen, A. Schmidt, and J. Billing. (2016). "Recent Developments in Hydrothermal Processing of Wet Biomass." South Dakota School of Mines and Technology, Rapid City, SD. Invited Talk.
3. Drennan, C. (2016). "Hydrothermal Liquefaction – A New Paradigm for Sustainable Bioenergy." Bioenergy Australia 2016, Brisbane, Australia.
2. Billing, J., A. Schmidt, T. Hart, G. Maupin, K. Albrecht, H. Wang, D. Anderson, R. Hallen, and D. Elliott. (2015). "Continuous-Flow Hydrothermal Liquefaction of Biomass Feedstock." TC Biomass 2015, Chicago, IL.
1. Zhu, Y., S. Jones, D. Anderson, R. Hallen, A. Schmidt, K. Albrecht, and D. Elliott. (2015). "Techno-Economic Analysis of Whole Algae Hydrothermal Liquefaction (HTL) and Upgrading System." Algae Biomass Summit, Washington, DC.

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