ORGANIC WASTE CONVERSION

TECHNOLOGY AREA

CONTENTS

INTRODUCTION

The Organic Waste Conversion Technology Area is one of 11 technology areas that were reviewed during the 2023 Bioenergy Technologies Office (BETO) Project Peer Review, which took place April 3–7, 2023, in Denver, Colorado. A total of 18 presentations were reviewed in the Organic Waste Conversion session by five external experts from industry, academia, and other government agencies. For information about the structure, strategy, and implementation of the technology area and its relation to BETO's overall mission, please refer to the corresponding Program and Technology Area Overview presentation slide decks (https://www.energy.gov/eere/bioenergy/organic-waste-conversion).

This review addressed a total U.S. Department of Energy (DOE) investment value of approximately $32,420,875, which represents approximately 6% of the BETO portfolio reviewed during the 2023 Project Peer Review. During the Project Peer Review meeting, the presenter for each project was given 30 minutes to deliver a presentation and respond to questions from the review panel.

Projects were evaluated and scored for their approach, impact, and progress and outcomes. This section of the report contains the Review Panel Summary Report, the Technology Area Programmatic Response, and the full results of the Project Peer Review, including scoring information for each project, comments from each reviewer, and the response provided by the project team.

BETO designated Beau Hoffman as the Organic Waste Conversion Technology Area review lead, with contractor support from Katie Davis (Lindahl Reed) and Brianna Farber (Boston Government Services). In this capacity, Beau Hoffman was responsible for all aspects of review planning and implementation.

ORGANIC WASTE CONVERSION REVIEW PANEL

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ORGANIC WASTE CONVERSION REVIEW PANEL SUMMARY REPORT

Prepared by the Organic Waste Conversion Review Panel

INTRODUCTION

Between April 3 and 7, 2023, BETO conducted a peer review conference to monitor, evaluate, and guide its portfolio of funded research and development projects. Projects were classified by area, with Organic Waste Conversion covering 18 projects. Five peer reviewers representing fields of microbiology, civil/environmental engineering, resource economics, and public policy convened over a 2-day period for presentations by representatives of each project team.

Organic Waste Conversion projects addressed novel methods to convert municipal and industrial organic wastes into bioproducts and biofuels. Targeted organic waste feedstocks included food waste; fats, oils, and grease; manure; treated wastewater solids; and paper mill sludge. Material throughputs addressed included lignocellulose, volatile fatty acids (VFAs), carbohydrates, and nutrients. A range of conversion processes were presented, including hydrothermal liquefaction (HTL), enzymatic hydrolysis, microbial electrosynthesis (MES), biomethanization, dark fermentation, cathodic electro-fermentation, and a range of pre- and post-treatments in conjunction with conventional and alternative approaches to anaerobic digestion (AD). Envisioned products included sustainable aviation fuel (SAF), a priority for DOE BETO, as well as a range of high-value products such as hexanoic acid, alcohol, and other precursors for chemical manufacturing/fuels or blendstocks of fuel products. Some projects also envisioned nutrient recovery of nitrogen and phosphorous for fertilizer applications.

Projects aimed to optimize carbon conversion efficiency (CCE) and to express market outcomes of conversion in terms of a minimum fuel selling price (MFSP) per gasoline gallon equivalent (GGE). Several projects considered the geographic context of project development, addressing the proximity of feedstocks to conversion facilities and to end markets, as well as local jurisdictional issues around facility hosting.

What follows is a compilation of general comments from the five peer reviewers on BETO program strategy and implementation, followed by recommendations for the future development of this program. Although there is broad overlap among the reviewer comments, some differences do exist within the Project Peer Review group. Bullets before paragraphs indicate different reviewer perspectives.

STRATEGY

- The review panel agrees that BETO's organic waste-to-energy (WTE) program is strong. There are numerous projects in diverse areas, increasing the likelihood of success. This program leverages academic researchers and researchers working at national laboratories well.

- The projects are nicely tackling the full array of wet organic wastes: food, treated municipal wastewater solids, and manure. In terms of conversion strategies and methodologies, the team seems to have a fairly comprehensive strategy. There do not seem to be any obvious missing pathways. All the products presented as part of the Project Peer Review begin with wet organic wastes. All of them are looking at deriving value from these streams. This includes deriving saleable products as well as minimizing waste. As a clearer strategy has come into play, the office has narrowed its focus on jet fuel and heavy vehicles as products that are difficult to decarbonize. The projects have responded well to these challenges and continue to demonstrate nimbleness and versatility. Each project is addressing key challenges around wet waste.

- BETO's programmatic goals are clear. BETO has set technical targets in their overall Multi-Year Program Plan process that make sense, including a focus on SAF as opposed to motor vehicle fuels, and an emphasis on small, "community-scale" AD. With regard to renewable natural gas (RNG) production from conversion operations, BETO has identified near-term supply bottlenecks that argue for growth in

RNG as a bioproduct. In focusing on SAF as a major targeted output, BETO has appropriately identified conversion technologies that stand to optimize the transformation of feedstocks into bioproducts that are less likely to compete with carbon-free renewable alternatives while minimizing unwanted byproducts.

- The projects that are being funded by the BETO program employ avant-garde techniques aimed at generating liquid fuel, products/chemicals, hydrogen gas, and RNG, which can be said to be the fuels of the future. Overall, BETO is pursing well-defined and highly impactful goals largely aimed at increasing environmental sustainability through the cultivation of energy sources such as RNG, liquid fuel, and hydrocarbons. In addition, these efforts mitigate decomposition in landfills, a leading source of greenhouse gas (GHG) emissions, as well as nutrient pollution from manure and wastewater management.

STRATEGY IMPLEMENTATION AND PROGRESS

Engaging Industry Stakeholders

- All projects require an industry (or similar) partner, which has merits. There may also be value in limiting industry partnerships for projects in their infancy and which display a low level of technology readiness. Such creative and/or risky projects would benefit from allowing the researchers simply to develop their ideas without partnering with an industry.

- Another positive is that teams are working with a range of industry professionals. The challenge is that the organic waste conversion industry is still nascent, particularly with regard to doing more with what most folks view as waste.

Extending Engagement to Other Stakeholders

- It is evident that BETO has considered industry input extensively. It has also acknowledged input from other stakeholders, including local utilities/management jurisdictions, businesses generating feedstocks and/or potentially consuming end products for particular projects, academia, and national laboratories. BETO should continue to guide researchers to seek greater degrees of input from local/regional utilities and service agencies, landowners, and community organizations, including those opposed to conversion technologies. Overall, there was good engagement with typical partners in project development, but more work is needed to provide stakeholders not directly engaged in R&D and finance to contribute to the selection and evaluation of projects as well as for researchers on selected projects to more proactively engage with local and regional stakeholders in these categories.

- One of the best features of BETO's strategy implementation is the launch of a technical assistance (TA) program geared to local/regional stakeholders in governments. BETO is to be commended for its emphasis on letting "communities define the problem statement" (as stated in slide 17 of BETO's Organic Wastes Session Overview presentation). BETO's partnerships with the Great Lakes Water Authority; Yarmouth, Massachusetts; and the city of Gainesville are excellent starts.

- BETO should also focus on promoting stronger stakeholder partnership to move these projects from the lab scale.

- The forced socialization of these projects to the broader community will be critical to overcoming the myriad challenges.

Using Techno-Economic Analysis (TEA) and Life Cycle Analysis (LCA) to Quantify Progress

- Reporting requirements for TEA and LCA were very helpful in a number of projects. In fact, the best projects took the LCA and TEA aspects of this work seriously and appropriately pivoted the direction of the project when the LCA and/or TEA indicated that they should.

- BETO positions ongoing work under organic waste conversion projects as having the potential for significant reductions in GHGs, including methane, carbon dioxide, and nitrous oxide. Overall, the structure of the individual project presentations did not allow for an apples-to-apples comparison of GHG profiles or projected impacts. Further, it would be helpful for reviewers and the public to have access to information on modeling assumptions used in the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) LCA tool or other tools used by researchers to estimate net GHG reductions. In particular, the goal of carbon neutrality through organic waste conversion heavily depends on assumptions of substitution between bioproducts and fossil-sourced products, especially in the case of fuels, to achieve a net system stabilization and overall GHG reduction. BETO must pay attention to the empirical verification of assumed substitutions once its funded technologies reach scale because of the possibility for net system growth due to bioproduct supply availability—regardless of the system stabilization envisioned in models.

- In generating energy from waste, the BETO program set economically and environmentally suitable targets that include reducing the levelized cost of energy (LCOE) by 25%, increasing the energy return of investment by 25%, improving CCE by at least 50%, and reducing the cost of disposal by >25%. To ensure that these set targets are well met, projects that are funded under the BETO program involve collaboration among industry experts, stakeholders, and researchers, which leads to the cross-fertilization of ideas and strategies. Also, the program includes projects that involve modeling, TEA, and LCA all aimed at finding optimized pathways (in terms of reducing cost and environmental contamination and increasing energy yield) for generating energy from waste. Further, the BETO program includes a WTE TA project where experts advise communities on the best avenues/methods for deploying WTE technologies.

Promoting Diversity, Equity, Inclusion, and Accessibility (DEIA)

- Overall, the requirements for DEIA were good, although some projects were better at appearing to have a DEIA component than demonstrating the implementation of DEIA initiatives. Many projects mentioned that key personnel came from underrepresented groups yet provided little additional information on these staff and/or their specific project contributions. Other projects required diversity, equity, and inclusion (DEI) training for project personnel. This approach is preferable because it is achievable and tangible.

- The current era (2020 to present) has been marked by three massive social upheavals that have affected nearly every aspect of political, social, and individual life. These include the COVID-19 epidemic; a new reckoning with justice that alternately recognizes, or denies, legacies and ongoing practices of harm to Black, Indigenous, and other people of color, LGBTQIA2S+, disabled, and migrant communities; and the now near-irreversible scale of the climate crisis, along with mass species extinction, the proliferation of new forms of toxicity, soil depletion and erosion, and air pollution. The combined impacts of these three upheavals have made clear, to varying degrees within some government agencies, that a more serious, complete, and inclusive approach to hearing and responding to local and regional concerns across a wide array of stakeholders is needed in public policy and planning. The establishment of DOE's Office of Energy Justice, and the recent incorporation of DEI and community engagement activities as criteria for funded project award and Project Peer Review criteria, reflect this trend but only in a nascent, unstructured manner with regard to organic waste conversion.

- With regard to the social impacts of organic waste processing, BETO is focused on siting inequities and disproportionate impacts falling on disadvantaged communities and recognizes the need for a "social license to operate" (slide 8 of BETO's Organic Wastes Session Overview presentation); however, it was not clear from the projects presented (1) that such inequities and impacts had been considered or (2) whether the project scopes even allowed for such consideration—because inequities and impacts typically appear upon reaching the commercialization scale, and not before. Moreover, there is more to gaining a social license to operate than siting considerations.

Project Management and Funding Mechanisms

- Project management and controls seem sufficient, although there were some delays due to COVID-19. All the projects are hitting their goals. The challenge is going to be integrating unit operations and finding sufficient human capital to make these projects go. Overall, funding mechanisms are sufficient. There is a good mix of funding opportunity announcement (FOA) and annual operating plan funding. There is a good mix of folks familiar with BETO and folks less familiar providing fresh perspectives.

- Another aspect of project management has to do with scaling up successful research. The challenge has been getting sufficient money to pilot/scale up these ideas and begin the long road to commercialization. The other challenge is addressing the potential downsides/risks with scale-up. For example, if a unit operation were to break at a wastewater treatment facility (WWTF), large quantities of treated solids would either need to be stored or disposed of. These kinds of contingencies are very difficult to handle within a research program's budget.

- One weakness in project management are the go/no-go interim goals. As a strong proponent of fundamental research, one reviewer felt that go/no-go metrics discouraged researchers from gaining a fundamental understanding of the issues and perhaps encouraged them to present their results in a way that was not entirely honest. Several projects seem to have been initially funded because they showed considerable promise; however, research often leads down dead ends, and negative results still have considerable importance. For these projects, a "completion" of the research to fully understand why these otherwise logical topics failed would be more beneficial than ending the project prematurely. Some researchers simply obviated the go/no-go requirements by setting an easily achievable go/no-go metric. Along these lines, a few of the projects were more focused on achieving a performance goal rather than learning how to optimize their process. In this sense, it would be beneficial to encourage more hypothesis-driven research rather than simply judging projects by cost/waste conversion/GHG emissions.

- So far, all the funded projects are showing tremendously good progress, indicating that the BETO program will meet its goals and targets. The level of progress of these projects was verified by the BETO program officials (Budget Phase I, Phase II, etc.). This gives credence to the fact that the BETO program is actively involved in managing the projects to obtain better outcomes. It is recommended that BETO finds a way of sustaining these projects beyond the assigned project periods. Also, it was observed that some of these projects are similar and apply the same techniques. These similar projects can be linked together because this will enable increased scale and wide applicability of the results from the projects.

Fostering Knowledge Transfer

- Many of these projects focus on the same technologies, such as HTL, AD, and biomethanization. Each process is basically being studied "empirically," meaning as part of a series of unit operations toward a specific goal. Each research has a slightly different research goal, so each process is investigated slightly differently. The problem with this approach is that there is relatively little transferrable knowledge from one project to another; alternatively, fundamental studies to understand how each process works over myriad conditions and feedstocks could lead to more transferrable knowledge and a better/more efficient pathway to producing commercially viable fuels from organic wastes.

Promoting Public Health

- Funded projects are mainly aimed at the protection of the environment. BETO can incorporate the protection of public health by including treated municipal wastewater solids as one of the wastes from which energy can be generated. Funds obtained from generating energy from human waste can serve as an incentive for properly treated municipal wastewater solids management and can, in turn, reduce the transmission of diseases. The projects should also consider monitoring the fate of pathogens and emerging contaminants in the biosolids and digestate.

- It can be noted that apart from producing fuels from the waste, the projects that generate energy from treated municipal wastewater solids have also started to consider the fate and removal of emerging contaminants in the waste (i.e., per- and polyfluoroalkyl substances [PFAS]) as well the generation of eco-friendly fertilizers. The funded projects make use of highly advanced and novel techniques. Some of the projects involve the incorporation of two or more innovative techniques in order to meet the program's strategic goals.

- The work that BETO has done since 2021 to advance HTL is of particular interest and value in light of the anticipated regulation of PFAS and other micropollutants in water resource recovery facilities (WRRFs), landfills, and potentially other generator outputs. The dimension of destruction of some or all PFAS species in these feedstocks will be a significant value add if landfilling, land application, and/or composting become unviable due to contaminants of concern and resulting costs and liabilities. BETO is encouraged to look closer at this dimension as it continues to advance HTL and potentially other high-heat technologies capable of PFAS destruction.

Integration with Solid Waste Management

- BETO recognizes the role of current solid waste management in the United States, especially for municipally sourced feedstocks such as food waste and treated municipal wastewater solids, and it has appropriately noted economic factors relating to hauling and landfill tip fee costs. This is evident in their solicitation and funding approaches.

- By virtue, waste is underutilized and undervalued. Converting this product to fuel and products is really critical to addressing sustainability challenges. Waste, though, has been a tantalizing target because of the tipping fees. The challenge has always been that waste is a bit of a catchall with a high degree of variability. This has always challenged processes. BETO has done an admirable job of forcing researchers to use real waste streams. Hopefully the efforts of the office continue to spur the development of an organic WTE industry.

RECOMMENDATIONS

Meeting Format

- These meetings are indeed expensive and take lots of planning, but they are worth it! I witnessed and hopefully contributed a few connections to resources and needs outside of the awareness of funded researchers. Contributions from reviewers will lead to furthered beneficial outcomes beyond those of what funded projects were doing on their own. (Examples: recommended deployment of technologies to remote areas with renewable energy abilities; ash from paper products potentially becoming a valuable input into energy-intensive concrete processes rather than a waste product.) All of this is to say that perhaps a similar, virtual review session could happen every other year, in between in-person meeting years.

- In the future, I recommend that all the presenters provide Gantt charts in their PowerPoint presentations tracking the progress of their work against the planned milestones.

Strengthen Approach to DEIA

- DEIA initiatives are clearly evolving as new funding opportunities become available. Training and substantive opportunities for those from underrepresented groups is a good baseline for all projects. Yet research, where reasonable, should also be deployed in communities where they can make the most difference. I struggle with assigning metrics to such a concept because applying DEIA to the rollout of new technologies in the field is complex. Deploying new technologies requires a baseline of infrastructure, personnel, and capacity on the ground that such communities typically do not have. But I do grow frustrated with training and hiring as a fallback. There are communities that have suffered from decades of disinvestment and disempowerment that need to see their government make a difference in their lives. These individuals cannot access benefits from training and hiring alone. We can only truly move forward in answering the challenges of climate change when everyone sees a benefit for their community.

- One of BETO's strategic goals is to "build diversity, equity, and inclusion into hiring and funding decisions, project plans, and community engagement" (BETO 2023 Multi-Year Program Plan). This is an area that needs to be better thought through and fleshed out with regard to providing guidance to research teams for selected projects. At a minimum, there is reviewer consensus that all funded project personnel be required to take DEIA trainings. BETO should also put together a robust guidance document for personnel on awarded projects that covers why DEIA is important in historical, political, and ethical contexts; covers how DEIA is achieved through formal and substantive (i.e. non-token) practices; and emphasizes the goal of DEIA to redress past exclusion of many groups in and outside U.S. society from senior-level roles in projects as opposed to primarily focusing on students and interns.
- In the area of organic solid wastes, there are specific concerns among disadvantaged communities, and others, regarding the diversion of potential feedstocks from composting and land application to bioproduct or biofuel uses. The value of soil-focused approaches, if compared on an LCA basis to alternatives such as AD and other conversion methods, may reveal inefficiencies, including higher rates of net GHG emissions; however, reliance on GHG-focused LCA comparison stands to exclude significant community benefits that are realized in terms of erosion remediation, soil improvement, and integration with locally reliant and resilient waste management and agricultural practices (which are, in turn, of increasing importance during periods of supply chain uncertainty, more frequent major weather events, and widespread hunger in the United States). Such community benefits are operationalized in community composting/urban agriculture projects and resiliency plans that are currently proliferating in the United States, in part as a response to health, justice, and environmental precarities that the three upheavals discussed above have made impossible to ignore. Such soil priorities may overlap with work that DOE and/or BETO is doing with the U.S. Department of Agriculture and U.S. Environmental Protection Agency. There is great room for improvement in BETO's overall approach to environmental justice and its relationship to community engagement and DEIA practice.

More Attention to Non-Market Project Benefits

- BETO's work to build a bioeconomy sourced with organic waste feedstocks has great potential but also needs to more fully consider the context of its mission. Researchers on BETO projects, including scientists and engineers, occupy an important role as pragmatic problem solvers focused on the development and optimization of carbon-neutral, environmentally safe energy technologies. To the extent that they are called upon to consider marketization potential through TEA, including metrics such as return on investment, equivalency pricing, or other cost metrics, this work may entail a focus on industrial profitability to the exclusion of more systemic consideration of appropriateness. Appropriateness here refers to a broader social and ecological context that represents interests and concerns outside the marketplace as well as within it. Among the most salient of these are questions of utilization and pollution of Indigenous lands; the siting of facilities in communities historically targeted for racial segregation and exclusion; and the transparency of industrial data reporting on material and energy flows, solid waste generation rates and fates, air and water emissions, and synergistic risks associated with old and new technological approaches.

ORGANIC WASTE CONVERSION PROGRAMMATIC RESPONSE

INTRODUCTION

The Organic Waste Conversion Program is grateful for the reviewers for their contributions, recommendations, questions, and feedback during the 2023 Organic Waste Conversion Project Peer Review session. The program recognizes that this is a significant investment of time to review the projects, travel, and prepare the reviews following the in-person meeting. The program appreciates that each reviewer was willing to contribute their time and expertise to this meeting. In particular, the program is grateful for the diverse perspectives that the individual reviewers brought to the meeting on matters of urban design, public health, sanitation, and national policy.

The program would first note that the work presented in these 18 presentations is comprehensive of all projects that contain organic wastes. For example, the Renewable Carbon Resources Program conducts work on preprocessing of fractions of municipal solid waste (MSW) bound for landfills. The Data Modeling and Analysis Program conducts various forms of air quality analysis and LCA. The intention of this session was to present groups of work funded by the Organic Waste Conversion R&D program focused on the conversion aspects of these waste streams.

The program is pleased to hear that the reviewers feel the overall strategy and grouping of projects is sound and strong. Over the years, the program has shifted its focus into several areas:

- Improvements to AD (including RNG)
- Production of liquid fuels from waste
- Production of products from waste
- Community-led project implementation.

With regard to fostering knowledge transfer, the program appreciates suggestions from the 2021 peer reviewers on how to do this. This served as some of the inspiration for the community-led projects and funding opportunities, and the program intends to continue those opportunities. In recent years, several technologies have since "graduated" from the program and are being scaled up using other DOE/federal funds and/or private equity funds. It is gratifying to see these successes make their way into the marketplace; however, reviewers might not have insight to that based on the information provided from these project presentations. In future Project Peer Review sessions, the program will include updates on past work that has concluded and its current status. The program would also note that several technologies developed from this portfolio are only just beginning with industry or community partners, and it was premature to invite them to present given that they have yet to begin.

In the response, the program did note some comments with regard to early-stage research and concerns about the expectations for these types of projects. While the program appreciates the sentiment of this comment and recognizes that overly prescriptive requirements or project management oversight can impact the overall technical progress, too much freedom goes against the program's ethos. In the past, the Organic Waste Conversion Program has received comments that the quantitative metrics were prescriptive to the point that it took away from the main mission of technology development. For this reason, the program has moved away from esoteric FOA requirements to the extent possible; however, other requirements, such as industry or end user engagement, really are critical to ensure that the technologies being developed (1) have engineering feasibility and (2) solve problems identified by the end users (see response to Recommendation 3 below).

Recommendation 1: Meeting Format

The program is pleased to hear that the meeting was indeed valuable and fostered collaborations and networking. The in-person element of this meeting, unlike what was possible in 2021, was highly beneficial and is another reason for this; however, the program has no intention to increase the frequency of the Project Peer Review because it is quite burdensome on the project teams and requires extensive logistical planning.

Recommendation 2: Strengthen Approach to DEIA

The program recognizes and concurs that work remains to be done with regard to DEIA efforts in the funded research. BETO has distributed a new set of guidance to national laboratory projects for the fiscal year (FY) 2024 cycle to provide examples of ways that research teams can integrate these values into their research. The program has recognized the unique environmental justice issues associated with organic wastes and has sought to incorporate these efforts into recent community-focused solicitations. The program also appreciates that there are sustainability indicators beyond just GHGs that are germane to this field, and projects going forward are now required to incorporate their tracking in their work, including PFAS, air quality, truck traffic, and others. Generally speaking, there is a dearth of publicly available research on these indicators at a local level, and the program recognizes the need and opportunity to support this area. The program intends to continue the TA program and other efforts that bridge the gap between applied research and the communities that will/could adopt these technologies.

Recommendation 3: More Attention to Non-Market Project Benefits

The program strongly concurs that the value proposition of organic waste conversion technologies extends far beyond those of economics. Organic wastes represent environmental and social liabilities, and it is critical to recognize that there is a need to ameliorate some of these impacts in the course of technology development. BETO would note that the metrics and desired outcomes from recent solicitations reflect metrics other than purely economic outcomes. Moreover, recent solicitations have had eligibility restrictions to increase the likelihood that projects are being led by the communities themselves as opposed to being based purely on profitability for entities that are looking to deploy technologies.

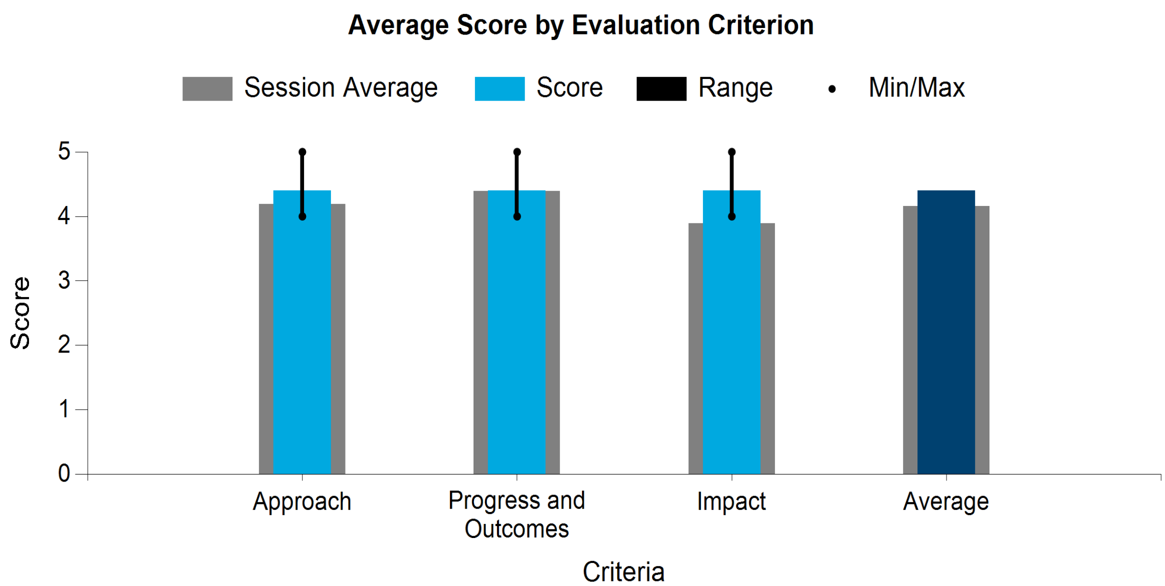
WASTE-TO-ENERGY TECHNICAL ASSISTANCE

National Renewable Energy Laboratory

PROJECT DESCRIPTION

WBS:	2.1.0.112
Presenter(s):	Anelia Milbrandt
Project Start Date:	10/01/2020
Planned Project End Date:	09/30/2023
Total Funding:	$1,200,000

The goal of this project is to mobilize data, information, and knowledge generated about organic waste streams to local governments and support their decision making. It builds on previous work related to wet organic waste resources (food waste, sludge, manure, waste fats, and oils). The project provides an improved understanding of local waste challenges and priorities to inform BETO's R&D strategies and decision making. It also supports local governments' goals and plans related to sustainable waste management, enables energy and/or resource recovery project development at the municipal level, and facilitates public-private partnerships. A key challenge is associated with more activities requested by entities than the program allows, which is mitigated by prioritization by the requesting agency. All FY 2021 and FY 2022 TA requests have been completed. Major accomplishments include (1) 34 requests managed in the past 2 years and (2) distilled key challenges faced by communities. Key outcomes include strong community participation since the inception of the program, a dedicated program website, deliverables tailored to communities' needs, and distribution materials (e.g., fact sheets, brochures) for a broader audience.



COMMENTS

- I want to better understand the impacts of the TA. I'm trying to judge if the advice was heard and taken. In this vein, advice heeded to not do something could be just as valuable as advice to do something. This presentation should be structured more like a bunch of case studies instead of speaking in general dimensions.
- The approach is sound. Overwhelming interest from communities. There were more meritorious applicants than money/time to address these issues. Project is oversubscribed going into the 2023 cohort.

- Good that there is a selection process. Engagement and communication strategies seem reasonable. Would desire a clearer presentation of expectations.
- DEI issues are well woven into this project. Looking at both staff assisting and the communities being assisted. Good geographic and socioeconomic factors.
- Engagements seem to lead to wider circles of involvement from the communities. It is great that it reached so many communities with diversity of location, size, etc.
- These slides read more like strategy/approach and less like progress/outcomes. Would expect more progress/outcomes for a project this far into its life cycle.
- Certainly believe this work is valuable and important.
- Overview/impact:
    - This project is the first WTE TA for local governments on the most appropriate WTE technologies and practices to adopt. The project provides assistance on a wide range of issues spanning land constraints, environmental justice issues, and organic waste management. This project provides a nuanced but relevant aspect of organic waste management. It involves garnering relevant information about different organic waste streams to provide the information needed for decision making by local governments. The project also gathers information about organic waste management challenges faced by different communities that will help inform the prioritization of projects by DOE.
    - Considerable progress has been made so far in this project, and the researchers have addressed a wide range of topics since the project began in 2021. They have completed all the milestones that they had set out at the beginning of the project; however, looking at all the approaches employed in the project, I do not see any novel or unique approach, as everything put forth by the research team is well known. Also, the researchers keep on mentioning what they did but did not clearly explain how they undertook the work.
- Strengths: It can be said to be the first study that provides WTE TA for local governments. The project team has a clear communication and management plan. Also, the fact that the selection process for applications in the project takes into consideration geographic and demographic diversity is commendable, as it ensures diversity and inclusivity, which is a core goal of BETO.
- Weaknesses: I feel the risks and the risk management strategies outlined in this study are weak, as the researchers only outlined factors that are related to the staff. Expected risks in this kind of project should include inaccessibility to relevant information and community pushbacks. Second, in the PowerPoint presentation, the researchers indicated that they had stakeholder outreach and engagement, and I am wondering if they could provide more information about the stakeholders who were involved in the community engagement activities and how they were selected.
- Questions: While presenting the progress and outcomes of the project on slide 7, the researchers indicated that they carried out a cost-benefit analysis on food waste comparing landfilling, AD, and composting. It will be great if the researchers can give more elaboration on how they carried out the cost-benefit analysis. In the same vein, I am wondering if the researchers have clear guidelines for communities to follow as they prepare these cost-benefit analyses to avoid missing or ignoring some key items or cost elements.
- This project consists of a TA program geared to local governments, which will support systemic analysis, planning, and tech evaluation around various WTE technologies. This is a very useful and needed project that will greatly aid localities, large and small, in critically evaluating new technology pitched to them by

private sector actors. This program will support localities in seeking funding and making community-informed decisions.

- In the last funding cycle, there were 17 community recipients with good geographic diversity. This program badly needs increased funding and staffing so that more municipalities can be reached. Over and above the resources offered, developing and providing technical expertise in the areas of cross-agency collaborations, agency siloing mitigation, novel and accelerated forms of municipal procurement, and data management/sharing will further assist localities grapple with the gap between federal funding availability, workforce shortages, infrastructural aging, and local institutional capacity.
- This project is a TA plan for public entities trying to increase their WTE output for various reasons.
- This appears to be a highly qualified team with a good risk management plan. The DEI approach is very good, covering multiple definitions of "diversity and inclusion," such as rural to urban, early to late career, gender, and race. This is definitely a strength of this project.
- The team provides 40 hours of TA per project. There seems to be far more interest by municipalities in receiving TA than there is opportunity to provide it.
- Perhaps most importantly, a lot of knowledge is gained by performing these projects; project personnel help disseminate this knowledge by producing fact sheets that are made available on their website, and these can be downloaded by other interested individuals.
- The project has clear targets, goals, and mission. As the project enters this next phase, it would be good to know how the project can convert their on-the-ground experience with municipalities into an actionable framework for future outreach. Are we starting to gain insight into which factors best help to categorize or standardize municipal bioenergy possibilities across the United States? For example, does a community's size, region, climate, or other factors (if any) best determine which actions it can take to move local wastes to energy? Can a tool be built to streamline the technical outreach that is offered to municipalities and leverage work from the Pacific Northwest National Laboratory's (PNNL's) project WBS 2.1.0.113: Waste-to-Energy: Optimized Feedstock Aggregation and Blending at Scale?
- The project is being managed well to ensure beneficial outcomes for the performer and the government. Outreach and education at this scale, with technical experts, to learn U.S.-wide lessons would be difficult to do without BETO funding, as well as the project's initial investigation into bioenergy technology workable solutions or offerings.
- This project is ambitious and has done a great deal to consider multiple technologies and their unique applications to various scenarios. The aggregation of data at this scale could help develop and coalescence a suite of organic waste technology offerings on the ground, an important strategic outcome. The project also sought to bring new technologies into offering as it considered the uniqueness of the requested topic in its applicants.
- This project offers the possibility of an important strategic outcome in how WTE options can be evaluated by analyzing outcomes of direct TA. This project's results could inform future outreach and education and potentially provide a suite of tools to streamline organic waste project development at the community level.

PI RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their time and valuable feedback. It is gratifying that the review recognized the value and importance of the WTE TA program and approved of the approach and progress/outcomes. One reviewer noted that we should have provided more information on progress/outcomes and structured the presentation in the form of case studies. We recognize and apologize for leaving some detail out of the presentation. This was done to protect confidential information, as many communities are not willing to share the specifics of their TA request. We are unclear about the comment about providing clear expectations. Would that be from BETO or the communities? In any case, we would like to think that expectations have been met on both ends, and testaments of that are both positive feedback from BETO and results from participating community surveys. With regard to the comment, "I don't see any novel or unique approach, as everything put forth by the research team is well known," we politely disagree. This is the first (and to the best of our knowledge the only) WTE TA program, which makes it unique. We agree that everything put forth by the research team is well known, which is the purpose of a TA program—to disseminate knowledge and provide technical transfer based on previous experiences. We apologize for not providing enough clarity on how we undertook the work and more specifically how we carried out the cost-benefit analysis. There was simply not enough time to do this given the prescriptive presentation formatting and mandatory content requirements for the BETO Project Peer Review. Each request was different, and it would take a long time to describe, even briefly, how we undertook 34 tasks within the given time frame. As noted in the presentation, the program builds on existing work, and in the case of the cost-benefit analysis, we ran a model we previously developed for communities that requested it with input data and scenarios provided by those communities. While most reviewers approved of our risk management plan, one comment was that we "only outlined factors that are related to the staff. Expected risks in this kind of project should include inaccessibility to relevant information and community pushbacks." While we agree that there may be expected risks with this kind of project, we did not encounter them. Our only challenges were related to staffing on both sides, the participating community and NREL. We have not had any issues related to data availability or pushback from communities. One of the reviewers asks us to "provide more information about the stakeholders who were involved in the community engagement activities and how they were selected." Many entities that participated in the program had a team that includes various stakeholders, such as external advisors, boards, and private citizens, connected to the local community. This is an excellent question: "How can the project convert their on-the-ground experience with municipalities into an actionable framework for future outreach? Are we starting to gain insight into which factors help to best categorize or standardize municipal bioenergy possibilities across the United States?" The insights gained through the program will inform not only future outreach but also future R&D activities. At the end of this 3-year cycle, we will analyze exactly that and present BETO with a written report summarizing our findings. We agree with the statement that "this project's results could inform future outreach and education and potentially provide a suite of tools to streamline organic waste project development at the community level."

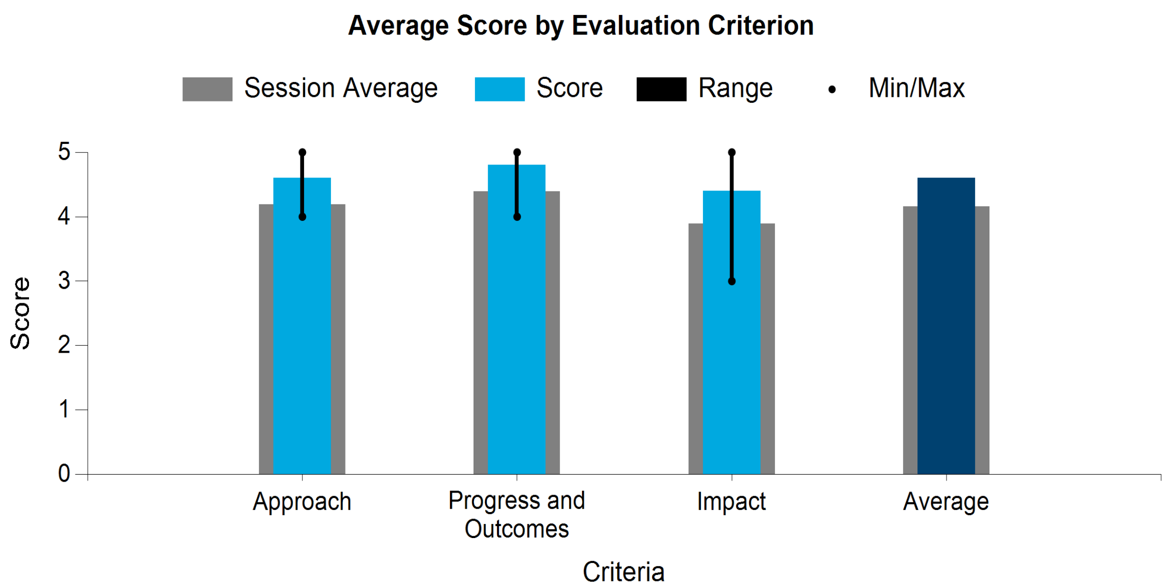
WASTE-TO-ENERGY: OPTIMIZED FEEDSTOCK AGGREGATION AND BLENDING AT SCALE

Pacific Northwest National Laboratory

PROJECT DESCRIPTION

WBS:	2.1.0.113
Presenter(s):	Karthikeyan Ramasamy; Katarina Younkin; Michele R Jensen; Tim Seiple
Project Start Date:	10/01/2020
Planned Project End Date:	09/30/2023
Total Funding:	$900,000

Wet organic wastes such as municipal sludges, manures, food waste, and fats, oils, and greases are considered priority feedstocks for conversion to biofuels. Feedstock costs have a major impact on the feasible scale of the proposed conversion and biorefining facilities and the final fuel price. BETO's 2019 draft Multi-Year Program Plan establishes an MFSP target of $2.50/GGE or less for biofuels by 2030. To validate whether proposed conversion pathways can meet this target, our project will deliver and apply a reusable, data-driven, geo-economic framework to identify practical and cost-effective opportunities for pilot- to commercial-scale deployments. Despite risks from imperfect engineering, spatial, and market data, our work improves understanding of the real-world possibilities to increase plant scale by combining waste feedstocks, thereby reducing the cost of biofuels.



COMMENTS

- Really great to see transportation handled on a micro/local level. The impact of this element of logistics is very local.
- With regard to the very large site data, does the model take into account truck turnaround times? It is a very big deal to be able to make 2–3 runs in a day from a personnel perspective. Also, is average traffic factored into this?
- Very impressed with the improvements since 2021. Think this model has great value.

- Great that the team is now looking at helping communities to develop their own plans. Would like to see targeted engagement as part of the DEI.
- Interesting to be including the national Freight Analysis Framework to minimize the impact of communities by trucking.
- Maps and graphics are great for conveying information. Great visuals.
- Want to ensure the tools are easy to use to maximize impact.
- The project is an analysis task and is not necessarily meant to be commercialized but rather to assist folks.
- Really great capabilities of this model around transportation costs, multimodal. Certainly would be interested in optimizing those issues, but acknowledge the cost and trade-offs. Understand that it would probably be best to incorporate this with community engagement because of rail challenges.
- Tim, you do not need to read the slides to us. Wanted you to cover more of the project's accomplishments
- Would be interested to see how the rest of the organic waste projects confirm these values/models with their independent activities—that is, to see how well the insights align. I do not think it is worthwhile to have a perfect model, but this should be enough to give confidence to folks commercializing WTE technologies.
- Need better engagement with communities and interaction with the TA program. Think this project is ready to engage with stakeholders.
- Overview/impact:
    - The researchers investigated how empirical data from novel WTE techniques obtained from laboratory experiments can be fused with real-world resource data to find viable WTE deployment opportunities and locations for siting energy generation plants. They achieved this using geospatial techniques to identify hot spots for cost-effective biofuel substrates, which they integrated with empirical technology and data costs, travel costs, and real-world resource data. The approach used by the researchers is inventive, as the model developed in the project has very insightful outputs, such as the net profit, total waste disposal savings, total fuel production, and total travel costs, which can be used to inform decision making when siting WTE generation plants. This project has a relevant impact on the waste management sector, as many WTE experiments usually end at the laboratory or pilot scale and are never scaled up; thus, having a project like this will serve as a basis for checking the feasibility of scaling up projects.
    - So far, the project has shown considerable progress and improvement since its inception—as the developed model has been adjusted to include dynamic feedstock pricing, realistic supply logistics, and fungible energy, price, and technology variables.
- Strengths: The project makes use of data-driven and scenario-based models, which means that the developed model is not rigid and can be applied/transferred to different scenarios. Also, an adept communication plan is applied in this project, as there is stakeholder communication with waste regulators and researchers as well as city leaders.
- Weaknesses: In discussing the model they are using in the project, the researchers provided the different variables and factors that were used in developing the model as well as the outputs expected from the project; however, they did not clearly describe the nitty-gritty of the model, such as how the different

factors (inputs) were applied/used in the model. Further, the researchers should also consider incorporating data trends in their model so that the changes in the supply of feedstocks and/or their characteristics could be captured, as in the past we have seen huge treatment plants constructed in locations with low feedstock supplies, and these plants failed as they never operated at the optimum loading rate.

- Questions: In slide 8 of the presentation, one of the milestones marked as 100% complete is model verification; however, there is nothing in the presentation showing how the verification was carried out. It will be highly appreciated if the researchers could shed more light on this.

- This project focuses on understanding wasteshed geography for multiple wet waste streams that can be converted to biofuels and products. This type of generation and flow analysis is crucially needed in all aspects of waste management to understand which flows or feedstocks make sense to consolidate, where, and at what scale. Regardless of the processing technology ultimately used (WTE variations or other treatments), a geographic model of this kind will be extremely useful for regional, state, and, in some cases, municipal waste management planning.

- The team is to be commended for consulting with stakeholders in a range of waste-related industries (refuse hauling, biosolids trade associations, plant operators, etc.). Seeking this input should be continued and expanded to the widest range possible of stakeholders, including municipal, state, and regional planners, as well as constituents engaged in regenerative and non-regenerative agriculture and livestock raising, community composting and food sovereignty groups and activists, and university cooperative extensions.

- The researchers note imperfect resource (presumably waste flow) data, which is typical of the distributed, heterogeneous, and localized nature of waste management in the United States. Another value add to government planners and other stakeholders would be to improve and publicize datasets publicly.

- The fact that the deliverable from this project is a dynamic model that can accept varying inputs and does not provide a single “right” answer is a plus, reflecting the realism of the approach. It opens the door to the productive consideration of various scenarios by stakeholders of all types who might in the future be able to use this tool, or a version of it, to engage in community-informed planning.

- This is a fantastic project with a lot of potential for cross-fertilization and future applicability to real-world cases all over the United States.

- This appears to be a very important project. In addition to developing the technologies for converting WTE, it is also critically important to identify various locations where the organic wastes are produced versus the locations of the facilities that can convert these wastes. Essentially, the researchers developed a very complex model that incorporated data regarding the locations and quantities of various organic wastes, transportation costs, conversion factors, etc. The results of this work essentially identify potential locations where WTE facilities could be located and profitable. Alternatively, this work could be used to exclude locations for WTE conversion because they are unlikely to be successful/profitable.

- These researchers appear to be highly responsive to previous review comments by the BETO panel and by others. Similarly, the researchers seem to understand that they have uncovered some very important and practical knowledge, and they are now focused on identifying entities/people who can take advantage of this knowledge.

- The project has clear targets, goals, and a mission. There is the potential for this project to have large impacts on the management of wet waste nationwide.

- The team's recommendation to move forward with designing a standard reporting package for city leaders, and potentially build dashboards, if budget permits, has a clear overlap with work from WBS 2.1.0.112: Waste-to-Energy Technical Assistance for Local Governments. Incorporating lessons learned from direct TA into a standard reporting package for cities would help address common upfront hurdles and considerations to assist municipalities in moving forward with organic waste reduction technologies that best fit their needs.
- This project is ambitious, and the aggregation of data at this scale could help develop and coalescence a suite of organic waste technology offerings on the ground, an important strategic outcome. The model that has been built is robust on many decision-making factors in policy, incentives, transportation, and geospatial optimization.
- The project is being managed well to ensure beneficial outcomes for the performer and the government. This is the leading edge of the comprehensive modeling of available wastes and technologies at this scale, and it would be difficult to do without BETO funding for this effort.
- The beneficial outcomes of this project have far-reaching positive outcomes for the reduction of waste landfilled, the intervention of methane emissions from wet organic waste degradation, and the potential of supporting large-scale bioenergy creation to further decrease the prices and availability of these fuels nationwide. This project offers the possibility of an important strategic outcome in how WTE options can be built out nationwide to achieve large-scale bioenergy nationwide. This project's results could inform future outreach and education, especially through the creation of a standard reporting package, that will streamline organic waste project development at the community level.

PI RESPONSE TO REVIEWER COMMENTS

- We greatly appreciate the personal investment made by each reviewer to improve the quality of our research. We are also thankful for your recognition that our work is impactful and relevant, and we look forward to continuing to serve the public.
- DEI focus and stakeholder engagement: We agree on the need to focus more on DEI and stakeholder engagement. The BETO DEI requirements were developed after our previous project cycle began (FY 2021–FY 2023); however, our FY 2024 project renewal proposal focuses entirely on partnering with and providing analysis support for waste-impacted underserved communities. If funded, this work will include a strong stakeholder focus when developing standard communication products and assessing the impacts of various waste management strategies. We are also committed to hiring staff from groups underrepresented in STEM to participate in model design and implementation to broaden the perspectives of our approach and improve our impact.
- Modeling traffic conditions: We account for average traffic conditions in our model, but we do not model traffic explicitly, which is resource- and cost-intensive. Instead, we represent average traffic conditions implicitly in the transportation network model in the form of variable truck speed limits assigned by road segment type, which are based on literature values. Speed limits also encourage trucks to find suitable highway routes as fast as possible and avoid neighborhood-level streets. Changing speed limit factors is easy but does require solving the network model again. We are exploring various traffic impact assessment methods on a related clean energy project, which could inform our model to improve travel time estimation and eventually estimate the impacts of potential neighborhood-level increases or decreases in truck travel associated with diverting wastes to energy recovery facilities. In the real world, waste transport is carefully scheduled to maximize truck and driver utility and reduce cost. This includes aggregating waste into larger vehicles at waste transfer stations. Due to limitations in our scope and budget, we cannot model optimized fleet and collection route management; however, we can carefully configure the input data to divert waste from intermediate diversion points—such as transfer stations, landfills, or similar collection/transfer/disposal locations—to represent likely waste diversion scenarios.

It is important to acknowledge that most wastes in the United States are handled through trucking with costs borne by ratepayers. This may also be the case in the future. Therefore, we are most interested in the difference between business-as-usual and projected traffic and cost impacts.

- Truck turnaround times: The transport model does account for truck turnaround times. Our current research focus is on modeling typical daily trucking requirements to estimate total annual delivery costs for wet organic wastes. We make the simplifying assumption that the number of trucks and drivers required will always be available. Waste pickups occur at prearranged places and times and are typically much faster than terminal or drayage turnaround services. Our specific method for estimating turnaround and total travel times is as follows. For each feedstock source, we know the location, type, and dry mass, and we can specify the "as-delivered" moisture content and density, truck type, truck capacity, truck charge-out rate, total fixed wait time (load + unload), and loading rate (e.g., gal/min). Dry waste mass is converted to a wet volume using moisture and density factors. Depending on the waste type and format (liquid, slurry, semisolid, solid), we may either assume a fixed wait time or estimate it dynamically based on a waste pump/loading rate. Load and unload times are assumed to be equivalent. The total wait time is then multiplied by the truck charge-out rate to determine the total turnaround cost. The turnaround cost is then added to the total two-way truck travel cost, represented by the modeled routing distance (i.e., least-cost network path plus on-/off-network connection costs). Finally, the total annual transport costs for each waste source are estimated by multiplying the per-trip costs by the total number of required trips per year as a function of truck capacity and waste volume. The model also supports the use of a default total wait time (e.g., 30 minutes) for all waste sources regardless of type. If the waste source and energy facility are collocated, the total travel cost is zero. We do not explicitly include factors for anomalous conditions such as site access issues, traffic congestion, and accidents; however, all model transportation factors can be easily modified to represent alternative truck turnaround assumptions. Further, we can represent turnarounds for other modes of travel (i.e., barge and rail), but implementing these modes of travel requires specific local knowledge regarding likely operating conditions and cost, which is why we do not yet use these modes in our national assessment scenarios, but we do plan to use them in planned local scenarios in FY 2024, if funded.

- Methodology details: We apologize for not sharing more details regarding the network and geospatially optimized siting models. We are in the process of preparing peer-reviewed manuscripts that will fully document and share our methodology, detailed model formulation, and underlying data. In the meantime, a more thorough description is offered here. Siting analysis is a two-step process, including (1) calculating realistic travel routes and costs and (2) using those data as the basis for a geospatial optimization to determine possible optimal facility and waste utilization solutions. The network modeling ("routing") was performed using parallelized automation routines we developed to iteratively execute the "pgr_dijkstraCost" function within the "pgRouting" extension of PostgreSQL 14 to calculate the least-cost path (travel time in hours) between each biorefinery siting candidate and its potential waste producers (i.e., neighboring waste generators) by traversing a roads network developed based on the U.S. Census Bureau's 2021 MAF/TIGER state-level edges datasets. For regional to local scales, we can use the routing data directly in the optimization model. But for national-scale assessment, we perform a regression on the travel costs by geographic region to enable the computational feasibility of the geospatial optimization (make it efficient) and to make the problem differentiable (continuous). The regression equations are then used as the primary input, along with the waste resource data, to the geospatially optimized siting model. The siting model is formulated as a (large) nonlinear optimization problem, which we solve using a standard open-source interior point algorithm (Ipopt: https://coin-or.github.io/Ipopt). Currently, the optimization is set up to maximize systemwide profitability, thereby determining the best use of each unit of feedstock when in proximity to multiple candidate facilities. But the objective function can be changed quite easily in the model.

- Model verification and alignment of results: We apologize for not sharing more details regarding the model verification. The following tests and quantitative metrics were designed and applied to evaluate the accuracy and consistency of the routing and siting models. We will describe the model verification in our planned peer-reviewed publications.

- Routing model accuracy and consistency: We performed a suite of manual, automated, and statistical tests to validate the routing model:
  - Run the "pgr_analyzeGraph" function to test the network topology.
  - A random sample of automated routing solutions was visually compared to manually queried route segments using the QGIS desktop to ensure 100% reproducibility.
  - Stress testing was performed to solve for all possible routes to identify potential network topology, software errors, or memory issues.
  - Auto-testing was performed to evaluate cumulative route error by ensuring that estimated travel times between all U.S. state capitals were within 2% of results from the Google Routes API.
  - Summary statistics were computed to (1) ensure 100% of routes had a solution and (2) assess average on- and off-network connection costs and total travel costs across all routing solutions to identify potential outliers, which may indicate network topology issues.
  - When used, the travel cost regression ends up being a linear regression, so its solution and associated error are well defined. Further, once we solve for an optimal siting solution, we can put the sited facility back through the more precise routing model to get a better estimate of true travel costs, if necessary.
- Geospatial facility siting model accuracy and consistency: The geospatial optimization relies on previously documented cost curves, calibrated parameters ("factors"), and constraints. The quality of the optimization solutions will be as good as the input data. Although not a perfect model, this approach enables us to quickly generate reasonable upper- and lower-cost and performance boundaries on emerging technologies to help reduce uncertainty and provide industry with confidence to take on transformative clean energy projects. Due to the unique combination of literature-based technology cost and performance data with actual waste mass and logistics data, a baseline for the direct comparison of our national siting projections does not exist. Although we cannot make 1:1 comparisons of our modeled feedstock gate price, energy productivity, or profitability estimates to previous experimental or empirical results, we can design special scenarios that allow us to approximate published cost and performance data for a particular technology at a specific engineering scale. For example, we can limit waste producers in our model to represent 100 dry metric tons of available sludge at a single site (or a few proximal sites), which should result in a sited HTL plant with similar total capital investment costs and net present value as the same sized HTL plant evaluated in the BETO HTL design study (https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-27186.pdf), which was prepared using a detailed discounted cash flow analysis. It is not a perfect match because our feedstock prices are dynamic compared to the fixed feedstock prices used in the earlier studies. Measuring siting model consistency is a little more straightforward. Because this is a nonlinear optimization, a gradient-based algorithm like Ipopt will converge to the nearest local optima, which could be one of many, and is not guaranteed to be the global optimum. Finding the global optimum of a nonlinear, nonconvex problem (like this one) is NP-hard and infeasible for the size of problem we are considering. Instead, to improve our chances of finding the global optimum, we may solve the same scenario many times and statistically compare the results. Randomness in how the model generates candidate facility siting locations ensures that each model solution is different, which is desirable because it helps us better explore the solution space. In practice, if we observe

(1) objective function values for all solutions within 3% and (2) Rand index = 0.9, it indicates robust results (similar siting solutions across model runs) and gives us some confidence that even if we missed the global optimum, it would not be much better than the solutions we are finding.

- Support for data trends: We agree, adding support for temporal variability would be useful. Modulating waste flows, costs, and performance inputs improves our ability to investigate impacts from population growth, waste policies, market dynamics, etc. Currently, we are working with average annual values to maximize profit for an average year. This approach meets our current need for rapid sensitivity analysis; however, if our project is renewed in 2024, we could easily incorporate input variability in several ways, each with their own advantages and disadvantages and with some computational cost:
    - Adding an explicit temporal component to the model by accepting input data arrays and evaluating each timestep of the time horizon
    - Treating waste sources as random variables with known distributions that account for variability (or uncertainty) without an explicit representation of time (i.e., value changes each iteration)
    - Use either method to modulate facility capacity factors, which provides an integrated control on productivity, not just from changes in feedstock supply.
- Data and findings dissemination and improvement: We agree that disseminating results is critical. We do our best to ensure that published findings and data are easy to retrieve and cite by publishing the data in multiple common spatial and nonspatial formats. Our current baseline for feedstock data is the National Wet Waste Inventory, which we published as a peer-reviewed open-source dataset jointly with NREL in 2020 (https://doi.org/10.17632/f4dxm3mb94.1). The sludge estimates were subsequently updated based on more detailed wastewater treatment modeling and published online, including mass and energy flow estimates by waste phase (https://doi.org/10.1016/j.jenvman.2020.110852). At the end of our current project (FY 2023), we plan to publish our findings in a peer-reviewed article with a link to data on Mendeley. If funded, our FY 2024 project renewal plan includes scope to build some prototype (web) tools to help end users explore WTE data and results more easily. Successfully developing, deploying, and maintaining software requires careful life cycle planning to ensure that tools can be available after the end of a particular project. Regarding improving our source data, we can improve some data but not others. The National Wet Waste Inventory dataset was the result of a multi-lab, multiyear national resource assessment. It remains the best publicly available national inventory of wet organic wastes. The waste flow data for sludges and manures are high-precision point-based data. Food waste and waste fats, oils, and grease were prepared at a mix of spatial scales from point to county level and were downscaled to representative point locations. Updating the national inventory would require a level of effort equivalent to the original assessment and is not something we can tackle on an analysis project; however, on another project, we are working on a methodology for modeling food waste in a new way that could substantially reduce spatial uncertainty for nonresidential food waste. If successful, we could request funding to apply the methodology to update the National Wet Waste Inventory. The remainder of our input data come from the literature or publicly available data published by federal and state agencies. We inherit the data quality from these sources.
- TA program coordination: It is not our goal to compete with or start a new TA program. Rather, we hope to leverage the synergy between our project and the TA program to maximize impact for the public. We deliberately scope our analysis and model-building activities to facilitate the development of results and tools that can eventually be deployed to serve the public through the TA program. In fact, our FY 2024 project renewal proposal is specifically designed to integrate all our data, models, and lessons learned to deploy a demonstration workflow through the TA program that helps underserved communities perform and explore the results from siting, impacts, and trade-off analyses using easy-to-access tools and a standardized reporting package. In return, we can leverage the learning done through the TA program to guide our communication deliverables and tool development.

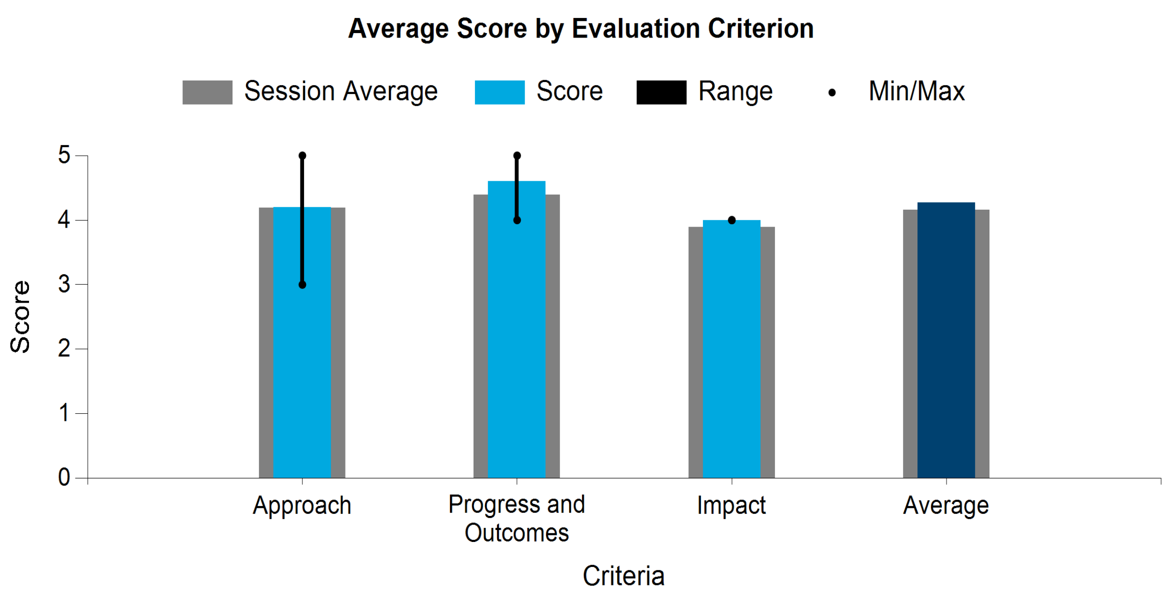
ANALYSIS AND SUSTAINABILITY INTERFACE

Pacific Northwest National Laboratory

PROJECT DESCRIPTION

WBS:	2.1.0.301
Presenter(s):	Karthikeyan Ramasamy; Katarina Younkin; Lesley Snowden-Swan; Michele R Jensen
Project Start Date:	10/01/2022
Planned Project End Date:	09/30/2025
Total Funding:	$1,800,000

This project provides technical, economic, and sustainability analysis support for several biomass conversion routes to hydrocarbon fuels and chemicals. In the context of the Organic Waste Conversion area, this presentation focuses on the project's wet waste HTL task. Building on previous wood and algae work, PNNL began testing, modeling, and TEA of the wet waste HTL and biocrude upgrading process in FY 2016. The design case projecting the 2022 cost target for the pathway was published in 2017, and annual state of technology (SOT) assessments were conducted since then to guide the research and track the modeled performance, GHG emissions, and MFSP toward BETO's targets. Data availability is a risk mitigated by frequent interaction with the team to continually review sustainable cost reduction strategies. The combined experimental/analysis efforts reduced the modeled SOT MFSP by $0.67/GGE and developed an initial assessment of jet blendstock production from HTL. Modeled SOT GHG emissions for the pathway are 77% lower than petroleum. Several options for the treatment of the aqueous phase were assessed, and our HTL reduced-order model was bolstered to include 29 continuous run datasets. Work in FY 2023 and beyond is focused on the development of business cases that will serve to bridge the gap between traditional SOT assessments and the needs of key external stakeholders to help accelerate technology adoption.



COMMENTS

- There is a clear management plan, communication strategy, and DEI goals to approach this work. The work has clearly incorporated a lot of learnings from HTL projects that BETO and others have funded. They seem to be incorporating them within a reasonable time frame.

- The team regularly incorporates the learning from the experimental members to update the SOT. This engagement and connection is valuable for the success of this project and also helping to unintentionally pass learnings between other projects. The project has achieved progress toward its goals and outcomes.
- While the dollars are fixed to a year, I'm curious about the impact of inflation around equipment, items, and labor versus general inflation.
- As an analysis task, this project is not intended to be commercialized by itself. The other challenge is that the commercial WTE space is still nascent, which would provide real-world feedback. The next phase of this project will address much of this, which should lead to an increased score in impact. Just the way the project is phased results in more of a wait-and-see score for impact.
- The team has reduced the Aspen model about HTL production to a publicly available Excel sheet. This simplified form makes the insights and analysis more accessible.
- The amount of 110 dry tons/day is a fairly large scale. The sensitivity of MFSP to this value will be critical. Not advocating for much smaller, but maybe one-third the size.
- Overview/impact:
    - This project generally aimed at optimizing the pathways through which bioenergy is obtained from wet waste with regard to cost reduction, increasing bioenergy yields, and reducing environmental contamination. To achieve this, the researchers used experimental values to develop HTL models and carried out TEA and LCA to obtain critical data, key cost drivers, and key techniques required for scaling up WTE techniques applied in the laboratory. They also used the aforesaid techniques to determine the most sustainable and environmentally friendly techniques for waste valorization to energy. GHG emissions that can emanate from HTL systems were also assessed. The approach applied in this project is very pragmatic, as HTL model parameters are based on real data and not on assumptions.
    - So far, within the short period of time the project has been operational, it has progressed well. For the first phase of the project, the researchers have been able to model a pathway that reduces MFSP by \$0.67/GGE and GHG emissions to 21 g CO_2e/MJ, which is 77% lower than the petroleum baseline value.
- Strengths: The project has very good management and communication plans. Also, the project has a good DEI plan that ensures that underrepresented and marginalized people/groups are well represented through their inclusion.
- Questions: One aim of the project was to assess the quantity/volume of GHGs that emanate from HTL—the researchers presented GHG reduction values predicted using their model; however, the researchers did not show the key elements of GHGs that were included in the model. Also, in slide 7, where the process flow of the model is presented, it can be noted that the solids from the HTL unit and those from treating the aqueous-phase units are sent to the landfill. Is there no other way the solids can be better managed? Further, the scenarios considered in the study make a lot of sense; however, some of the assumptions used are superficial (e.g., the assumed scale of the HTL unit is too big). The researchers should consider conducting a sensitivity analysis to assess the impact of different HTL unit scales on the economic viability of the system. In slide 13, the researchers present the sensitivity analysis results; however, it would be great if the researchers could also use other methods for assessing the economic viability of HTL units, such as breakeven point and net present value.
- This project provides useful contextual research for HTL and biocrude upgrading projects, taking an iterative approach to identifying and sharing insights on cost drivers and real-world operations as

research in these areas progresses. They are to be commended for including waste generators as stakeholders to inform this research direction. Among positives of this important work are leveraging the modeling/analysis work across other BETO projects and industry/university collaborations. The project's FY 2023 plans to engage a broader audience of stakeholders are good.

- The DEI aspect of the project plan could be strengthened. The stated goal of hiring only one student intern from an underrepresented group and/or disadvantaged community is a start of what should be a more comprehensive effort to pursue representation among project staff at multiple levels as well as to proactively consider community impacts of projects that will involve infrastructure, wastes, and emissions
- This project (as I understand it) is primarily a TEA for the application of HTL to convert organic wastes into SAF. This project basically seems to be a more practical envisioning of how organic wastes to SAF (via HTL) could occur. For example, an initial assumption might be that the WWTFs would house the HTL facility, but this is not likely feasible given that wastewater treatment personnel are poorly suited/trained (and they are already busy) to produce SAF. The outcome of this work is more reasonable/achievable visions for how organic wastes to SAF can be achieved.
- The project has an excellent team with a very good project management plan. The project has an appropriate focus on DEI with numerous internships going to women and to various underrepresented groups. I expect very high impacts from this work, although this has yet to be achieved because the project is still relatively new (i.e., about halfway through the project period).
- Similar ambitious goals to WBS 2.1.0.112 and WBS 2.1.0.113; together, these analyses can inform the information modeled and shared with local governments and industry to further reduce organic wastes to produce bioenergy.
- The project has clear goals and targets to convert dry wastes through HTL to SAF. The project has provided a survey to industry to ask what information they need to analyze the project's viability, demonstrating collaboration with industry to guide project deliverables.
- How have initial assumptions of HTL owned by the municipality set back TEA/MFSP? WRRFs could continue to pay tipping fees for sludge removal, but would the demonstration of the profitable conversion of wastes presumably lower tipping fee expenses for WRRFs?
- Looking forward to developments as this new project continues. The characterization of wastes at this scale will enable large shifts in production and GHG reductions and lead to decreasing costs of bioenergy-derived fuels.

PI RESPONSE TO REVIEWER COMMENTS

- We appreciate the time spent by the reviewers and for all their insightful feedback.
- Response to Reviewer 1: Thank you for your acknowledgement of our contribution to multiple BETO projects, efforts in management, communications, and the value of the open-access HTL process model from the reviewer. We regret that under the time constraints we did not emphasize the efforts of evaluating our technology at multiple pricing years. The impacts of inflation around equipment, items, and labor on the sludge HTL process can be found by comparing the results shown in slide 10 (2016 pricing basis) and slide 13 (2020 pricing basis). The modeled MFSP increased from $2.85/GGE to $3.15/GGE (10.5%) when moving from a 2016 to 2020 pricing basis. The general inflation from 2016 to 2020 is 7.8% according to the U.S. Bureau of Labor Statistics. The increase in MFSP is slightly higher than the general inflation rate (10.5% vs. 7.8%) because different indexes were used for chemical, labor, and equipment in the TEA model. We appreciate the reviewer's acknowledgement in our ongoing business case study and its potential to address feedback from the commercial WTE space. Industry

partners are actively participating in the project to establish specific sites of interest, key metrics, and priority outputs for deployment. We agree that the sensitivity of MFSP on the plant scale is critical. Due to the time limitation, we did not present related sensitivity studies in our previous works and other projects. The 2021 SOT study (https://doi.org/10.2172/1863608) presented a sensitivity study on a 2016 pricing basis regarding the plant scale. The modeled minimum biocrude selling prices are $1.7/GGE at a scale of 110 dry tons/day, $2.8/GGE at 50 dry tons/day, and $5.0/GGE at 20 dry tons/day. We would like to emphasize that the sensitivity of MFSP on the plant scale will change as the HTL technology keeps advancing. It is valuable to understand the impact with the most recent SOT. We are working closely with our industry partners and the Waste-to-Energy: Optimized Feedstock Blending at Scale project to understand the real-world supply and infrastructure of organic wastes and determine the plant scale for the baseline and sensitivity study.

- Response to Reviewer 2: Thank you for highlighting our effort in using real data instead of assumptions for modeling and our management, communication, and DEI plans. We would like to acknowledge that the GHG reduction evaluation of the sludge HTL process was conducted by our collaborators at Argonne National Laboratory. Details were presented by Argonne in another talk under the Data, Modeling, and Analysis session during the Project Peer Review ("Life Cycle Analysis of Biofuels and Bioproducts and GREET Development"). The key GHG emissions contributors can be found in slide 17, including natural gas, quicklime, and electricity. The modeled process improvements in the SOT over the past 2 years significantly reduced the chemical and utility demand, resulting in GHG reductions increasing from 53% for the 2020 SOT to 77% for the 2022 SOT. Thank you for pointing out the gaps in solids treatment. PNNL's HTL experimental team is actively investigating valorization options for the solid product (i.e., fertilizer production). We would like to emphasize that in this project, process modeling and TEA were performed based on actual data. We will follow our communication plan and include alternative options for the solid products once we receive quantitative results from the experimental team. Regarding the plant scale, a survey of existing wastewater treatment plant scales was conducted in our 2017 design case study (https://doi.org/10.2172/1415710), where a scale of 110 tons/day was selected in the base case due to the concern of economic feasibility. A number of U.S. wastewater treatment plants have scales greater than or equal to 110 tons/day, including the Great Lakes Water Authority, the specific site selected for this year's business case study. In addition, a sensitivity study varying plant scale from 20 to 500 dry tons/day is presented in our 2021 SOT report (https://doi.org/10.2172/1863608, Figure 13). As the HTL technology keeps advancing, it is important to revisit the sensitivity study regarding the plant scale. Moving forward, we will work closely with our industry partners and the resource analysis projects to determine the most relevant base case scale and range of scales for sensitivity studies. Thank you for suggesting other economic methods. Actually, this is included in the scope of our FY 2023 work as a critical component. Particularly, the team will study the economics of a first-of-a-kind plant for the specific site application, including the metrics of most value to partners, such as MFSP, net present value, payback period, and/or breakeven fuel price.

- Response to Reviewer 3: Thank you for highlighting the value of this project and our collaborations with other BETO projects, industries, and universities. We regret that due to the time limitation, we did not get a chance to present the organization-level plan of DEI. PNNL's strategic philosophy entails more than just looking at the demographic numbers related to diversity but also focusing on developing leadership competencies that create and maintain an inclusive culture. The bioenergy research area at PNNL is woman-led by Sector Manager Corinne Drennan. We are using the FY 2022 BETO Lab Call to increase the involvement of members from underrepresented STEM groups as project leads. In the current portfolio, 28% of co-PIs are women. In the response to the current lab call, 33% of responses are women-led, and 43% of co-PIs are women. For pursuing representation among staff at multiple levels, we will require contributions from multiple projects instead of one single project, and an organization-level plan. Environmental justice is not within the scope of this project; however, a team of experts at PNNL has developed the environmental justice LCA capability that complements conventional LCA by considering geospatial and community-level impacts. We are actively collaborating with the environmental justice LCA team at PNNL to evaluate the community impacts of sludge HTL regarding infrastructure, wastes, and emissions under different projects.

- Response to Reviewer 4: Thank you for highlighting our achievement in the past 2 years. In the remaining project period, we will increase the impacts from this work by including more collaborations with industry stakeholders, first-of-a-kind plant costing for a specific site, carbon credits, sensitivity study, and uncertainty quantification into the FY 2023 design/business case study.
- Response to Reviewer 5: Thank you for highlighting our collaboration with the waste resource analysis projects and potential impacts at scale. Regarding your question, the change in system boundary assumption with the inclusion of a $40/wet-ton tipping fee and waste disposal fees resulted in a $0.76/GGE reduction in modeled MFSP ($3.61/GGE for old system boundary vs. $2.85/GGE for the new system boundary). We regret that we did not emphasize our investigation on the tipping fee assumption and sensitivity study. In the base case, the tipping fee was set based on a survey of the present market status, of which the value is also within the typical range of organic waste landfill cost. We agree that the demonstration of the profitable conversion of wastes presumably may lower tipping fee expenses for WRRFs. At the same time, regulations for waste disposal are becoming stricter and may potentially result in higher landfill costs and therefore higher tipping fees. Due to the uncertainties in market scenarios, a sensitivity study was conducted in the 2021 SOT study (https://doi.org/10.2172/1863608, please refer to Figure 13), where sludge credit varied from $0 to $350/dry ton. The modeled minimum biocrude selling price would decrease by $1/GGE with a $100/dry-ton increase in the sludge credit.

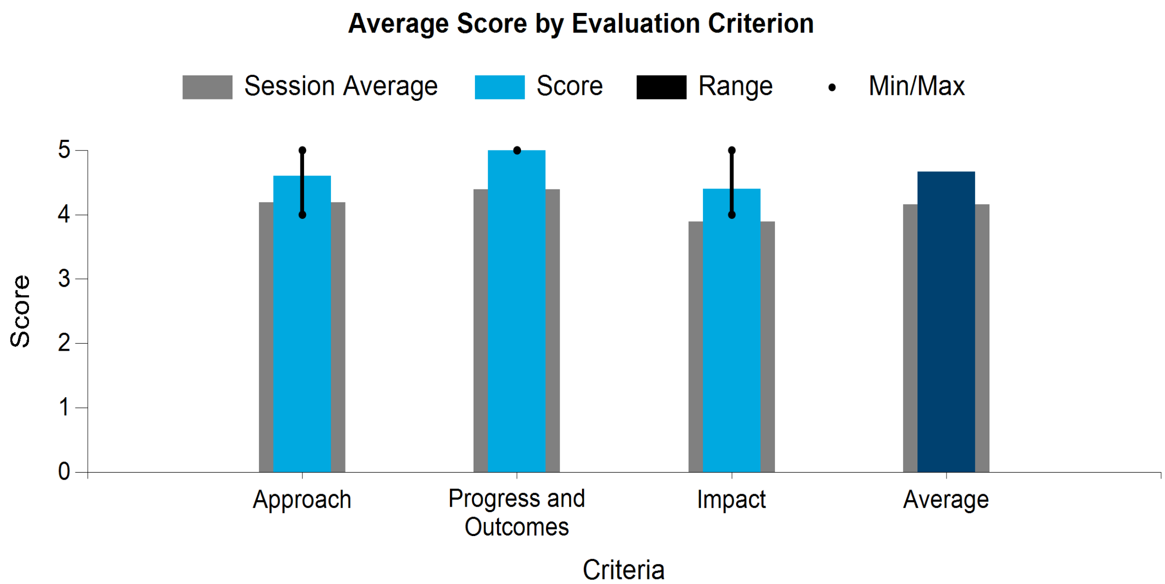
BENCH-SCALE HTL OF WET WASTES

Pacific Northwest National Laboratory

PROJECT DESCRIPTION

WBS:	2.2.2.302
Presenter(s):	Karthikeyan Ramasamy; Katarina Younkin; Michael Thorson; Michele R Jensen
Project Start Date:	10/01/2022
Planned Project End Date:	09/30/2025
Total Funding:	$1,200,000

HTL can solve the wet waste disposal problem by converting wet wastes to fuel with the potential for 5.5 billion gallons/year of transportation fuel in the United States. The focus of this project is to advance HTL to enable the conversion of waste feedstocks to biofuel intermediates that can meet industry-relevant cost and performance requirements with a focus on SAF capable of >70% reduction in GHG emissions. This project has made key advances by (1) demonstrating the industrially relevant and stable hydrotreating of the HTL biocrude to fuels (2,000 hours of hydrotreating) and (2) demonstrating the potential for regional blending of wet wastes to improve process yield and performance. Current research efforts are focused on (1) side stream disposal, including aqueous and solid streams, which are crucial barriers for commercial deployment; (2) forever chemical destruction, including PFAS and perfluorooctane sulfonic acid (PFOS); and (3) nutrient recovery of P/N for fertilizer applications. Thus far, this project has demonstrated the applicability of a mild wet air oxidation process to increase the bioavailability of the HTL aqueous stream by converting organic content to carboxylic acids with a high yield (>60%), improving ammonia capture, and reducing the volume of residual solids. This project tracks forever chemicals through all HTL process steps to quantify the destruction and partitioning of residual PFAS through hydrotreating, wet air oxidation, and struvite recovery.



COMMENTS

- Addressing some of the significant remaining barriers to commercialization: aqueous waste stream, nutrient recovery, catalyst life, and scale.
- Also tackling a big use case in addressing PFAS chemicals, as this is going to substantially increase treatment costs and/or land disposal/tipping fees.

- Progress has been clearly made on these items, as witnessed by the data and the substantial decreases in the SOT values.
- Tackling SAF clearly has value with the coming electrification of most vehicle fleets. The pivot and proof around the quality of the fuel shows high promise for this technology.
- Appreciated the layout of the goals and the show of progress. Clean and easy to follow.
- Incorporation and execution of DEI goals.
- HTL is coming up against the limits of commercialization that can be done by a national laboratory. Private projects have developed slowly for myriad reasons, which is less than ideal.
- Curious to understand more about the fate of the F atoms from the PFAS.
- Overview/impact/progress:
    - The project examined the feasibility of using HTL as a means of treating and managing wet waste while simultaneously generating biofuel SAF. Using HTL to convert wet waste to fuel eliminates the need for drying, which is one of the most expensive steps in the process of converting WTE.
    - What makes this project particularly interesting and impactful is that the researchers are addressing key issues, such as the fate and removal of emerging contaminants (i.e., PFAS) from wet waste (i.e., sewage sludge) during HTL as well as the extraction of nutrients (phosphorus and nitrogen) from the resulting HTL side stream. They also apply mild oxidation for treating the aqueous-phase liquid resulting from the HTL process, which removes recalcitrant contaminants, thereby making it recyclable. In sum, the researchers are also looking at how to make the use of HTL more sustainable. The project is highly relevant to the aviation and energy sector, as it is aimed at increasing the proportion of jet fuel that is made from renewable energy, leading to the gradual decarbonization of the aviation transport sector.
    - So far, the researchers have made considerable progress in this project. The researchers were able to achieve stable continuous hydrotreating of biocrudes from mixed fuels (>1,500 h) and >75% extraction of phosphorus from HTL solids.
- Strengths: The researchers are employing a multi-integrated framework, as they are collaborating with industry partners, and they use the results of their research to inform the commercial design of hydrothermal liquefiers.
- Weaknesses: In the presentation, the researchers indicated what they want to do and how much progress they have made so far; however, they did not clearly present the steps/process they used in achieving the set objectives. For instance, one objective of the study was to develop a process to extract valuable fertilizer coproduct from HTL side stream, and they were able to extract >75% phosphorus, but they did not provide the methods they used in doing this. The researchers also need to consider the feasibility of scaling up the proposed technique. Further, the researchers indicated that they made use of catalysts in the conversion process and that they achieved industrially relevant catalyst lifetimes; however, they did not mention the type of catalyst they used in the process and why.
- This project tackles a timely and important topic, which is the conversion of treated wastewater sludge and other dirty wet waste feedstocks into usable fuels, with the essential added-value aspect of PFAS destruction and N and P recovery. This suite of approaches, if scaled and economically viable, and proven in a transparent, public fashion, stands to be a game changer in wastewater treatment as the understanding of PFAS risks throughout the food web increases. It also poises WRRFs for a new role as

net withdrawers of PFAS and other forever chemicals from ecosystemic circulation, which is also a massive system improvement at this time in the history of human-induced ecological collapse.

- The researchers are encouraged to document the destruction rates of as many PFAS/PFOS compounds as possible, not only those that are currently identified by the U.S. Environmental Protection Agency for designation as hazardous, and to include steps to verify that the resulting biocrude is indeed hydrotreated, commenting on the presence of HF in the resulting product, which was mentioned. The worst thing that resulting work from this project could do is to provide WRRFs with the assurance of PFAS destruction without complete and transparent end-to-end verification.
- With respect to the DEI aspects of the project, the team should go well beyond hiring one student from an underrepresented group to engage students from schools, colleges, and universities that serve Black, Indigenous, and other people of color communities, including historically Black colleges and universities (HBCUs) and tribal colleges, with attention to outreach, recruitment, retention, and promotion, as well as building an understanding of the context of industrial operations such as are studied in the project for diverse communities and stakeholders. While staff have taken required trainings, they are encouraged to consult DEI practice literature around the history of racism, sexism, and other forms of systemic exclusion in the field of environmental engineering R&D to refine their approach.
- To the extent they have not yet done so, the researchers are encouraged to make contacts with water/wastewater trade associations, such as the Water Environment Federation and Water Research Foundation, as part of future community engagement, as well as with trade associations seeking to continue land application of biosolids, such as Northwest Biosolids, whose business model stands to be destabilized by near future PFAS regulation, as well as the emergence of HTL as a treatment alternative at scale.
- This project focuses on the HTL of sewage sludge and/or food waste to produce SAF. One major outcome of the work was to demonstrate the stable, long-term processing of waste to fuel (1,500 hours). Another aspect of the product focused on the nitrogen and phosphorus content of the waste stream/feedstock. One solution was to precipitate this material as struvite, which is a mineral sometimes intentionally produced at municipal WWTFs (and it is attractive as a fertilizer). Much of this work is driven by TEA and LCA, with the goal of producing cost-competitive SAF via HTL. After watching this presentation, I am optimistic that this goal is achievable.
- The project is well managed, organized, and highly productive. The DEI goals appear to have been met; I am particularly pleased that DEI training is part of the requirements for participating in the proposed project. I like this because other metrics of DEI "success" appear to be easily manipulated, whereas the completion of a DEI training program is tangible.
- The project demonstrates HTL treatment processes that create fuel, usable solids, the destruction of PFAS-group chemicals, and the recovery of fertilizers (P and N) to further reduce the need for expensive, fossil-fuel-derived fertilizers that are prone to supply shocks.
- The research has utilized many partners for deployment and feedstock analysis to ensure full consideration of real-world fuel types. Results are showing clear benefit for the performer and government while providing valuable SAF. PFAS will be an emerging expense for municipalities in treating organic waste streams. This process offers the ability to finance facility upgrades by creating several revenue streams and offers a solution to reduce the flow of PFAS-containing water and biosolids into other areas of our natural environment.

PI RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their thoughtful feedback on our project. We are grateful for the recognition of the progress we have made ("Progress has been clearly made on these items, as witnessed by the data and the substantial decreases in the SOT values"), that we "are addressing key issues such as the fate and removal of emerging contaminants (i.e., PFAS)," that this "project is highly relevant to the aviation and energy sector," and that "the researchers have made considerable progress in this project."

- Barriers to commercialization: We acknowledge the significant remaining barriers to commercialization, including the aqueous waste stream, nutrient recovery, catalyst life, and scale. We are actively addressing these challenges and making progress in overcoming them. The data presented in our work demonstrate substantial decreases in the model SOT costs, indicating clear advancements in these areas.
- PFAS chemicals: We recognize the importance of addressing PFAS chemicals in our project. We are aware that their presence can substantially increase treatment costs and land disposal fees. Our research aims to tackle this issue and find effective solutions to minimize PFAS contamination. We will continue to provide updates on the fate of F atoms from PFAS and include more information in our future reports to enhance understanding.
- DEI goals and community engagement: We value the importance of incorporating DEI goals into our project. We agree that our DEI impact needs to extend beyond hiring one student, and we are actively engaging with the broader community. We will leverage our contacts with water/wastewater trade associations and biosolids trade associations to foster community engagement and address the concerns of diverse communities and stakeholders.
- Complete PFAS destruction: We acknowledge the need for complete and transparent verification of our PFAS destruction results. As noted by Reviewer 3, "The worst thing that resulting work from this project could do is to provide WRRFs with the assurance of PFAS destruction without complete and transparent end-to-end verification." We will ensure that destruction rates of various PFAS compounds are documented, and we will include WRRFs in the workflow process to ensure that we provide complete and transparent verification of our PFAS destruction results. Again, we sincerely appreciate your positive feedback and insightful suggestions.

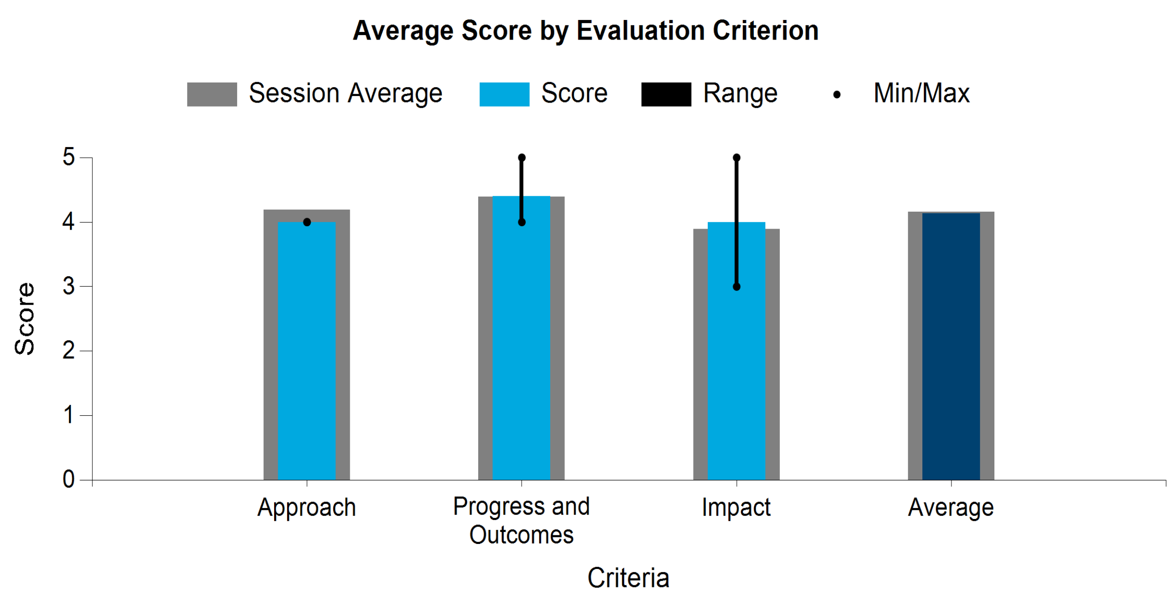
CATALYTIC UPGRADING OF CARBOHYDRATES IN WASTE STREAMS TO HYDROCARBONS

North Carolina State University

PROJECT DESCRIPTION

WBS:	2.3.1.209
Presenter(s):	Rosemary Loycano; Sunkyu Park
Project Start Date:	10/01/2018
Planned Project End Date:	09/30/2023
Total Funding:	$3,094,759

The primary objective is to develop a technology for converting the carbohydrates in paper sludge, a wet organic industrial waste stream, into a hydrocarbon biofuel, both economically and sustainably. BETO has identified wet organic waste streams as valuable potential feedstocks for the bioeconomy. This project will develop an integrated process using wet paper sludge where no drying of the feedstock is needed. The process includes (1) ash removal from paper sludge, (2) enzymatic hydrolysis of carbohydrates to monosaccharides, (3) dehydration of pentoses and hexoses to furfural and hydroxymethylfurfural, (4) aldol condensation of furans with ketones to intermediates having molecules with 10–14 carbons, (5) hydrodeoxygenation of the intermediates to paraffins with excellent properties for blending in jet or diesel fuel, and (6) robust TEA and LCA to focus research on developing cost-effective routes to address key cost barriers and ensure the sustainability of the process. The developed process will be validated at a relevant scale to produce sufficient hydrocarbon biofuel for fuel property testing.



COMMENTS

- It is really quite refreshing to see all the contact that was done to paper mills. The team took the time to visit plants and speak with staff. These kinds of conversations are the most invaluable kinds of customer discoveries.

- The team then took the time to solicit real feedstocks and do the characterization. Subsequent tests were done with one of the actual feedstocks, which is ideal. Truly appreciate the effort around this issue.

- Pulp and paper waste is certainly a big challenge to turn into SAF relative to a lot of other feedstocks. The team is tackling quite an important issue, alongside the other feedstocks being tackled by BETO projects.
- The team has a good management, communication, and risk plan. There did not seem to be any DEI elements as part of the project plan.
- The team did a lot to pivot from diesel to SAF part of the way through the project, and they navigated those changes fairly well.
- Relative to many other WTE feedstocks/conversion processes, this material seems to have a much higher MFSP.
- The technology seems to be at an earlier stage; it will require a lot of valorization of other streams. Certainly see a lot of promise in being a supplementary cementitious material if it as rich in Ca as it is.
- Does not necessarily seem like it is ready to be commercialized/deployed immediately following this program. Also does not seem to have an involved commercialization partner.
- The project has met all the goals as they have been set out, and it appears on target to meet its final objectives/deliverables.
- Overview/impact:
    - The researchers in this project developed a sustainable and economic technique for transforming the carbohydrates in paper sludge into hydrocarbon using a combination of enzymatic hydrolysis, aldol condensation, and hydrodeoxygenation. The production of fuel from paper sludge serves as a means of incentivizing and sustaining the proper management of paper sludge. The approach used in this study is futuristic and will help with the effective management of paper sludge produced by mushrooming paper industries.
    - Considerable progress has been made in this work, and most set targets have been met. In the pretreatment of the paper sludge, the researchers were able to obtain about >90% ash removal and >65% carbohydrate retention. The project findings suggest that carbohydrates in the sludge could be converted to 150 million gallons of diesel fuel, showing that this project aligns with DOE’s strategy for the production of high-performance biofuels from waste feedstocks.
- Strengths: The project involves the collaboration of several academic and industry partners. Also, the channels of communication used in this project are highly commendable.
- Weaknesses: The researchers did not indicate anything about the originality and novelty of their work. In the presentation, it is indicated that a lot of progress has been made with respect to the set objectives; however, the PowerPoint presentation does not provide a clear overview of how each of the objectives was achieved. Further, the catalytic upgrading of carbohydrates in waste streams to hydrocarbons using enzymatic hydrolysis is a novel approach; however, I am wondering if the researchers have considered its applicability to the existing paper production facilities for sludge management. In slide 23, the TEA provides an MFSP of about $5.67/GGE, and this seems high. I am wondering if researchers could consider other economic benefits associated with their proposed technique that would help reduce the fuel selling price. For example, costs associated with the disposal of paper sludge should be considered. Last, in slide 10, the researchers present the ash percentage in the paper sludge; however, these values significantly varied. Therefore, characteristics of the paper sludge should be given a high priority in the scaling up of the technique, as this will have a significant effect on the ash content and viability of the proposed technique.

- Recommendations: The authors made mention of examining three different paper sludge types and developing solutions that fit each sludge type; however, it would have been good if the authors consider using the chemical composition of these sludge types and the way they react to the catalytic upgrading to develop models that can fit different sludge types and not just the three sludge types they plan to examine. This is done as a way of tackling sludge variation between mills.
- The project seeks to develop an economic and sustainable process for the conversion of carbohydrates in paper sludge into a biocrude output that can be refined into SAF considering this feedstock's high ash content. Researchers showed good engagement with industry participants and regular communication among project partners.
- As the project proceeds, researchers should take note of major differences in pulp composition from virgin versus recycled feedstocks. Recycled papers contain, among other things, varying levels of added PFAS and microplastics used in coatings and finishings. Researchers should also contrast project cases with alternative pathways for carbohydrate conversion, including fermentation. Finally, the researchers should draft a DEI engagement plan for project staffing and outreach that includes students from underrepresented groups at levels between the high school and doctoral levels.
- The goal of this project was to convert organic wastes from the pulp/paper industry to hydrocarbons. Paper sludge is about 10% of the raw product used, but the disposal of the remainder costs about $30 per wet ton, which translated to about $250,000,000 per year for waste disposal for the industry. The project is a collaboration among researchers at North Carolina State, Yale, and NREL. There were regular (monthly) online meetings among the project participants as well as less frequent in-person meetings with all collaborators.
- NREL does conversion of paper to hydrocarbons. Trying to make biofuel from paper. In Year 3 of the project (about 6 months left). Monthly meetings. In-person meetings with all collaborators.
- The project approach was very linear and logical. The investigators have done a nice job meeting all their various milestones. I was particularly pleased that the TEA (and LCA) process identified a financial bottleneck, which the researchers identified and then pivoted to reduce the cost of the process (i.e., shift from using dioxane to acetone).
- Really nice application of the TEA driving a modification of the plan to get a more reasonable price to produce the jet fuel.
- In many ways, this seemed like a nice example of how BETO's various requirements (i.e., required partnerships, LCA, and TEA) can work very well.
- The team is actively managing the project and includes clear roles and interactions among researchers and the inclusion of industry partners. The project includes waste from 11 facilities that produce paper sludge to analyze input factors and design a treatment solution. Risk in ash management and alternative methods to manage high-ash waste has been an issue, but the project has found a simple, low-cost, low-input way to separate ash.
- This project has the potential to create high-value SAF bioenergy from typically low-potential, high-moisture waste, moving 8 million metric tons of waste from current disposal practices (land application, lagoons, and incineration) while separating ash product that may further reduce energy inputs in the concrete industry.
- The project in its remaining months will need to consider the incentives available for the creation of renewable SAF and valorize ash resources in order to move this technology further toward deployment and increase its impact.

PI RESPONSE TO REVIEWER COMMENTS

- We thank the review panel for their supportive and constructive comments regarding this project.
- The reason that DEI elements are not currently included in this project's plan is that DEI objectives were not required when the request for project proposals was made in 2018. All the organizations currently taking part in this project are aware that the importance of DEI has become recognized since then and are looking to involve underrepresented groups in the research being conducted in projects such as ours.
- As the reviewers noted, there are some scenarios where the MFSP is relatively high ($5.67/GGE) for the base case; however, we have changed our solvent system to acetone after the intermediate verification, which considerably reduces the calculated MFSP to $3.49/GGE.
- A recommendation was made for us to consider how the chemical composition of different sludge types might affect the catalytic upgrading of the carbohydrates to hydrocarbons. In our work to date, we have determined the carbohydrate, lignin, and ash contents of the paper sludge samples we have obtained, plus the elements present in the inorganic component of the sludges, which is mostly Ca from the $CaCO_3$ filler used in making paper. A large fraction of this inorganic component is removed during deashing. Residual $CaCO_3$/ash does affect how much HCl must be added to get the proper pH for efficient enzymatic hydrolysis of the carbohydrate; however, it has not so far appeared to affect downstream catalytic processes. Elemental analyses of used hydrodeoxygenation catalysts have not found levels of elements (such as Ca, K, Mg, Na, P, S, Sr, Cu, and Cr) significantly higher than those found in unused catalysts.
- So far, we have not identified the presence of PFAS or microplastics in the paper sludges we have obtained, nor any effect they might have on our catalytic processes. One sample of low-ash-content sludge we received from a mill making paper tissue was resistant to enzymatic hydrolysis. We think this was due to the addition of a polymer (wet strength agent) that coated the paper fibers, restricting access of enzymes to the fibers.
- The main variable we have encountered between different paper sludge samples is their ash contents, and we believe that the side hill screen provides an efficient means of removing the ash from most paper sludges, allowing subsequent downstream operations to convert the carbohydrate component into hydrocarbons without a problem.

NOVEL AND VIABLE TECHNOLOGIES FOR CONVERTING WET ORGANIC WASTE STREAMS TO HIGHER-VALUE PRODUCTS

The Research Foundation of SUNY, University of Albany

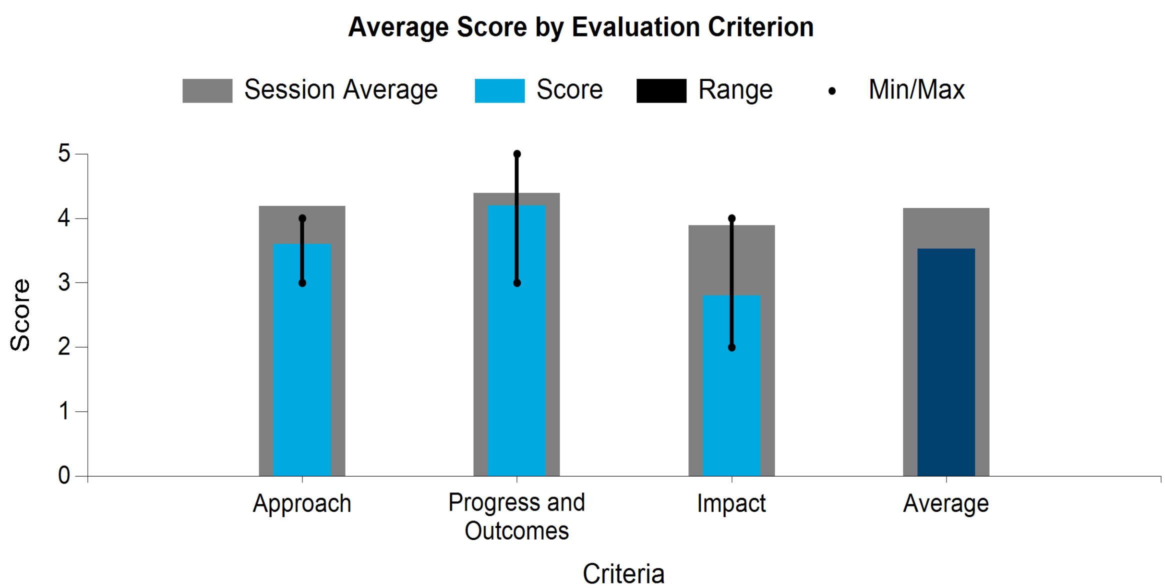
PROJECT DESCRIPTION

WBS:	2.3.2.226
Presenter(s):	Yanna Liang
Project Start Date:	10/01/2019
Planned Project End Date:	05/31/2023
Total Funding:	$3,408,092

The overarching goal of this project is to develop an integrated and efficient process for converting wet organic wastes to VFAs. To achieve this goal, we aim to accomplish seven different objectives:

1. Identify the optimal pretreatment method for each target waste stream.
2. Determine the best process parameters for arrested methanogenesis.
3. Evaluate the product yield and titer of VFAs from the waste streams separately through MES with CO_2 capture and conversion.
4. Develop an innovative membrane-based liquid-liquid extraction process for extracting VFAs and carboxylic acids out of the fermentation broth.
5. Perform preliminary LCA and TEA for each process block and the overall process.
6. Operate the integrated process continuously at a 5-liter scale for at least 3 months.
7. Operate the integrated process continuously at a 50-liter scale for at least 100 hours. TEA and LCA will be performed for this operation.

Upon finishing all the proposed objectives, we expect to have developed one of the first scalable, economically competitive, and environmentally sound processes for converting wet organic waste streams to high-value products.



COMMENTS

- The team did quite well at arresting methanogenesis in this project and driving production toward VFA production.
- The modeling analysis was quite strong, and it shows potential in describing what was seen experimentally.
- It would be curious to see, if a different wet organic waste stream were chosen, if the model would be robust enough to still function reasonably well.
- The project seemed to fastidiously proceed through the individual steps and is well positioned to complete their final goals around the 50-L reactor.
- Glad to see that someone explained that H_2 has demonstrated greater electron efficiency than direct contact.
- Given the early technology readiness level (TRL), I'm not sure about the commercial potential. Also, this team did not seem to engage with commercial entities.
- The research accomplished its goals and presents an opportunity for this team or others to continue.
- The GHG emissions savings for these products appear to be important, but does it also make financial sense?
- Not really sure about the integration of these unit operations at industrially relevant scales.
- The research is solid; the challenge is with programmatic offices at DOE, it needs to be applied.
- Did not seem to spend much time discussing project management, but given its performance to date, success is inferred.
- Did not see any comments on DEI or outreach.
- Engaging with local WRRF.
- Overview/impact/progress:
    - The researchers investigated the use of a novel technique: membrane-based liquid-liquid extraction for the continuous extraction of VFAs from wet organic waste streams. The novel technique was applied after improved VFA production from wet organic waste streams through MES and arrested methanogenesis. The project is highly impactful as it entails the conversion of food waste and sewage sludge to biofuel, thereby serving as a way to avoid the negative impacts associated with landfilling the waste.
    - The project is on track, as all the milestones that were set out at the beginning have been reached. Also, the plethora of presentations, awards, patents, and publications associated with this project shows that the project is of high importance to the scientific community.
- Strengths: It can be said that the researchers developed a vanguard technique for continuous VFA production from organic waste, which is very laudable.
- Questions/weaknesses: The researchers indicated that the overarching goal of the project is to systematically evaluate the whole process of converting organic wastes to high-value products, but from the presentation, the only high-value target product is VFA, as they did not make mention of any other

product. In the PowerPoint presentation, it can be noted that the researchers were dealing with the extraction and conversion of VFAs from food waste and sewage sludge; however, the methodology used is not clear—everything seems jumbled up, as there is no logical flow from one step to another. Also, the researchers state that they are converting the organic wastes to high-value products, and in this case, VFA using different methods. I expected the researchers to take the initiative of explaining/examining the composition of different VFAs they obtained from different methods to know which method gives the best results. Further, I am wondering if the researchers have considered the variability of the feedstock and its effect on the performance of the system. It would be great if they could assess the effect of feedstock type and characteristics on the performance of the system. Last, the researchers should consider assessing the feasibility of scaling up this technique or incorporating it into the existing system.

- This project is a systematic evaluation of wet waste conversion to high-value outputs such as biomethane and biocrude, with emphasis on the capture of VFAs. Among the project's strengths are that it addresses both food and wastewater residuals as feedstocks, and it proposes a continuous process to produce VFAs that can be valorized as bioproducts. The GHG profile of this process, compared to a fossil benchmark, heavily depends on pretreatment with arrested methanogenesis. Researchers should keep the viability of this treatment configuration (integrated system), in terms of commercialization and community acceptance, in mind as the progress progresses.

- The award was made prior to BETO's DEI requirements, but the researchers should start to develop a proactive DEI strategy that includes outreach and staffing, targeting students from the high school through doctoral levels, to ensure continuous participation of underrepresented groups on the project team.

- The idea is to operate an anaerobic digester fed with food waste at very short residence time to limit methanogenesis and then primarily produce VFAs. These VFAs could then be used to help make various value-added products. The researchers also tried to use MES on the residual waste (i.e., after partial treatment) to produce hydrogen gas to enable the growth of acetogenic microorganisms. The researchers then used LCA and TEA to help guide the optimization of these processes to reduce cost and GHG emissions.

- The project seems to be well managed and generally successful.

- Research seeks a strategic/novel goal to target VFAs for separation to provide revenue streams for organic waste processes. The interesting ultrasonication approach differs from other methods that require a high thermal load and additional reactor cost. The TEA indicates that capital and operating costs are on the same order as the other unit processes, with ultrasonication less energy-intensive than hydrothermal treatment, which could reduce energy inputs once proven at a larger scale, above 50 L over 4 days. With the project drawing to a close, it is unclear if there is potential for significant impact and outcomes of this technologies to commercial applications; however, there are lessons learned that can be applied to other technologies in organic waste processing and reuse.

PI RESPONSE TO REVIEWER COMMENTS

- We deeply appreciate the reviewers' time and effort in providing critical evaluation and valuable feedback for this project. In particular, we appreciate the strengths, uniqueness, and potential impact raised by the reviewers. All five reviewers gave no weaknesses regarding the technologies, approaches taken, and progress made so far. The impression is that the reviewers are satisfied with what has been accomplished so far. Four of the five reviewers commented on commercialization. The project team does desire to see the technologies commercialized in the near future. The process commercialization, however, is not the goal of this project. The final milestone of this project is to test the whole system at a 50-L scale. At present, we have been in communication with a local city to perform a test at 1,000 gallons. Whether we can get this done or not depends on the available budget and other logistics, such as collecting enough organic wastes and how to deal with the residual wastes. Two reviewers commented on DEI. As one reviewer pointed out, DEI is not a requirement of this project, starting from October 2019. Although as researchers, all team members have been engaging students from K–12 and especially those from disadvantaged communities, but implementing DEI for this project has been severely affected by the pandemic, as universities were shut down immediately after the initial verification in March 2020. As a result, most project tasks were accomplished during the pandemic, and recruiting high school students to work in the lab has been nearly impossible until recently. One reviewer commented on how different feedstocks may affect the composition of VFAs and which method can give the best results. These questions are specifically tied to the viability of food waste. Throughout the project, we have collected different types of food waste, such as wasted food from dining halls, grocery waste, and kitchen waste. Different food wastes have different compositions and lead to different VFA profiles after arrested methanogenesis. Typically, acetic acid and butyric acid are the dominant ones. The change of VFA compositions can be minimized or eliminated when the process is scaled up. On an industrial scale, as food waste from different sources are blended, mixed, and digested, the variability of the feedstocks will be minimal. At this scale, the VFA profile should be stable and predictable.

ADVANCED PRETREATMENT/ANAEROBIC DIGESTION

Washington State University

PROJECT DESCRIPTION

WBS:	2.3.2.228
Presenter(s):	Birgitte Ahring
Project Start Date:	10/01/2019
Planned Project End Date:	10/31/2023
Total Funding:	$3,035,351

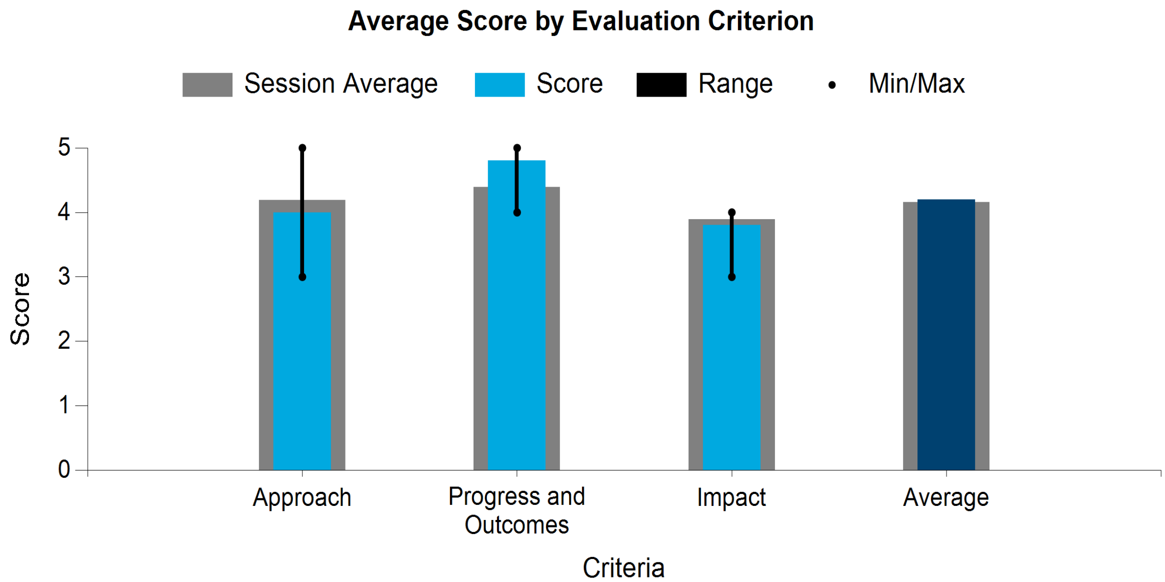
The goal of the Advanced Pretreatment and Anaerobic Digestion (APAD) project is to significantly improve the CCE of AD of sewage sludge by implementing pretreatment technology in the form of Advanced Wet Oxidation and Steam Explosion (AWOEx) pretreatment. This pretreatment has been shown to be superior for pretreating lignocellulosic materials, but it has not previously been tested on sewage sludge.

In addition, the project aims to convert CO_2 from the biogas (approximately 40% of the gas) to methane with the addition of hydrogen. This process will further increase the methane yield of the sewage sludge and produce RNG, which can be used as a transportation fuel.

The end goal of the project is to increase the CCE by 50% or more and to further produce a final biogas with maximum 5% residual CO_2. This will increase the amount of methane produced by the APAD process by an extra 134% compared to the methane produced by conventional AD.

The results from Budget Period 2 (BP2), which finished at the end of spring 2022, showed that the APAD process worked very well on sewage sludge and resulted in a CCE of 60.4%, far exceeding the end goal for the project. The CO_2 conversion further produced a biogas with 5% or less CO_2, which was the end goal for this task. Overall, the project showed 84% conversion of the organics in the sewage sludge by the APAD process, leading to more than 100% more methane, while the upgrading further increased the methane production with 115% extra, leading to a final extra production of methane of 215% compared to conventional AD.

The project is now in BP3, consisting of a small pilot testing. The pilot facility is expected to be in full operation later this spring. We expect to finish the work in the pilot mid-September 2023, after which the final mass and energy balance will be produced. The project is therefore on track for closing as planned at the end of October 2023.



COMMENTS

- Solid work.
- Demonstrated significant improvements on all measured metrics/baselines.
- Would be better to frame this research relative to the true state of the industry.
- Curious as to the baseline of some of the other AD-enhancing strategies being considered by WRRFs: thermal hydrolysis processing (THP) (Cambi), chemical pretreatment, etc. (slides 21 and 24).
- Overview/impact:
  - This project investigated approaches for improving the CCE of sewage sludge by at least 50% and upgrading biogas to RNG.
  - The investigators used a novel APAD technology that involves the use of AWOEx on the remaining biosolids after the first AD followed by a second AD.
  - The investigators have made significant progress against the project goals, especially in BP2 and BP3. The project results show that using the APAD technology helps to improve the methane production rate in the AD system for sewage sludge. Further, the investigated APAD technology for the increased conversion of sewage sludge to bio-natural gas in small-scale wastewater plants is an innovative technique that is relevant to the DOE program goals, and it can be easily integrated into the existing wastewater AD facilities for sewage sludge treatment.
- Strengths: The technique applied in the project is novel and improves the CCE of sewage sludge by AD to approximately 60% and the methane yield by about three times, thus reducing the costs of waste disposal. Further, the communication plan and the collaboration and diversity activities are highly commendable.
- Weaknesses:
  - In this study, the researchers did not report the characteristics of the digestate from the first AD process. The researchers need to note that the characteristics of digestate from the first AD may

vary depending on the feedstock, and I am wondering if we could see the same results when this type of pretreatment is used/applied to the digestate of different characteristics. Also, the researchers noted that to solve the challenge of concentrating the AD-digested sewage sludge, they used other flocculants and concentration methods; however, they need to be careful with the addition of chemicals in the process, as this has a significant effect on the quality of the end products and sometimes the AD process itself.

  - Second, on slide 24, the researchers indicated that their APAD technique generates Class A biosolids; however, I am wondering if they considered the other emerging contaminants (e.g., PFAS) in the biosolids before claiming that their technique generates Class A biosolids.
  - On slide 2, the researchers recommend the optimal pretreatment conditions of AWOEx; however, I am wondering if these conditions apply to all types of digestate from different sewage sludge ADs. Ideally, the characteristics of sludge significantly vary, and therefore I expect the effectiveness or optimal pretreatment conditions of AWOEx to vary too. Therefore, a series of more studies are needed to determine the optimal conditions with a 95% confidence interval.

- Questions: The advanced pretreatment stage only occurs before the second digester; what about the first digester? Is it really economic to run two digesters? Further, the aim of any project is to ensure that the results are transferable and applicable to other similar products; is this advanced pretreatment process applicable to other kinds of sludges or organic wastes? Looking at the flowchart provided for the APAD process on slide 3. Why is the liquid digestate from the second anaerobic digester sent to the biogas upgradation stage? And what happens to the liquid digestate after the biogas upgrade? Last, the authors made mention of operating the methanogenic fermentation process in two steps after each other to increase the overall efficiency of converting methane to carbon dioxide, but they do not categorically state how they did so. In addition, as part of the impact statements, the investigators stated that the major steps in the process were optimized separately, but the results of the optimization process are not provided anywhere in the slides.

- This project seeks to improve the CCE of AD of sewage sludge through pretreatment. This project was well managed and had a well-developed communication plan. Among its strengths was stakeholder involvement with the host municipality, the city of Walla Walla. The project showed good progress toward the goals of improved CCE and the biomethanization of CO_2. Among suggestions for future improvements, the researchers are encouraged to go beyond hiring students from unrepresented groups generally, to specifically reaching out to Black and Indigenous Americans, as well as provide guidance to existing students on a pipeline of study to professional employment. The acceptability of this approach to small-quantity WRRFs may be limited by the need for two AD reactors in terms of capital and footprint. This may not be avoidable in future iterations of the project, but it is something to keep in mind.

- The goal of this project was to improve the conversion efficiency of carbon to methane during the AD of sewage sludge and to increase the methane content of the biogas so that it is more amenable for commercial applications. The proposed solution was to treat sewage sludge via conventional AD, sending the biogas from this process to a "biogas upgradation" process and sending the treated material to a liquid/solids separator. The concentrated solids material was then treated via an AWOEx process, which had been previously used to make lignin more bioavailable. The AWOEx-treated solids were then remixed with some of the digestate (from the liquid-solid separation) and treated by a second (thermophilic) AD process. The biogas from this AD process was then also processed by a "biogas upgradation" process to increase the methane content. The research demonstrated that the process was able to achieve its goals as far as CCE and methane content of the biogas. There are plans to design and implement the process at full scale at the Walla Walla, Washington, WWTF.

- The project is a success in many ways because the investigators reached their metrics and they achieved their goals, particularly when this process is compared to conventional AD; however, it remains unclear whether this type of design would be better (e.g., incorporating cost, reductions in GHG emissions) than other designs also intended to achieve greater CCE and high-methane-content biogas (RNG). The investigators provided excellent information on the optimization of the AWOEx process; however, it is not clear whether similar optimizations were considered for the first-stage anaerobic digester, the second-stage anaerobic digester, or the biogas upgradation process. It would be very interesting to learn the results of a TEA considering each of these unit operations to identify an optimal strategy. In contrast, the TEA that was performed seemed to consider the inclusion or exclusion of each unit operation.

- The project has clear targets, goals, and a mission. A biosolids reduction of 59% and a levelized cost of sludge treatment at $79 could greatly impact WRRF processes and budgets for the better. What is the landscape of applying this technology to operations smaller or larger than Walla Walla?
- Does this project have updated information on the destruction of PFAS-group chemicals? Although this is not the primary focus of this research project, concerns continue to grow about PFAS-group chemicals, and this technology could provide multiple bottom-line benefits. An integrated process that can be employed at WRRFs could greatly reduce the flow of PFAS-containing water and biosolids into other areas of our natural environment.
- The project is being managed well to ensure beneficial outcomes for the performer and the government. There are HTL opportunities employed at larger WWTFs. The economics can be difficult to pencil out at medium- and smaller-sized WRRFs, as RNG incentive values do currently and will continue to change in the future. It is important that lessons learned through this effort are incorporated over time into existing facilities, reducing cost and complexities for smaller-size operations with smaller-sized budgets.
- The overall goals of this project could solve a reoccurring issue at municipal WRRFs and forgo many tons of waste in already decreasing landfill space, all while providing RNG to support the needs of WRRFs and the greater community.

PI RESPONSE TO REVIEWER COMMENTS

- We are truly thankful for your many positive remarks from the reviewers as well as their constructive suggestions!
- Response to comments from Reviewer 1. Frame the research toward the true state of the industry: From slide 12, it is obvious that thermic hydrolysis followed by steam explosion of digested sewage sludge as performed by Cambi will not deliver the same positive impact as we have seen (we found less than 25% more methane with THP at 175°C and approximately 10% more at 165°C as normally used during THP compared to simple AD of the input digested sludge material). In contrast, the AWOEx process delivers an increase of approximately 130% more methane compared to the digestion of sewage sludge without any treatment and 85% higher methane production compared to THP at 175°C. It is important to understand that our APAD test setup is different than the process operated by THP in general. We do not pretreat the raw material, and we use higher process temperatures for shorter times. Unfortunately, due to the lack of public data, we do not currently know what the TEA and LCA are of the currently used THP processes; however, we know from our study that the effect of this pretreatment on the recalcitrant parts of sewage sludge is limited and that the effect on reducing the amount of biosolids out of the WWTF is further limited. Using AWOEx up front instead of after AD 1 would overall produce the same methane production, but the cost would be higher due to the higher throughput; however, as AWOEx is developed as a continuous process, this would have a lower impact compared to companies such as Cambi, which operates in batch mode with long retention times. The technology is approaching the commercialization phase, and new team members are needed; we fully agree with this statement, and our company partner Clean-Vantage is working on a commercialization plan for getting the technology to the market.

- Response to comments/questions from Reviewer 2. Thank you for seeing the novelty and value of the project. Weakness. Characteristics of the sludge used are not shown: The characteristics of the sludge and the composition analysis of the sludge before and after AWOEx and AD 2 were unfortunately part of the slides but eliminated due to the time constraints for the presentation (the data are, however, in the publications described on slide 26). We agree with the reviewer that these slides should have been kept at least in the appendix. As discussed at the meeting, we did further test sludge from another small WWTF (the one in Richland, Washington) and found similar results as found for Walla Walla. We are therefore convinced that our results will show the same trends for sludge from other WWTFs. Flocculant: Additional chemicals can have negative effects. We presented our test of the different flocculants/coagulants used at the last review meeting 2 years ago just after the startup of the project. We found no inhibitions on methane production for the concentrations used in our experiments. We do, however, agree with the reviewer that additives should be avoided as much as possible. Class A biosolids: Must know about of fate of PFAS in the sludge to claim Class A. Class A biosolids are defined by the concentrations of pathogens in the sludge, not the amount of chemicals. We do meet all the requirements for Class A biosolids after AWOEx pretreatment. The U.S. Environmental Protection Agency does, however, further regulate the amounts of heavy metals for use of the sludge for land application. Right now, there are no regulations or guidance for PFAS-contaminated biosolids; however, some counties are setting up their own rules for use. Questions: Is it economic to run two bioreactors? The setup is based on the fact that over 50% of all WWTFs already have AD installed. In these systems, the AD plants convert all the easily digestible parts of the biosolids and leave the recalcitrant part behind. After AWOEx, the rheology is changed, and the second AD can be operated with high solids loading using a far smaller AD 2 system compared to the AD 1 bioreactor. Modeling of the cost of upfront pretreatment before the AD bioreactor compared to our APAD setup clearly demonstrates that APAD gives a higher reduction in cost. Why is digestate sent to the biogas upgrading? Good question! We use parts of the upfront separated liquid from the concentration of the digested biosolids before AWOEx as the liquid stream for operating the trickling bed bioreactor for biogas upgrading. We have data demonstrating that our methanogen grows with similar doubling rates in this stream compared to laboratory media. This will further reduce the cost of operating the upgrading process, and no supplements need to be added for operating the process! As shown in slide 3, this liquid stream goes back to the wastewater treatment units after use. Operating the biogas upgrading in two steps? No—it is a one-step process. This was one of the solutions we suggested if our process was not efficient enough; however, our results were very promising, and we managed to operate the trickling bed reactor for several months with 98% CO_2 conversion efficiency with a 4:1 relationship of H_2:CO_2. This was higher than the 95%, which was the original end goal for the project. Some optimization steps are not presented in detail: We operate several processes in the APAD project, where the main aim was to show over 50% improvement of the CCE over conventional AD. The presentation therefore focused on demonstrating the effect of AWOEx on the CCE. The tasks related to the concentration of digested sludge and the upgrading of biogas are further presented with several slides. Seen in the light of the time constraints for the presentation, as well as the priority of the FOA we responded to, we find that our presentation is well balanced.

- Response to Reviewer 3. Potential problem with having two AD reactors: The cost of landfilling of sewage sludge is significant (see slide 25). The advantage of producing far less sewage sludge, which needs final disposal (15% compared to 50%), while at the same time producing far more biogas or RNG is significant! The data shown in this slide include all the capital and operational costs involved! The data clearly show that the APAD process with all its extra cost is far less costly for the community than sending the sludge for landfilling!

- Response to Reviewer 4: No optimization of AD 1: Sewage sludge contains some parts that are easily digestible and parts that are recalcitrant (the first part is mainly primary sludge, while the second part is waste-activated sludge). Most conventional biogas systems in WWTF are operated with low solids loading and long retention times, which might be optimized, for instance, by operating at thermophilic temperatures instead of mesophilic conditions or by concentrating the sludge upfront; however, overall, this would not significantly affect the CCE of this treatment. We can optimize AD 2 and operate with high solids loading as demonstrated because of the changed rheology. The results from our biogas upgrading test are right now better than what has been published in the literature. The TEA needs the full process for understanding the impact of the different parts. For instance, it does not really make sense to model biogas upgrading without understanding the nature of the needed hydrogen source.

- Response to Reviewer 5: Thank you for seeing the impact of the project. Any destruction of PFAS: The team has planned to do some measurements of potential PFA/PFOS degradation during the pilot testing, which is currently in progress.

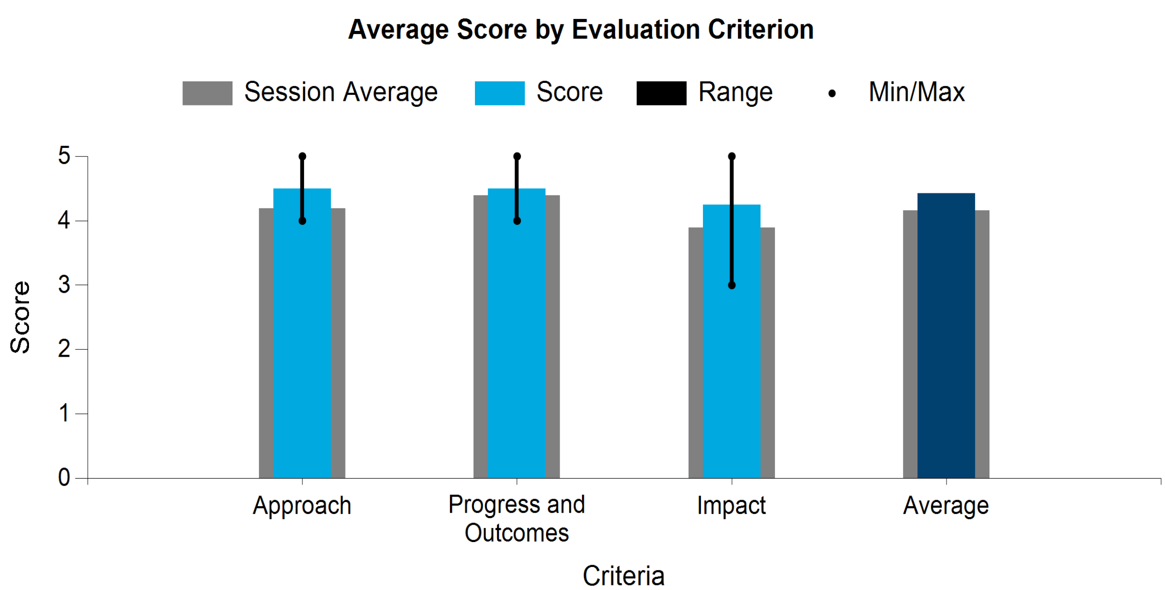
INNOVATIVE POLYHYDROXYALKANOATE (PHA) PRODUCTION WITH MICROBIAL-ELECTROCHEMICAL TECHNOLOGY

University of Maryland

PROJECT DESCRIPTION

WBS:	2.3.2.230
Presenter(s):	Stephanie Lansing
Project Start Date:	10/01/2020
Planned Project End Date:	03/31/2024
Total Funding:	$2,481,536

The project goal is to valorize food waste by shunting traditional AD toward value-added bioplastics (PHAs) to improve the economics of community-scale systems treating wet organic wastes. We are currently moving from intermediate verification to BP3 to meet our end goals of increasing value by 25% and carbon conversion by 50% (from 36% to 56%) through PHA formation from food waste compared to AD. This project valorizes wet organic waste streams for the bioeconomy and manages wastes locally, resulting in a profit from waste and increased sustainability. We have exceeded expectations for dark fermentation, with our robust bacterial consortium creating high VFA concentrations (>30 g/L) over long-term operation (>1 year), exceeding our 3-g/L target. The use of a novel *Haloferax mediterranei* bacteria effectively created extractible PHAs using a 78-day semicontinuous reactor, with a maximum polyhydroxybutyrate co-valerate (PHBV) content of 65% wt/wt and polyhydroxyvalerate (PHV) content of 10% wt/wt, exceeding our combined 30% target. The team of researchers from universities, national labs, and industry is overcoming challenges in blending high-salinity food waste for PHA production, which increases the profit margin and decreases the salt content needed for the halophilic *H. mediterranei* bacteria. The team will be the first to operate a continuous-flow reactor system (50 L) for PHA production from food waste for at least 100 hours, with TEA and LCA informing process effectiveness.



COMMENTS

- One would think there are numerous high-salinity water streams. Curious about the widespread availability of this feedstock, and if any are particularly better than others.

- PHA as a commodity good/product needs to be discussed. Does what is being produced meet industrial specs? Or is an organization willing to take off-spec?
- This project has commercial potential and will address BETO's goals of offsetting significant carbon intensity in plastics production. It also valorizes wet waste.
- Really promising piece on VFA concentration via dark fermentation.
- Have met all technical goals for BP2. The project team seems to coordinate well. Plans include DEI goals and staff investment in these outcomes. The project is advancing to BP3.
- Efforts around dark fermentation have been quite successful in advancing the state of knowledge.
- Commercialization efforts were not discussed, but should have been given the ending TRL.
- DEI goals have been well met. Engaged numerous underrepresented students of science backgrounds.
- Significant increase in VFA production—good job on the arrested methanogenesis piece.
- Seem to have made a lot of positive insights and adjustments as the project has progressed.
- The team has done good work socializing the research as part of the presentation. Will be good to get formal academic publications into the literature.
- Unit operations have significant time online, well beyond what is required for the project. Bodes well for commercialization.
- Would have liked to see more about the involvement/engagement of a partner in the commercialization. Curious about the timeline they see to get to market.
- Overview/impact/progress:
    - The researchers on this project apply a novel and innovative technique for the production of PHAs that are fungible with plastics from food waste. They combined microbial electrolytic technology and dark fermentation to optimize the continuous production of VFAs and PHAs. A lot of inventiveness is shown in the project, as the researchers made use of halophilic cultures (*Haloferax mediterranei*) to produce PHAs as opposed to conventionally used mixed cultures. The project is designed in such a way that the technique can be deployed beyond laboratory-, bench-, or pilot-scale experiments. Producing PHA from waste will help reduce the dependence on fossil fuel for plastic production, and since microbial-electrochemical technology produces a clean form of energy, it will also reduce the release of GHGs into the environment.
    - So far, within the past 3 years of its inception, the project has shown good progress and is on track. The intermediate verification of enhanced VFA and PHA production at the lab scale has occurred and was successful. Also, compared to baseline values, the applied technique in this project produces >100% increase in VFAs.
- Strengths: The steps outlined in this project have good flow and follow a logical pattern. The researchers showed the methods of the project in a detailed and concise manner. The project involves collaboration between researchers from different universities and industry experts, which results in cross-fertilization of ideas. In addition, the project incorporates the DEI plan of the BETO program as underrepresented groups comprise part of the staff.
- Weaknesses/question: Though the researchers have outlined different logical steps for the project, the characterization of organic wastes to be treated, which should be a major step before all other steps in the

project, is not included in the study. In the TEA model, the researchers made an assumption that the bioreactor will be a continuous stirred-tank reactor. Why? What advantages does it have over the types of reactors that it has to be used?

- The goal of this project is to produce PHA, a biodegradable, compostable polymer, from VFA derived from food waste. The project acknowledges BETO's goal of organic waste valorization at local scales of waste management. This is an important consideration for any tech dealing with food waste.
- The project team has integrated good DEI actions into their project staffing plan. Something to consider: When reporting DEI efforts, show denominators (e.g., of *X* students working on this project, *Y* are from underrepresented groups; of *XX* team members in professional roles on the project, *YY*% are from underrepresented groups), rather than listing staff by race and gender.
- Net revenue from PHA production was estimated at four times the cost of disposal. This is reasonable, as PHA markets are growing, especially in Europe, and increased demand is forecast. Should this project's approach be used with municipal food waste, ensuring community benefits from PHA production will be crucial.
- The goal of the project was to convert food waste into VFAs and PHAs (bioplastics). The work on the VFA production was performed at the University of Maryland, and then the conversion of VFAs to PHAs was performed at Virginia Tech. The TEA and LCA were performed at Idaho National Laboratory. The baseline comparison was traditional AD of the food waste.
- A portion of the project focused on high-salinity food wastes, which is something of a niche but also a nice opportunity. The research on the conversion VFAs to PHAs seemed to be rigorously tested under numerous conditions. This was excellent. The work was partially guided by the LCA and TEA results, which is a strength.
- Project management seemed to be good, and there were a number of DEI-related hires. The project partners (industry) appear to be well suited and strong participants.

PI RESPONSE TO REVIEWER COMMENTS

- We agree that this project is a novel and innovative method for PHA production, with the use of a halophilic bacterial strain at the pilot scale. As stated by the reviewers, this project has commercial potential and will address BETO's goals of offsetting significant carbon intensity in plastics production while valorizing wet waste. We also agree that the VFA concentrations achieved via dark fermentation are very promising and have advanced the state of knowledge, with positive insights as the project has progressed on track with operational capacity of more than 1 year (more than what was required). Additionally, as stated by a reviewer, the conversion of VFAs to PHAs was rigorously tested under numerous conditions. As stated, we have met all technical goals for BP2, with a logical project flow, solid project coordination, and real staff investment in meeting our DEI goals. In the future reporting of our DEI efforts, we will state that of the 18 team members in professional roles on the project, 22% are from underrepresented groups and 39% are female (rather than listing staff by race and gender). There are numerous high-salinity water streams available, which can be hard to properly dispose of or treat. As stated by one reviewer, having one portion of the project focusing on high-salinity food waste is a niche but also a nice opportunity. We assessed one high-salinity waste stream from one of Quasar Energy Group's current vendors. We are sourcing more high-salinity waste streams and comparing their performance on PHA production as part of BP3. High-salinity feedstocks can be fermented and produce VFAs to PHAs but are usually detrimental to anaerobic digesters due to the low salt tolerance of methanogens. Having an avenue to utilize this waste stream would be profitable. Properties of the real organic waste streams (both high-salinity and regular food waste substrates) have been properly characterized prior to feeding the fermenters, with the results included in the DOE quarterly reports.

Specifically, the regular food waste had the following composition (pH: 4.60; total solids: 24.6%; volatile solids: 23.5%; phosphorus: 1.95 g/L; total nitrogen: 7.15 g/L; ammonium: 0.03 g/L; sodium: 1.79 g/L). The high-salinity food waste had higher salt content, less volatile solids, lower nutrients, and a higher pH (pH: 10.04; total solids: 35.9%; volatile solids: 10.2%; phosphorus: 0.68 g/L; nitrogen: 0.25 g/L; ammonium: 0.0001 g/L; sodium: 113 g/L). For BP3, we will examine various blends of the two waste streams guided by the TEA, estimate the availability of the waste streams, and evaluate the value of processing more of the economically favorable high-salinity waste and reducing salt inputs for the PHA process against any reductions in overall PHA production with high salt inputs. Some companies, including our own partner Quasar Energy, have interest in our VFA-derived PHA polymers; however, they will need to have kilograms of products for testing and evaluation. We will invite industry partners to visit during our pilot-scale testing and evaluate the performance against their specifications during BP3. As PHA will be used as an ingredient for copolymer, the blending recipes can be tuned to meet the specification of the final product. As stated by one reviewer, the estimation of net revenue from PHA production at four times the cost of disposal was reasonable, as PHA markets are growing, especially in Europe, and increased demand is forecasted. As stated by the reviewer, when using municipal food waste, we need to be clear on elucidating the community benefits from PHA production. As stated by a reviewer, the work was guided by the LCA and TEA results, which was a strength. In the TEA model, the assumption that the bioreactor will be a continuous stirred-tank reactor was made because we designed based on experiments that used batch and sequencing batch reactors, and the closest continuous system to these systems is a continuous stirred-tank reactor. The specific advantage over other reactors is that it provides the residence time required for the reactor in a continuous mode of operation.

DENITROGENATION OF WET WASTE-DERIVED BIOCRUDE TO MEET SAF SPECIFICATIONS

Pacific Northwest National Laboratory

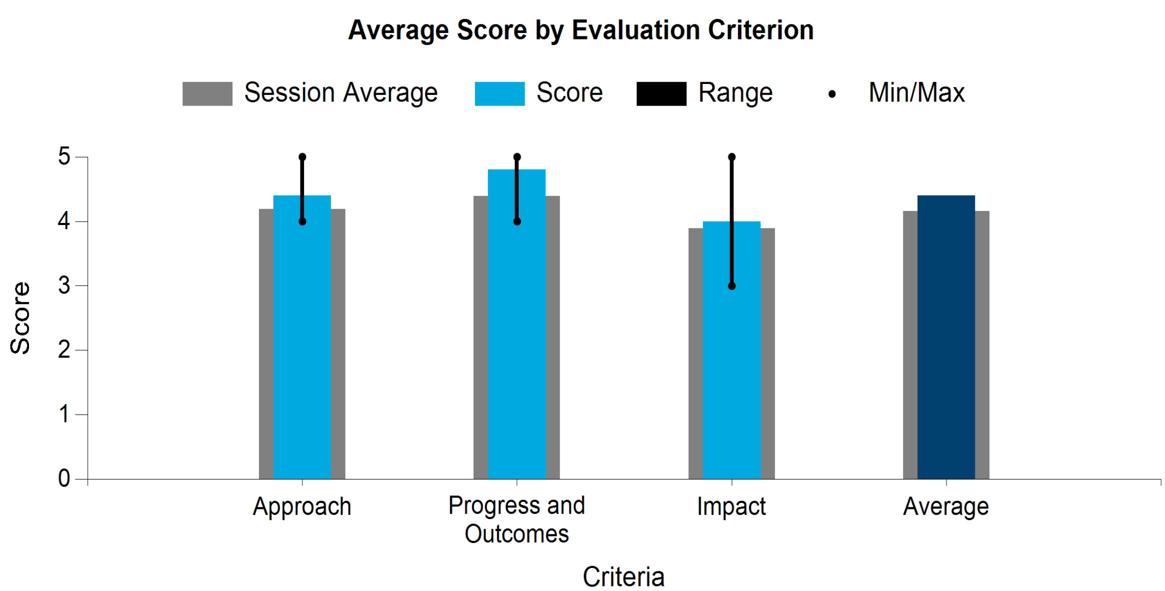
PROJECT DESCRIPTION

WBS:	2.3.3.301
Presenter(s):	Karthikeyan Ramasamy; Katarina Younkin; Michael Thorson; Michele R Jensen
Project Start Date:	10/01/2022
Planned Project End Date:	09/30/2025
Total Funding:	$1,155,000

Wet waste feedstocks have the potential to produce approximately 4 billion gal/yr of SAF (>20% of the total U.S. aviation demand in 2019) via HTL. We will enable the efficient conversion of wet wastes to SAF through HTL by addressing the key challenges associated with nitrogen removal and jet fuel yield in addition to studying the impact of nitrogen from HTL on SAF fuel stability. This project will address the following needs: (1) determine the impact of nitrogen (N) on fuel stability in SAF derived from HTL, and (2) develop a pathway to reduce the N content to <2 ppm.

Using the conventional approach, N-containing molecules are difficult to hydrotreat. This necessitates research to address the removal of these species or the addition of a polishing step to remove trace components to meet the ASTM requirement. In conjunction with Topsoe, we will demonstrate the ability to reduce the nitrogen content from 6 wt % to 2 ppm in a two-stage hydrotreater.

The N specification for all approved SAF pathways (synthetic paraffinic kerosene, synthetic isoparaffin, and alcohol-to-jet) is 2 ppm, likely because these pathways use feedstocks containing no N. Common guidance is that an HTL SAF specification should meet a 2-ppm N level based on precedent from other SAF pathways. No data on thermal stability for HTL SAF fuels currently exist, and this task will provide those data to help assess the importance of N reduction for fuel stability.



COMMENTS

- Early work on framing the topic is good. Clear what is being addressed. Did not spend any funds in FY 2022. Not clear why this project is being evaluated so early after starting.

- Plan looks solid with clear goals to get HTL SAF to something that is compatible with the existing market. Plan includes DEI goals.
- Important collaboration with an industrial catalyst company.
- Score reflects uncertainty on how to judge the impact of something so early in its life cycle.
- Preliminary progress was able to reduce N from 60,000 to 5,000 to 50 ppm. Confident they can meet the 2-ppm standard.
- Interesting conversation about N limit in jet fuel.
- Milestone should include preparation of the data for the ASTM standard for HTL-derived jet fuel. While PNNL cannot do it alone, this is too big of a barrier to commercialization to wholly ignore.
- Overview/impact:
    - The researchers assessed the use of HTL to convert wet waste to SAF to act as an eco-friendly substitute for jet fuel. They used hydrocracking to improve the yield and quality of the resulting fuel (reduced nitrogen content), thereby addressing a major limitation in nitrogen sulfur interactions in the use of biomass biofuel for jet fuel. Using biofuel as jet fuel will help reduce overreliance on fossil fuel and enhance the decarbonization of the aviation industry, thereby reducing the amount of GHG emitted by the industry.
    - Within a short period of time, the project has made appropriate progress toward addressing the project goals. The researchers were able to obtain about 25% of the upgraded fuel in the jet range and also reduced the nitrogen concentration from 60,000 ppm to 53 ppm in the produced SAF.
- Strengths: The researchers are collaborating with a plethora of industry partners who have different expertise and skills, which leads to cross-fertilization of ideas needed to improve the quality and suitability of the biofuel that will be produced. The researchers applied a DEI plan that involves hiring students from underrepresented communities and training PIs and task leads on diversity, inclusion, and belonging. Further, commercialization efforts are being made to increase the marketability of the biofuel that will be developed in the project. It is also commendable that the researchers were able to reduce nitrogen content in SAF by 97%, thereby increasing the stability of the SAF produced.
- Weaknesses: In presenting the tasks that have been carried out for the DEI aspect of the project, the researchers indicated that all the PIs and task leads completed courses on diversity, inclusion, and belonging with documentable action; however, it is not clear to me what documentable action was taken. Jet fuels have stringent fuel requirements, and the process of approving the fuel is very complicated. I am worried that this may limit the process of scaling up the proposed technique. Therefore, I am wondering if the researchers have carefully evaluated the approval process. And, if so, what steps have they taken in trying to overcome these approval process barriers? Further, the researchers proposed a novel approach for reducing nitrogen content in SAF so that all SAF pathways have a nitrogen spec of 2 ppm, which is a stringent jet fuel requirement. I am wondering if the researchers could try different feedstocks with low nitrogen content, as this may not complicate the process of reducing the N content in SAF. Second, the researchers should also consider assessing the economic viability of using different feedstocks with low nitrogen content. Last, I am wondering if the researchers have evaluated the feasibility of scaling up the process of reducing nitrogen content in the SAF to 2 ppm.
- This project tackles a timely and important topic of relevance to the conversion of treated wastewater sludge and other dirty wet waste feedstocks into usable fuels, specifically addressing the denitrification of fuels. The research team is making good progress on the project goals at this relatively early stage in

the project. DEI efforts and community engagement efforts can be strengthened beyond basic training and hiring one student, as noted in comments on the related WBS 2.2.2.302.

- This project focuses on the problem of nitrogen being in the waste during a WTE conversion via HTL. This problem is essentially unavoidable because virtually all organic wastes will have some nitrogen content (i.e., it is part of most cellular material). Simultaneously, the presence of this nitrogen is a major bottleneck for the production of SAF from organic wastes.

- The team does a really nice job of handling DEI. Like other projects, they try to hire a diverse group of people. Beyond that, though, they require DEI training for all project personnel, which I like because it is tangible.

- The initial progress of this research is fantastic. The investigators have been able to reduce the N levels to approximately 50 ppm at an estimated cost of $0.04/GGE. Similarly, the HTL of sewage sludge also appears to be insensitive to the presence of the PFOS, which should likely partition to the biofuel and then be combusted during flight. This latter issue is much more attractive than applying sewage sludge to land, where the PFOS could enter the food chain.

- The project seeks to understand additional barriers to nitrogen sulfur interactions on fuel thermal stability and to achieve stringent fuels standards. Compositional changes in Jet A/A-1 fuels would delay the introduction of sustainable/decarbonized fuel deployment. SAF needs to meet ASTM fuel specification D7566-18, but no nitrogen content (derived from organics) is typically present in fossil fuel Jet A.

- Samples indicate an average of 2 ppm in fossil Jet A, and many partners have provided input for the project in the initial 6-month stage to guide research needs, including N reduction testing, analysis, and the assessment of economic viability of the reduction to determine what is the acceptable N content in SAF. Minor quibble, but recommend researchers continue to investigate barriers in aviation alternative fuel deployment and policy barriers (e.g., unleaded general aviation fuel has recently been approved by the Federal Aviation Administration, yet challenges to its deployment nationwide remain).

- If SAF standards are achieved on par with existing Jet A/A-1 fuels, significant GHG reductions will be possible, quicker, through the use of existing infrastructure and approved equipment, providing beneficial outcomes for the performer and the government. Promising early results in N reduction indicate further N reductions are possible and to what extent those reductions are needed. Excited to continue to see research progress, given the work and accomplishments achieved in the first few months of the project.

- The project has demonstrated actionable DEI outcomes from training to improve hiring questions, and it strives for a more inclusive research environment.

PI RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their valuable feedback. We appreciate the positive comments and the recognition of our early progress in addressing the challenges associated with nitrogen content in HTL for SAF. We would like to address the comments based on the different topics raised.

- Framing and goals: “Early work on framing the topic is good. Clear what is being addressed. Did not spend any funds in FY 2022. Not clear why this project is being evaluated so early after starting.” We are glad to hear that the early work on framing the topic was well received and that our goals are clear. We acknowledge the concern about the evaluation timing, as the project kicked off in FY 2023. Hopefully, in the FY 2025 Project Peer Review, we will be at the end of the project cycle and will have a lot more to update the committee on.

- DEI efforts: "In presenting the tasks that have been carried out for the DEI aspect of the project, the researchers indicated that all the PIs and task leads completed course diversity, inclusion, and belonging with documentable action; however, it is not clear to me what documentable action was taken." We appreciate your recognition of our commitment to DEI. Two actions after completing DEI training included creating consistent interview questions for candidates to eliminate bias in the hiring process and participating in a seminar workshop series at Columbia Basin Community College, a minority-serving institution, to share examples of pathways into STEM.
- Nitrogen reduction and fuel standards: We appreciate the concerns raised by the reviewers regarding the complexity of the fuel approval process and the need to carefully evaluate and overcome the barriers associated with meeting stringent fuel standards. We are committed to meeting the stringent jet fuel requirements and ensuring that our SAF complies with the ASTM standard for HTL-derived jet fuel. Further, we are actively engaged with industry partners and fuel testing experts regarding the fuel approval process, which is why we are focusing on thermal stability testing of the produced SAF.
- Feedstock selection and economic viability: We have completed extensive HTL and upgrading of organic wet wastes and have found that all classes of organic wet wastes include nitrogen in the biocrude because all organic wet waste classes contain proteins. Wood or cellulosic feedstocks not containing nitrogen are a very different value proposition. While this is an exciting area of research, we believe that the waste disposal advantages of organic wet wastes make it a much more attractive feedstock for HTL.
- Scaling up and approval process: We acknowledge the concerns raised about the scalability of the process for reducing nitrogen content and the complexity of the approval process. As such, we are limiting our denitrogenation to using existing hydroprocessing unit operations, and hydrotreaters focused on hydrodenitrogenation, such that this process will be scalable at refineries.

ELECTRO-ENHANCED CONVERSION OF WET WASTE TO PRODUCTS BEYOND METHANE

Colorado State University

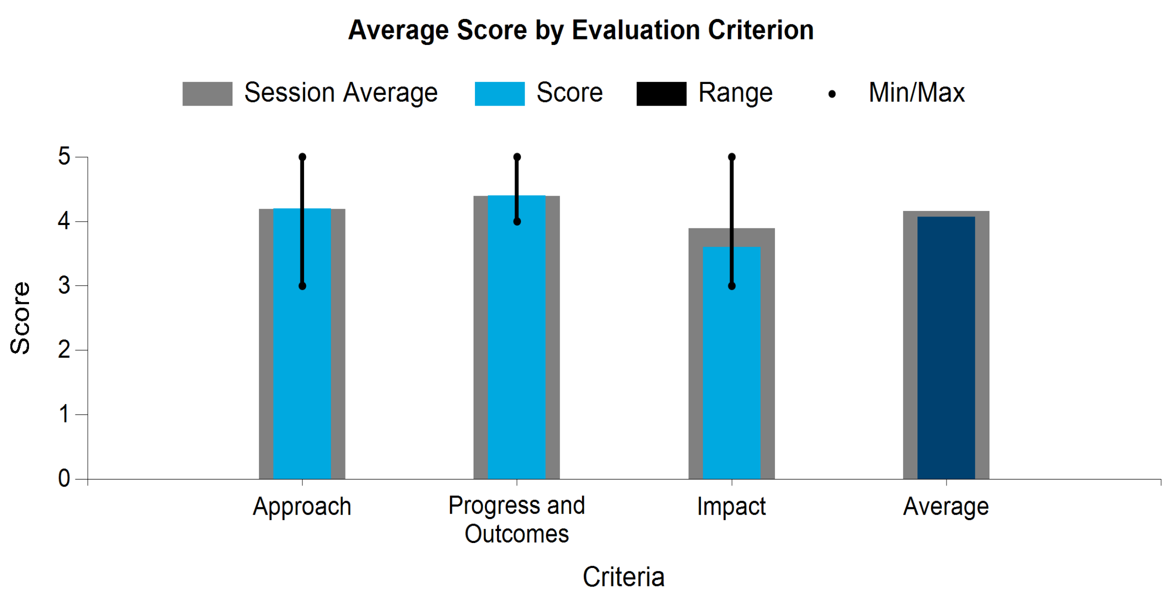
PROJECT DESCRIPTION

WBS:	2.3.4.605
Presenter(s):	Ken Reardon
Project Start Date:	10/01/2019
Planned Project End Date:	10/31/2025
Total Funding:	$6,335,445

Wet organic wastes present problems in disposal cost and environmental impact and represent lost opportunities as inexpensive feedstocks to displace fossil-based products. AD, composting, and incineration strategies are limited by their CO_2 production (wasted C) and low-value/uncaptured methane production. Surplus renewable electricity could provide inexpensive electrons to enhance wet waste processing and generate drop-in liquid transportation fuels.

The goal of this project is to improve wet waste conversion by inhibiting methanogenesis, increasing the production of VFAs, and elongating VFA chains to produce higher-value medium-chain fatty acids and iso-butanol. This interdisciplinary project is designed to achieve the project goal through four objectives: (1) enhance VFA production in AD, (2) upgrade AD gaseous and liquid product streams, (3) evaluate and optimize the system to assess economic viability, and (4) integrate education with research.

Technical accomplishments to date include the identification of conditions yielding high VFA levels, including high levels of C4 and higher acids; the conversion of acids to alcohols using synthetic biology; the development of software that relates microbiome composition to VFA production; the demonstration of scale-up from 2-L to 600-L bioreactors; and TEA and LCA based on a comprehensive process model.



COMMENTS

- Significant figures seem to change in the goals. Is that level of precision even necessary or real?
- Good use of TEA/LCA to identify inoculum that has an MFSP that meets the goals of this project.

- Significant improvement demonstrated in most metrics, particularly around C6–C8 production.
- Approach to improving upon AD seems to be fairly all-inclusive of ideas/techniques.
- The omics analysis in the backup slides looked quite interesting.
- There did not seem to be any conversation about the commercialization or other entity. Leprino Foods just seems to be an interested party, but not the commercialization party.
- There is a lot of outreach with undergraduates and students as well as strong communication activities.
- The team relies a lot on the basics of this project for impact—that is, it is a bit more detached from the real implementation and commercialization that would be needed to take something like this to market. A more nonacademic/non-research-focused partner would help provide the necessary advice.
- AD is a commercial technology; improvements should be easy to commercialize. The difficulty is that this changes the unit operations and products significantly enough.
- Looking at adding CO_2 to drive additional VFA production.
- Looking at process intensification, combining some of the unit operations, and potentially avoiding separations.
- Overview/impact/progress:
  - In this project, the researchers are using renewable electrons to facilitate targeted pathways in the AD of wet organic wastes (manure and food wastes) to produce energy and other high-value products, such as hexanoic acid and alcohol. This is a very insightful and innovative project. The project will help in reducing GHGs that emanate from the AD process. Apart from the environmental benefits of the project, it also has economic benefits as the LCOE can be enhanced with it. The researchers demonstrate a lot of technical expertise as they apply avant-garde techniques such as arrested methanogenesis, electro-enhanced AD, and electro-elongation of MES to increase the quantity of VFA that can be generated from the AD process. The researchers also employ advanced molecular biology techniques to improve the efficiency of the process.
  - The researchers have made a lot of progress in this project, and the results provided in the presentation show that the implemented technique is exceeding the set target values; greater than 50% increase in VFA production was achieved.
- Strengths: The researchers clearly outlined the steps that are being used in the project in a detailed and concise manner. They also provided means through which the results of the project can be verified and validated to ensure that it is economically feasible. In addition, the project provides hands-on practical training for undergraduate, graduate, and postdoctoral students who are participating in the project and helping to disseminate the results of the study to their colleagues.
- Questions: In reporting the progress of the work in slide 22, the researchers state that they constructed *E. coli* capable of converting C4–C6 acids to alcohols. I would like them to give more elaboration on what they mean by constructed *E. coli* and how this will be used in scaling up the technique. In addition, it will be great if the researchers can investigate further why the amount of VFA generated using only food waste as the substrate is higher than that generated when food waste and animal manure are co-digested; could it be that co-digestion is not suitable for the process? In the economic analysis, the researchers should try to compare the benefits of producing VFA from the AD process to those of producing methane.

- The goal of the project is to improve the efficiency of wet waste treatment through AD by maximizing VFA production and conversion to commodity fuel blends and chemicals. The researchers made good progress and met milestones toward project goals. A few suggestions. First, the project mentions "renewable electrons." In future presentations, especially to nontechnical stakeholders, researchers should take care to fully contextualize and define this term to avoid confusion with renewable energy as commonly understood. Second, the research team is to be commended for inclusiveness and outreach among students. As the project progresses, they should build on this work to proactively seek to include students at the high school through Ph.D. levels, in particular students from underrepresented backgrounds, including outreach to HBCUs and universities serving tribal communities and students.

- This project is relatively early in its time frame. It involves personnel at Colorado State University, South Dakota School of Mines, University of California Irvine, and NREL. The project management seems to be good. There are numerous project partners, but there are strong ties because there is sharing of data, methods, and materials among partners. There are biweekly meetings (electronic).

- The goal of the project is to make medium-chain organic acids and alcohols from organic wastes (food waste and animal manure). Solid-liquid separation is achieved via centrifugation. The production of VFAs is achieved by optimizing pH and identifying the appropriate inoculum (termites!). Cathodic electro-fermentation is used to produce the medium-chain organic acids and alcohols. A lot of work has been performed in optimizing the inoculum. I am skeptical of this work, specifically because it essentially is trying to extrapolate 16S rRNA gene profiles (i.e., microbiome) to "metagenomic" information, although it is well understood that suggested metabolic potential via 16S rRNA gene sequences is likely spurious (with a few exceptions that do not apply to this situation).

- The work has met its pertinent milestones to date. The work is also guided by LCA and TEA, and there appears to be good adherence to DEI principles.

- Research targets arrested the AD process to develop more refined pathways for organic waste conversion to products other than methane. Products include needed precursors for chemical manufacturing/fuels or blendstocks of fuel products, which can diversify organic waste revenue streams in volatile energy markets with changing policy incentives.

- Researchers have investigated improved microbial biomes to increase VFA production, yielding higher productivity of VFAs. The microbiome scales well to larger reactors. Testing of microbiome community has found interesting susceptibility to shear in the population, but given that mixing adds complexity and cost to AD of organic waste, it would serve to only lower TEA and LCA of potential future deployment.

- Recommend partnership with other industry or municipality to investigate the technology's applicability to other waste streams (e.g., use of microbiome with termite gut bacteria, although useful in high-lignin feedstock, may impact VFA results when processing other wastes).

PI RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their thoughtful comments, and we appreciate that they have recognized the innovation of our project and the progress we have made. In the following paragraphs, we provide responses to these reviewer comments.

- Commercialization partner: We are searching for an appropriate partner to commercialize our findings. As noted, the process we are developing would present changes to standard unit operations, and thus not all current AD technology providers will have an interest.

- DEI: We appreciate the suggestions for enhancing the diversity and inclusion aspects of our project. While the FOA under which our project was funded did not have a DEI requirement, our team is committed to the principles of DEI. We make efforts to recruit a diverse set of students, especially undergraduates, to participate in this project, and our outreach efforts at Colorado State University's Spur campus in Denver allow us to connect with K–12 students and their families from a wide range of backgrounds.

- Research scale: One reviewer commented that our work is at the level of basic research and is detached from real implementation; however, we have already conducted experiments at 700 L in a pilot-scale bioreactor with a capacity of 2,000 L, and more research at this scale is planned for BP3.
- Information on the strain developed for alcohol production: An *E. coli* strain has been metabolically engineered to convert organic acids to alcohols. Two pathways and a variety of sources for each enzyme in each pathway were evaluated. The best strain from this work has been shown to convert C2–C6 organic acids to the corresponding alcohols and to be tolerant to both electrodialysis-purified digestate and the digestate itself. Current research is directed toward developing a bioreactor configuration that would allow this strain to be used in a scaled-up bioprocess.
- Higher yields of VFAs from food waste than from co-digestion of food waste and manure: The reason the yields are lower in the co-digestion case is that yields from manure are lower. This is a common observation that stems from the lower content of readily digestible carbon in manure compared with food waste.
- Economic analysis: A reviewer suggests that we compare the benefits of producing VFAs (and alcohols) to standard biogas production via AD. We are doing that analysis because it is our baseline case for calculating the improvements that are among the project metrics. The TEA presented focused on the economic trade-offs of different pathways because that information helps steer our experimental work.
- Inoculum optimization: A reviewer commented that inoculum optimization from 16S data may have challenges because it assumes an accurate extrapolation from phylogenetics to metabolic potential. This is a reasonable concern, and we are aware of that potential limitation; however, our modeling incorporates our experimental data and some published metagenomic data, and the results to date are encouraging. All methods have limitations. For example, the best approach for inoculum modeling would be multi-omics analyses that include proteomics—but this would be very expensive and time-consuming. We seek to extract information from methods that are simpler and less expensive, but we are also incorporating some data from methods that provide more detail and accuracy.

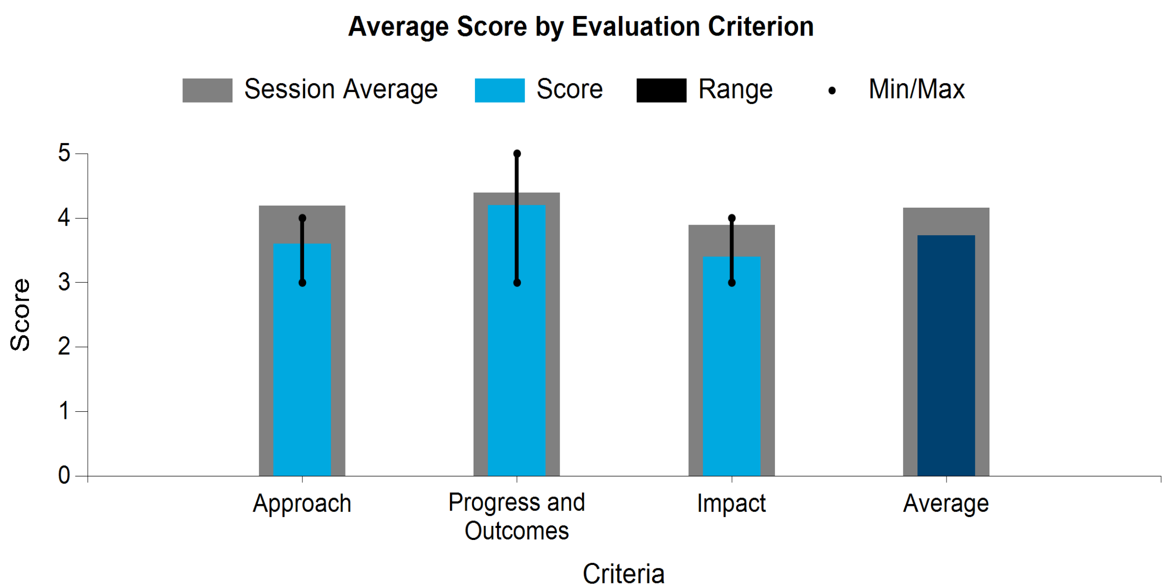
SYNERGISTIC THERMO-MICROBIAL-ELECTROCHEMICAL APPROACH FOR DROP-IN FUEL PRODUCTION FROM WET WASTE

Princeton University

PROJECT DESCRIPTION

WBS:	2.3.4.609
Presenter(s):	Jason Ren
Project Start Date:	10/01/2020
Planned Project End Date:	03/31/2024
Total Funding:	$3,124,665

The overarching goal of this project is to develop a synergistic thermo-microbial-electrochemical process that converts food waste to jet fuel blendstocks and simultaneously treats aqueous wastewater, thereby recovering H_2 and nutrients. The project will utilize HTL to convert food waste into biocrude. The biocrude wastewater will be processed in a microbial-electrochemical process that utilizes microbes and electricity to generate H_2, NH_4^+, and clean water. The H_2 generated from the microbial-electrochemical process will be utilized for hydrotreating/upgrading the biocrude into jet fuel. The outcome of the project will be the continuous operation of a process on 1 ton of wet food waste that encompasses all technologies developed to achieve >50% CCE improvement and/or 25% levelized cost of disposal reduction relative to traditional AD.



COMMENTS

- Lot of work framing the progress against the current baseline, and really helping to showcase the importance of the project.
- Clear focus on the cost of a material versus performance. Quite interesting that base metals for 1% of the cost are performing relatively similarly. This helps to make a big difference in the final selling price.
- Cathode alloys show significant progress beyond what has been demonstrated by other efforts for electrolyzers/electrolysis.
- The project's HTL shows improvement over AD for CCE.

- Project decisions have an eye on commercialization, but does not appear to be pursuing it.
- Team is tackling one of the major issues with HTL in aqueous waste.
- The HTL element of this project does not seem to be pushing the envelope.
- DEI elements were briefly discussed, involving students and PIs underrepresented in STEM. Working to incorporate even though it was not part of the original scope.
- Did not spend time speaking about management/communication plan, but did not appear to be any concern.
- Some of the graphics, particularly the Sankey diagram, are quite instructive. Others are a bit dense and require a bit more explanation than can be had by reading slides.
- Team seems to be coordinating well, but is struggling with a bit of geographic dispersion.
- In this project, the investigators simultaneously convert food waste to jet fuel using a synergistic thermo-microbial-electrochemical process and recycle HTL wastewater by using it as substrate for the HTL process, thereby producing hydrogen and nutrients as byproducts. The project is aimed at improving carbon yield by >50% and reducing waste processing costs by >25%. This is a very interesting and unique project. It not only deals with the generation of energy from food waste through HTL, but goes a step further to find solutions to the problem of disposing of the resulting wastewater from the process. The project is unique in the sense that not so many studies look at the post-treatment/utilization of waste generated from energy generation. Also, the project incorporates a closed-loop circular economy approach where everything generated is still recycled within the same system, and this is highly commendable. Apart from having environmental benefits, it also has economic benefits as it reduces the cost of energy generation. A lot of benefits will accrue from implementing this project on a large scale.
- So far, the project has shown tremendously good progress. In the microbial-electrochemical cell, one day was enough to remove most VFAs and alcohols from the liquefaction wastewater, the CCE of food waste used in the process is more than 50% that of the conventional AD process, and the chemical oxygen demand (COD) removal efficiency is greater than 90%.
- Strengths: It is very impressive that high-purity hydrogen was recovered during the treatment of post-HTL wastewater, and there was also very strong degradation of the organics present in the wastewater. Apart from carrying out laboratory experiments, the researchers go a step further by carrying out TEA and LCA for the project. The project has patents, publications, presentations, and awards, which show how good the project is.
- Question/weaknesses: The researchers stated that two types of post-HTL wastewater (PHW) were tested with the microbial electrolysis cells (slide 12). I want the authors to throw more light on this by stating the two types of PHW that were tested. In the same slide 12, the researchers indicated that the microbial-electrochemical cells will generate hydrogen gas during the treatment of the liquefaction wastewater while removing organic pollutants from the wastewater; however, throughout the PowerPoint presentation, nothing was mentioned about quantifying the organic pollutants present in the wastewater before and after treatment.
- This project seeks to improve the CCE of food waste in an HTL process generating biocrude as an output. A particular strength of this project is that it addresses wastewater arising from HTL. The reduction of COD and N in PHW is an important topic. The LCA presentation of the proposed technology, compared to AD and HTL with upgrading, shows improvements in ecotoxicity, eutrophication, and global warming potential compared to one or both alternatives.

- For applied settings, the process relies on clean food wastes. Should the project seek feedstock from curbside collection of source-separated food wastes, attention to contamination with plastics, as well as potentially other materials, should be taken into account.

- The DEI approach can be strengthened in future phases of this project. The team should proactively seek students between the high school and Ph.D. levels to support this team, and it should organize educational outreach to engage HBCUs in this process in particular. In general, more information on industry engagement and commercialization potential, as well as procedures to ensure communication among project partners, would improve this project.

- The goal of the project was a more holistic approach to HTL of food waste. The researchers used a couple of representative food waste simulations and then performed HTL with the subsequent treatment of the waste streams of the HTL. The focus of the entire process is on higher CCE and reduced energy costs for treatment. A goal of the waste treatment portion of the project was to convert remaining carbon compounds to molecular hydrogen. The authors conclude that microbial electrolysis cell and HTL leads to better CCE than AD of food waste. There was a good emphasis on TEA, which the researchers seemed to use to guide their research as they met various milestones.

- The project appears to be meeting its goals (albeit I cannot really critically evaluate this conclusion because I did not understand the presentation). There are multiple project partners, who had their first in-person meeting as part of the BETO presentations. The speaker claimed to have met various DEI metrics but did not provide details.

- Interesting concept with a compact, modular thermal-microbial-electrolysis cell to treat HTL aqueous wastewater, recovering H_2 and nutrients.

- The research has considered TEA by investigating lower-cost catalysts with base metal to provide lower-cost options to optimize organic waste streams. Organic wastes are sourced from a number of partners to investigate the applicability of this technology to various waste streams. The technology is cost-competitive with AD at facilities above a 50-ton/day limit but has a positive LCA, as natural gas inputs are required for operation (could this system take advantage of local renewable energy to replace natural gas inputs?).

- As more investigations continue, recommended valorization of nutrients recovered through the process that may further reduce costs or reduce LCA due to the offset of fossil-derived nutrient removal and reuse.

PI RESPONSE TO REVIEWER COMMENTS

- We appreciate the positive and constructive comments from the reviewers. All reviewers commented positively on the value of the project and the progress made to date, and we are grateful for the feedback. The reviewers raised a few questions regarding technologies, DEI, and analyses, and we address them here. Regarding the HTL tasks pushing the technology envelope, we will perform additional HTL pilot runs in Phase 3 to obtain additional biocrude oil and PHW for downstream processes. Using a rotating furnace (in development), we will investigate the mixing effect on HTL performance in terms of conversion efficiency, oil quality, and char formation. We are currently conducting the catalytic hydrotreatment of HTL biocrude oil based on PNNL's work, with the first set of experiments completed. We have also identified the key steps for upgrading HTL biocrude to the jet fuel standard. Regarding organic removal in microbial-electrochemical treatment, we did not get a chance to provide many details in the presentation. Here, we add some results regarding the removal of organics in PHW. More data presentations can be found in our manuscripts. We characterized the COD of PHW from salad dressing PHW and food processing PHW, and in both cases, the COD removal was gradually increased 80%–90% in several days. We also characterized the transformation of different organics during microbial-electrochemical treatment. High-performance liquid chromatography and nuclear magnetic resonance results showed sequential glycerol fermentation to VFAs and subsequent microbial-electrochemical VFA degradation. Regarding the DEI metrics, we strove to recruit and retain students with diverse backgrounds, and our leadership team has a good balance of gender, race, and ethnicity. We have been active in increasing the diversity of our team members. We have multiple female graduate and undergraduate students in the project. Our labs host visitors and open houses about our research to high school students multiple times per year. In addition, the project supports and aligns with the Justice40 Initiative because it aims to collaborate with a school and a food manufacturing company seated in a disadvantaged geographic area in the Champaign-Urbana, Illinois, region. The project takes food waste from a food manufacturer within an identified disadvantaged area. The disadvantaged community will benefit from the reduction in GHG emissions created when this unused food goes to landfills. Regarding the positive LCA and replacing natural gas with renewable energy, we have performed more analysis. The proposed technology has higher electricity requirements compared to AD, which means that the reduction in the environmental impact associated with the use of renewable electricity will be more pronounced for the proposed technology relative to AD. We do acknowledge the limitation of the analysis, as we only considered electricity source without counting other factors such as CH_4 process emissions from AD, chemical uses, and others. We expect that efficiency improvements in the processes studied in this project will result in parity in these LCA measures.

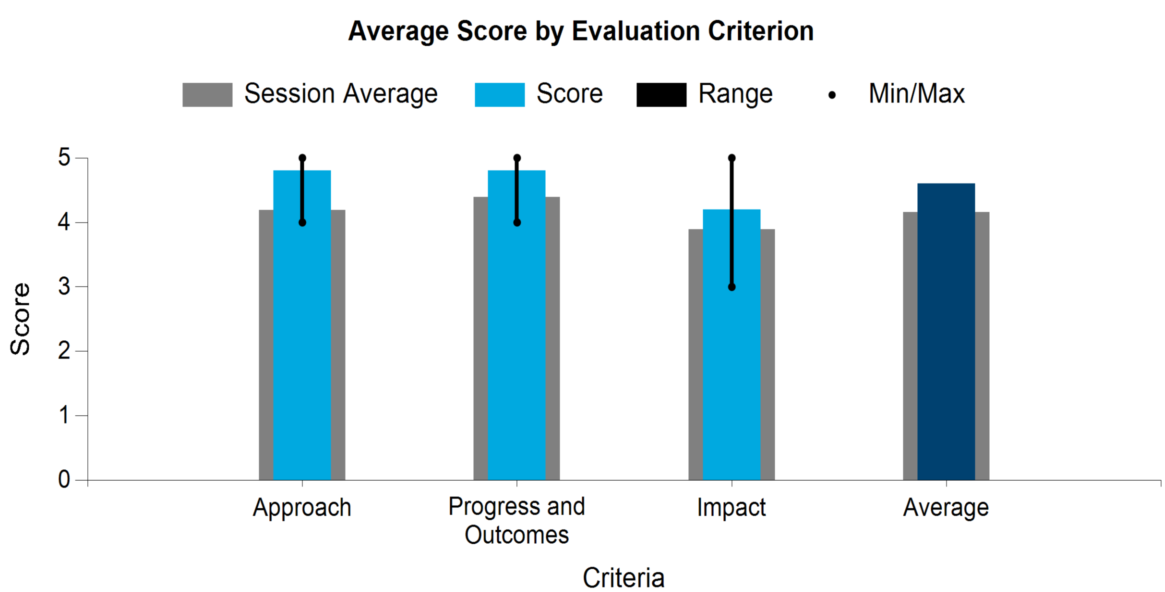
INTEGRATED BIOCHEMICAL AND ELECTROCHEMICAL TECHNOLOGIES TO CONVERT ORGANIC WASTE TO BIOPOWER VIA NORTH AMERICAN RESEARCH AND EDUCATIONAL PARTNERSHIPS

University of Michigan

PROJECT DESCRIPTION

WBS:	2.3.4.611
Presenter(s):	Lutgarde Raskin
Project Start Date:	10/01/2020
Planned Project End Date:	01/31/2027
Total Funding:	$6,790,983

In this project, we aim to reduce the production cost of pipeline-ready biomethane from urban and suburban organic wastes by at least 25% via the demonstration of a pilot-scale system with integrated biochemical and electrochemical technologies, making bioenergy production more market competitive. The system combines three modular components to achieve this goal: A two-phase anaerobic dynamic membrane bioreactor system produces biogas from mixed organic wastes at high yields and production rates; an electrochemical reactor for CO_2 and H_2 delivery purifies the biogas by capturing CO_2 as HCO_3^- and simultaneously produces H_2; and a gas-phase methanogenesis bioreactor converts captured HCO_3^- and H_2 to high-purity CH_4. Each component involves significant innovation compared to the state of the art. A primary challenge of this project is the integration of the three components, which requires diverse technical backgrounds. We address this challenge by establishing strong collaborative programs to facilitate knowledge transfer between research and industry partners, including technical meetings, student co-mentorship and exchange, course development, internship opportunities, and consortium meetings and symposiums. This project will help BETO achieve its Multi-Year Program Plans to “validate proof of performance at integrated pilot, demonstration, and pioneer scale” and “reduce biorefinery capital and operating costs.”



COMMENTS

- Very impressed with the early progress and the preparation for piloting at a real WRRF. Impact is as expected for the moment; will be much stronger after the completion of the planned pilot.

- Commercialization potential is present, but is not discussed at this stage. Not expected, as it is still early.
- Motivation is strong to address this challenge because the issue is commercialized in many markets. Marked improvements like this with regard to AD would make the technology more widely commercialized.
- Have done several things to address DEI, including education and outreach.
- The team has made solid progress toward their goals. Have met their target/interim goals on the project. Actually seems to be doing even better.
- I'm assuming that the proposal detailed how these goals would lead to the 25% reduction, but would like to see a brief summary in this presentation to recap.
- Solid management and feedback processes involving numerous stakeholders.
- Doing a lot of co-siting of project meetings to educate beyond the project team.
- Missing a high-level discussion on some of the operating principles of these units. Curious to better understand implementation strategy (retrofit vs. new).
- AD is being run at mesophilic temperatures, making these data more impressive.
- Risk discussion is focused on the integration of unique unit ops. Doing a lot to build trust and relationships between the partners (monthly meetings, work-study program, student exchanges).
- Looking at each of the unit ops as both independent and collective items. As the modeling is done, I would be curious to see these scenarios spelled out.
- Overview/impact:
    - This project is investigating the conversion of organic wastes to biopower using integrated biochemical and electrochemical technologies. Three extremely innovative techniques—a two-phase anaerobic dynamic membrane reactor, an electrochemical reactor, and gas-phase methanogenesis—were applied to improve the hydrolysis process, enhance the efficiency of biogas production, and improve the purification process for methane. The project focused on producing renewable energy from organic wastes at a reduced cost, which is a key consideration in scaling up the techniques applied. Further, the proposed techniques present environmentally friendly ways of converting organic wastes to biomethane, thereby reducing the production of carbon dioxide and the GHGs released into the environment.
    - Considerable progress has been made in this project, and the results obtained speak volumes about the efficiency of the applied techniques, as they have achieved production rates beyond the target values. The researchers have been able to achieve greater than 94% carbon dioxide capture, improved methane and volatile fatty production, and reduced the amount of power consumed during the AD process to less than 12 kWh/kg CO_2.
- Strengths: One component of the project involves the electrochemical conversion of electricity to bioenergy; this presents a highly efficient and easily utilizable method for storing energy when surplus electricity is produced. In addition, the project involves a synergistic collaboration between researchers from different universities who have different areas of expertise. This promotes the cross-fertilization of ideas and improvement in the quality of the output of the project. Another commendable aspect of the project is that it includes a mentoring plan for students through symposiums and conferences. The results

of the project are also incorporated into online courses, bringing about research-led teaching activities. Importantly, the project has made substantial efforts in promoting DEI.

- Question: Though the project involves a collaboration between partners with different areas of expertise, there is a need to provide more clarification on how the techniques from the different partners are interconnected in the project.
- Recommendations: The researchers tested their technique using food waste and sludge as feedstock; it will be great to know if the technique will also provide suitable performance for other types of feedstock. Even though the project involves conducting AD in a mesophilic state, the results obtained are very impressive. This implies that if the researchers make use of thermophilic temperatures, better results will be obtained; however, I can understand that this was not the goal of the project, as they wanted to mimic the rumen conditions. Further, the researchers should try to see how they can retrofit existing AD systems/plants with their techniques.
- The project seeks to improve biomethane production from AD of food waste by addressing recalcitrant (fibrous) fractions of this feedstock. Its research question is clear and well focused. Other strengths include good integration of a multicomponent process, with regular communication and coordination among multiple stakeholders. There is an excellent focus on workforce development, engaging with minority-serving institutions and institutions in Mexico, and offering bioenergy online courses in the context of socially engaged design.
- These researchers are attempting to integrate a handful of novel biotechnologies to convert organic wastes to high-purity methane (RNG). Each individual technology is reasonably novel, and the researchers explicitly admit that integrating these technologies together poses a significant challenge.
- The management of the project seems to be excellent, especially given that there are researchers at the University of Michigan, Northwestern University, and Argonne National Laboratory. There are regularly (monthly) meetings between project personnel, as well as less frequent in-person meetings. I particularly like that the research appears to be quasi-iterative in that process modeling partially drives the experimental design, the results of which (presumably) help improve the modeling effort. The LCA and TEA efforts appear to be ongoing.
- DEI goals are met via collaboration of multiple and diverse partners, grad student exchanges, and the development of online courses.
- I am generally very optimistic about the chances of this project for long-term success. My biggest "criticism" at this phase is basically an acknowledgement that predictions are not facts, and this project is still relatively early in its process and development.
- Research into electrochemical and biology biogas upgrading technologies represents a leading edge of research work with few technology providers that offer cost- or energy-efficient upgrading options. Developments could significantly improve the net performance of biogas derived from all organic streams of waste given the expensive and energy-intensive systems currently in operation, offering beneficial outcomes for the performer and government. But more information is needed about the optimization challenges of the electrochemical reactor for CO_2 and H_2 delivery and gas-phase methanogenesis bioreactors as they move into testing phases.
- High-lignin waste streams significantly impact the ability to digest waste streams without significant upfront sorting, at the expense of additional energy inputs and time (reducing organic waste conversion rates). Is it possible to quantify the benefits not only in improved organic waste conversion but also in streamlining organic waste processes?

- Improving the hydrolysis of lignocellulosic components would improve the applicability of AD to process organic waste streams that are not currently feasible. A breakthrough in this area could greatly impact the amount of bioenergy available from waste by forgoing the energy, time, and expense of sorting out high-lignin streams of waste. Additionally, given the typical high cost of refining biomethane resources into pipeline-quality gas, this research area has the potential to reduce cost across the bioenergy economy spectrum. The goals of this project could impact the initial and final steps of the bioeconomy. It will be exciting to see this research as it moves forward into the pilot-scale phase.

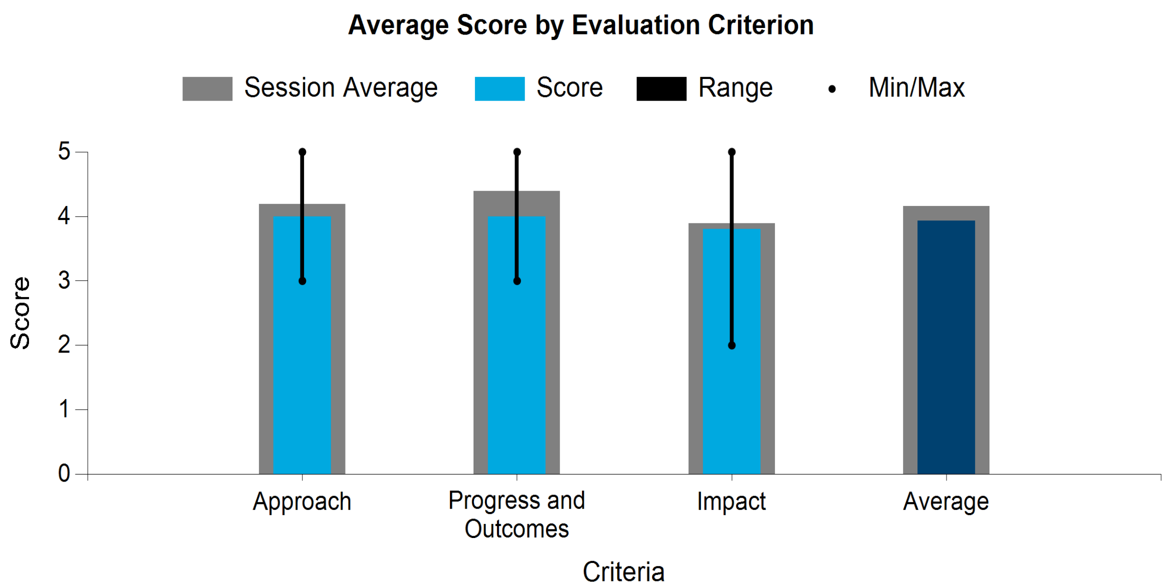
UPGRADING BIOGAS THROUGH IN SITU CONVERSION OF CARBON DIOXIDE TO BIOMETHANE IN ANAEROBIC DIGESTERS

Washington University in St. Louis

PROJECT DESCRIPTION

WBS:	2.4.1.500
Presenter(s):	Zhen He
Project Start Date:	10/01/2021
Planned Project End Date:	04/30/2025
Total Funding:	$2,881,916

This project aims to develop an innovative system for the *in situ* biological conversion of CO_2 to CH_4 through integrating several existing processes/technologies—such as membrane-supplied H_2, thermoelectricity, and microbial-electrochemical systems—in innovative and synergistic ways to ensure both novelty and a high chance of success. At the end of the project, an integrated bench-scale system will be able to produce pipeline-quality RNG containing >97% CH_4 via two steps: biological CO_2 conversion to CH_4 that generates a biogas of >95% CH_4 and gas cleaning that reduces impurities and further enhances the CH_4 content to >97%. Our target CO_2 concentration in the final RNG is <1%. The H_2S content will be kept below 5.7 mg/Nm^3 (or 0.25 grains/110 scf). Advancements in research and development, as well as a holistic understanding of the potential impacts of system deployment across economic and environmental indicators, are critical to the successful transformation from bench-scale to transitional-scale systems (i.e., not yet pilot scale). In this project, a multidisciplinary and multi-institute team is built to jointly advance the proposed technology. The potential technology users/stakeholders will be involved in the early-stage research and will attract more users/stakeholders in its further development. This project will act as a bridge to transform basic research toward further technological development.



COMMENTS

- Not clear on the inclusion of the H_2/CO_2 ratio, as that trend line seems to not be a good fit. Understand that a 4:1 ratio is ideal, but there seems to be very poor process control.
- Great DEI elements.

- The tangential elements around sorbents and thermoelectric materials is not as well tied back as the whole project. I see how it is part of the schematic, but it is not clear where it needs to be to meet project goals. Still seems early on those tasks though.
- Good initial slides to help frame the project, particularly where we as reviewers do not have the full proposals.
- This project is very focused on improving AD efficiency. Clear approach in moving toward a zoned *in situ* methanogenic process.
- Team management seems to have a clear management process and appears to be following it.
- Engagement of commercialization partners could use some more work. Not as clear on the ultimate pathway to the market.
- Production costs of methane seem quite high. Typically, market values are reported in cubic feet (probably worthwhile to include when speaking to commercial partners).
- Overview/impact:
    - This project is investigating innovative methods for upgrading biogas through the *in situ* biological conversion of carbon dioxide to biomethane in anaerobic digesters. The investigators employed an adept technique by applying an external microbial-electrochemical system to infuse hydrogen into the AD system and increase the quantity of methane obtained from carbon dioxide in the AD process. This simultaneously reduces carbon emissions by utilizing CO_2 for upgrading biogas.
    - The project has made significant progress toward addressing the project goals, and it is now moving forward as scheduled in BP2. So far, the investigators have been able to show that the proposed system can upgrade biogas to >90% methane while treating synthetic wastewater, which is a significant contribution; however, the researchers should note that the performance of the system may significantly vary when they use it for treating municipal wastewater.
- Strengths: The project employs a microbial-electrochemical system to provide the hydrogen gas needed for converting carbon dioxide to methane, thereby avoiding the limitations of transferring hydrogen in the liquid state. The project has an excellent team management plan and education outreach program that addresses DEI issues.
- Weaknesses: The title of the project, which states that biogas is being upgraded through the *in situ* conversion of carbon dioxide to methane, belies the actual work done. The project involved external techniques, such as the use of MES to provide hydrogen, and also a biogas purification step for upgrading the biogas to methane. In this study, there is no mention of the quantity of hydrogen that is normally generated in the AD system to serve as a guide for determining the quantity of hydrogen that needs to be infused into the system. Further, the way the results section of this project is presented is discombobulated. The researchers do not clearly state what they have achieved so far in the project.
- Questions: One thing that baffles me is the practicality of providing hydrogen gas into the reactor for increasing methane production by hydrogenotrophic methanogens; won't this disrupt the AD process? Also, at what stage of the AD process was the hydrogen gas added to the system? Was it added throughout the process or just at a particular stage? In addition, the process flow in slide 4 shows that effluent is generated in the MES; what happens to this final effluent from MES? Further, it is noted in the process flow diagram of your proposed system that the heat from methane combustion is supplied to the anaerobic digester. What is the rationale for supplying this heat to the anaerobic digester? This was not clear to me. In slide 6, the investigators state that the project had passed the initial technical verification

step but did not explicitly state what the verification entailed. Last, the researchers should also comment on the feasibility of scaling up this system or incorporating it into the existing AD systems.

- This project proposes a novel, *in situ* method to upgrade biogas and increase methane yield. It has exceptionally strong DEI engagement with students at a range of levels, including outreach activities and HBCU engagement. The project shows that applicability to real-world cases has been thought through and is potentially applicable to a range of feedstocks.
- The presentation provided a nice introduction to the project and its focus. The goal was to produce RNG through a single-stage bioreactor treating organic waste. This was achieved using a gas transferring membrane. Personally, I feel like these gas transferring membranes offer a substantial opportunity for biomethanation, which these researchers are attempting to exploit via a single bioreactor design. My counterpoint (although I agree with Dr. Ren that a single-stage system would be better) is that these membranes would also be attractive for a two-stage system (i.e., stage two would produce the RNG).
- The management of this project appears to be excellent, with multiple project partners serving well-defined roles. There is excellent education and outreach, although an industry partner is still being sought.
- I suggest that the researchers more carefully investigate the ability of gas transferring membranes for biomethanation. There has been a good deal of work on these membranes for oxygen transfer; the researchers could benefit from this work but shift its application to transferring hydrogen rather than oxygen (look up the past publications of Semmens, Nerenberg, and others!). I am particularly optimistic about this technology because I think they should be self-optimizing, meaning that the transfer of hydrogen should be primarily controlled by microbial uptake, thus ensuring the optimal 4:1 hydrogen-to-CO_2 ratio. The researchers have attempted some preliminary optimization of the hydrogen addition, but they only saw increases in the methane content of the biogas; ideally, I'd like to see the researchers continue to increase the hydrogen addition until methane quality reaches a plateau (or decreases).
- This project is still relatively early, but I am very optimistic of its chances for success. LCA and TEA work is planned but is still quite preliminary. The DEI aspects of this work are good, establishing a connection with grade school students and an HBCU. The researchers also claim that 50% of the personnel working on the project are from an underrepresented group, but this is not explained well.
- I'd like to see a more rigorous experiment of hydrogen addition. What is the optimal condition to get highly pure methane? I would like to see a hump-shaped profile.
- Each task is aligned with new and strategic work in biogas upgrading technologies; however, there seems to be the potential for siloed work products, as tasks progress from 1 through 5 with limited industry or potential end-use partners. There is the potential for disjointed work products/separate teams pursuing work apart from one another with current project partners.
- The design of the system setup is unique and may not be applicable in many real-world operational settings. I would recommend that upcoming research reviews typical system design, as there may be significant operational barriers to the deployment of this technology.
- I recommend the inclusion of additional industry partners to secure real-world waste streams for testing and analysis. What is the current LCA and TEA of the progress to date? How has this informed potential improvements? Overall, there are few results available, possibly due to patent processes underway.

PI RESPONSE TO REVIEWER COMMENTS

- We are excited to receive the feedback from the review panel, and we deeply appreciate their efforts and comments. As the reviewers pointed out, this project is still in an early stage. That makes it challenging to address some issues but will allow us to improve or revise toward successful completion of the project. In the following, we are responding to the key questions raised by the reviewers. Because the 4:1 ratio was widely used in the literature, we include it as a factor of study; however, the design of the proposed bioreactor makes it (nearly) impossible to know the precise ratio given that the produced carbon dioxide would be converted within the bioreactor. Therefore, we will focus on monitoring the quality of the produced gas (and residue hydrogen gas) as a means to control the hydrogen gas supply. The reviewer has raised a great point that microbial activities may accelerate or help with the hydrogen supply through gas-permeable membrane. We will conduct more extensive literature analysis and necessary experiments to understand this process. In this project, pure hydrogen gas is used and will be replaced by hydrogen produced from MES (or electrolysis when MES is replaced due to limited hydrogen production). Our unique design allows the reaction of hydrogen with carbon dioxide “outside” the AD zone, thereby minimizing the effects on AD process. It is typical to heat AD to either mesophilic or thermophilic temperature by combustion of the produced biogas. The effluent from MES will be returned to the mainstream treatment, like that of AD effluent treatment. In BP3 we will explore the feasibility of system scale-up. Because AD is a mature technology, the key challenge to scaling up the proposed system will lie in where/how to install membrane units for hydrogen supply. It will be one of our key tasks to involve industry partners (beyond what is in the original proposal) for multiple purposes, such as technology transformation, market discovery, and system development/scale-up.

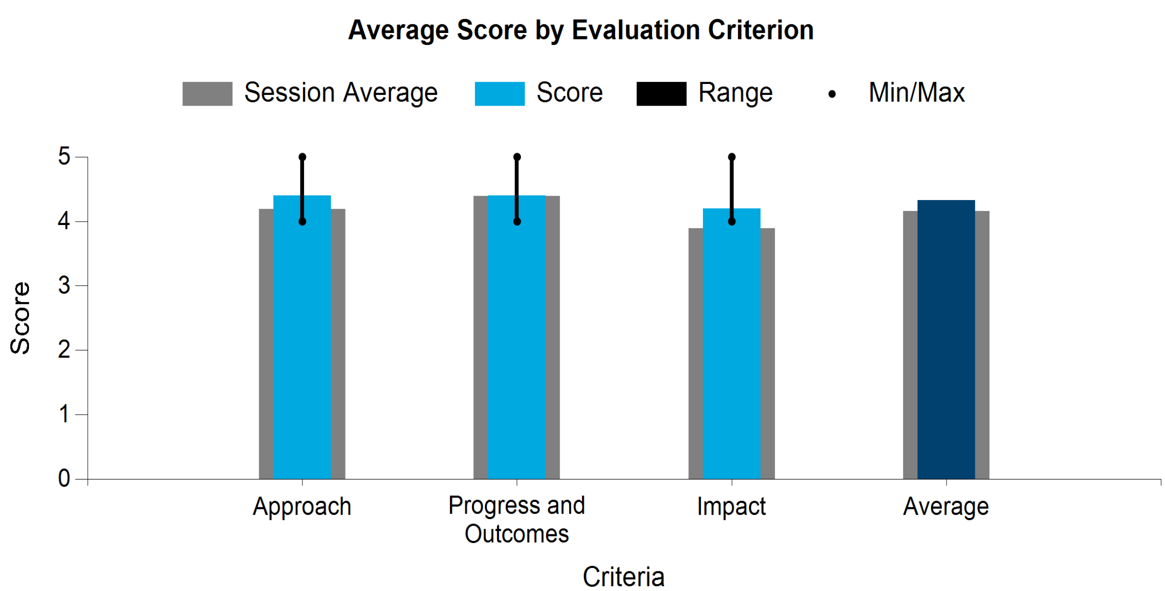
BIOMETHANATION TO UPGRADE BIOGAS TO PIPELINE-GRADE METHANE

National Renewable Energy Laboratory

PROJECT DESCRIPTION

WBS:	5.1.3.102
Presenter(s):	Kevin Harrison
Project Start Date:	10/01/2018
Planned Project End Date:	06/30/2023
Total Funding:	$1,500,000

NREL is working closely with DOE, Electrochaea GmbH, and Southern California Gas Company (SoCalGas) to reduce the costs of a biomethanation process capable of megawatt-scale deployment that upgrades organic biogas waste streams to produce pipeline-quality RNG. Biomethanation uses a single-celled methanogenic archaea that converts low-carbon, low-cost hydrogen and waste carbon dioxide to produce renewable methane. The process upgrades the biogenic CO_2—while allowing the CH_4 to pass through—from biogas sources like dairies, wastewater treatment plants, and landfills. NREL and Argonne National Laboratory have completed an LCA using the GREET model to show that the product RNG can be carbon negative even when H_2 production is driven by the existing carbon intensity of California's electricity grid. And, of course, even more carbon negative (−233 kg CO_2e/kWh) when the electricity is produced from low-carbon sources like wind and solar. Leveraging lessons learned from operating SoCalGas' 700-L, 18-bar bioreactor system, NREL is designing and building a flexible research, development, and deployment platform that will enable field trials at biogas and other CO_2 sources. A 16-foot-long trailer will house a 20-L, 18-bar bioreactor, 10-kW electrolyzer, and dosing and thermal systems with only power, biogas, and water feedstocks required by the field locations. The end-of-project goal is to demonstrate pipeline-quality RNG production using real biogas feedstocks.



COMMENTS

- Would be valuable to have the LCOE/TEA because it is also about commercial viability.
- The Low Carbon Fuel Standard does not currently credit CO_2. The 45Q tax credit does provide value. As the LCOE is presented, it will be important to be more transparent about what is/is not included.

- Thank you for including the selling price of RNG in California as a good reference point.
- This project is really tackling a valuable issue. I think the presentation is struggling to convey the steps this project is tackling to lead to commercialization.
- Understand that DEI goals were not part of the original project in 2019. Will be doing a bunch of educational/outreach activity (would have liked to have seen more, particularly for something as well suited to address DEI and remote communities).
- Very excited that so many companies seem willing to invest money in this project. Speaks well about its ultimate commercialization. Seventy percent production of RNG is a big deal. Easy economics to convey.
- As best as I can tell, this most recent phase of the project was to build the mobile unit. Knowing about the supply chain disruptions, it is certainly a feat that this was accomplished during COVID.
- The baseline is other gas separation technologies of biogas feedstocks.
- Methanogen is very robust to impurities, oxygen, and H_2S; easy to inoculate.
- Can do load following with this technology; an important grid technology and for remote applications.
- Overview/impact:
    - The project focused on scaling down the entire hydrogen-biomethanation system into a mobile electrolyzer-bioreactor system to enable faster research in the field, intellectual property development and validation, and improved gas mass transfer. This is all aimed at reducing the cost and de-risking the biomethanation process by supporting on-site renewable energy production from animal waste, landfills, and wastewater treatment by using the CO_2 typically released by these facilities to nearly double pipeline-quality RNG production compared with gas separations systems.
    - The research project has shown considerable progress as the design-build-deployment of the mobile bioreactor system is in the finishing stages, patents have been applied, and papers, publications, and presentations have been made.
- Strengths: The project involves a large group of university researchers, industry partners, and utility partners who have different forms of expertise that are used to improve the quality of the project. The project is environmentally friendly, as it biologically upgrades carbon dioxide.
- Weaknesses: Though the technology is interesting and impressive, one main concern is the level of risk associated with the process. The project seems risky, as leakage of hydrogen gas may lead to casualties, especially when the system is not operated by highly skilled personnel.
- Questions: The researchers mentioned that one advantage of the system they are designing is that the reactors can be made in small sizes to fit the needs of a particular area; however, they only talk in terms of size. The cleanup requirements for gases can vary from place to place; the researchers should throw more light on how they intend to incorporate this in their design.
- This project seeks to improve the efficiency of biomethane production from a variety of feedstocks through the conversion of CO_2 to methane using hydrogen as a fuel source. Among the strengths of the project is the engagement of a range of potential partner utilities in the United States and abroad. Another strength is the demonstration of the scalability of the process in tandem with supply and the development of a mobile R&D platform. The TEA presented makes a strong case for the viability of the project

concept at full scale. Two recommendations for future improvement. First, although the BETO award was prior to the DEI requirement and the project will not be assessed formally on that basis, researchers need to educate themselves more fully on what DEI requirements entail internally to project staff, as well as externally to communities. Specifically, researchers should strengthen their understanding of the importance of diversity in project staffing at senior as well as junior levels, and they should integrate a proactive strategy of engagement among students from the high school through doctoral levels. Further, researchers should pursue community engagement among community and/or nongovernmental organization groups working in waste sustainability and renewable energy. In addition, the concept of excess wind/solar energy storage in biomethane is intriguing but may be concerning to many stakeholders, including policymakers and elected officials, as it entails the conversion of carbon-free energy to a chemical form that emits carbon upon use. This may not be a contradiction from an engineering or business perspective, but it does present a system contradiction at a societal scale.

- The researchers did a nice job of framing the problem and their associated solution. Their partnership with SoCalGas appears to be very strong and very helpful to the success of the project.
- Scientifically, the researchers did a good job of framing their research in terms of the fundamental constraints (i.e., hydrogen addition is mass transfer limited). They did a nice job of explaining their novel use of an “evolved” hydrogenotrophic methanogen (i.e., not a genetically modified organism). They do a nice job of recognizing the limitations of their work (i.e., the focus on hydrogen sulfide as a limitation). One issue appears to be their ability to add hydrogen at the optimal molar ratio; this was shown to be successful but not explained very well (possibly for confidentiality reasons?).
- The DEI aspects of this project were weak, albeit the project was initiated prior to 2020, so there were no specific DEI requirements.
- This project seems closer to commercialization than many of the other projects that I have seen so far.
- An increase in the production of RNG to 60%–70% would increase the feasibility of ever-smaller organic resource facilities participating in RNG projects and accessing the incentives available to such projects. This project provides a clear path toward commercialization and the potential for significant impact and outcomes.
- Once tested in Maine, it would be ideal to evaluate and mitigate issues related to the transportation and deployment of these mobile units nationwide. Industry and research partners assisting with this project are well poised to evaluate such issues to ensure operability and safety of the unit.
- This mobile unit technology seems ideal for deployment in remote areas with an available renewable energy source and a biogas resource (e.g., landfills, wastewater) yet unreliable or poor quality electricity. Such communities (e.g., West Virginia, desert Southwest, Alaska) could benefit from increased RNG resources while forgoing the emissions of degraded organic waste streams and transportations cost to secure delivery of fossil fuels to remote areas. Utilities and their customers would benefit from increased grid stability and additional renewable energy.

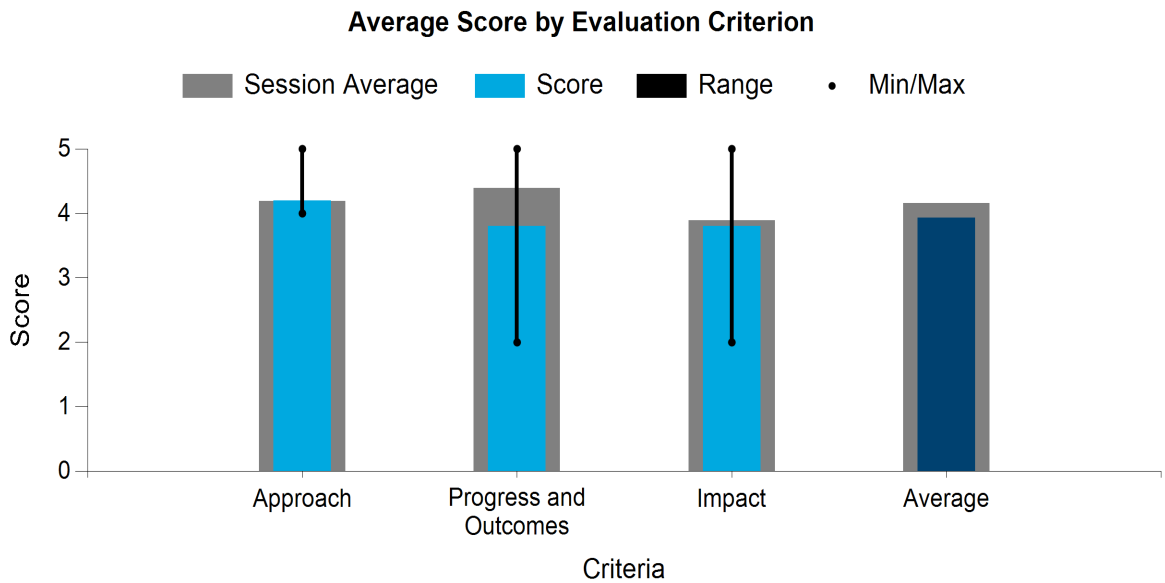
PI RESPONSE TO REVIEWER COMMENTS

- Thank you to all the reviewers for their thoughtful and constructive feedback. While most comments were positive, especially regarding industry involvement and pathway to commercialization, one minor theme about risk and gas cleanup was identified. The mobile electrolyzer-bioreactor research apparatus being designed and built under this project will provide an opportunity to conduct research in the field at various biogas or carbon dioxide sources. The NREL team acknowledges that the mobile system carries some risk of not having all the required gas cleanup technologies when first deployed to handle every biogas source; however, the team is building in flexibility to add or remove subsystems as needed. In other words, if one of the biogas sites to be visited ends up being a landfill, requiring additional input gas cleanup for siloxanes, for example, the team will take extra measures to ensure that gas cleanup technologies are integrated to address typical impurities prior to the site visit.

MAXIMIZING BIORENEWABLE ENERGY FROM WET WASTES

University of Illinois at Urbana-Champaign

WBS:	5.1.3.201
Presenter(s):	Lance Schideman
Project Start Date:	10/01/2018
Planned Project End Date:	06/30/2023
Total Funding:	$1,981,397



COMMENTS

- Was able to clearly see the effect of temperature on the productivity of the AD organisms (seasonality). Not much of an issue because the effective solids retention time is increased in that situation. How clean is the ammonia coming out of the cloth filter anaerobic membrane reactor (CFAnMBR)? Wondering if the additional step of electrolysis is worthwhile. Ammonia is also a liquid as opposed to H_2, which is a gas. The H_2 market is not as well developed nationally as NH_3.

- Overview/impact:

  - The researchers investigated techniques for maximizing biorenewable energy from wet wastes (sewage sludge) using an integrated system that comprises novel cloth filter anaerobic membrane bioreactors (CFAnMBRs), ammonia ion exchange, and ammonia electrolysis to hydrogen gas. The aforesaid techniques were used in improving the efficiency of conventional anaerobic membrane bioreactors (AnMBRs), which have limitations such as low gas flux and high membrane fouling. Applying the techniques used in this project in wastewater treatment plants will help to reduce their energy costs, as there will be no need for aeration (which usually consumes a lot of energy) at the treatment plants.

  - Quite a lot of progress has been made in this work. The researchers were able to achieve about 80%–90% removal of COD from the influent waste stream, which is about twice the COD removal efficiency of conventional AnMBRs. The production of hydrogen from ammonia helped to improve the fuel energy output of the AnMBR by 22%.

- Strength: Rather than stripping ammonia and releasing it to the environment, the project involves ammonia ion exchange and electrolysis to produce hydrogen gas, which makes the project eco-friendly. The project also has a very good management plan.
- Weaknesses: One main goal of this research was to increase the net energy yield from municipal wastewater treatment; however, the researchers need to note that energy in wastewater may be lower than the energy invested in energy recovery, as in most cases the wastewater is highly dilute, especially during the wet/rainy season. Further, the researchers should also comment on the feasibility of scaling up this system or incorporating it into the existing treatment systems. In the same vein, the researchers indicated in slide 20 that the overall distributed low-energy wastewater treatment (D-LEWT) process is net energy positive. The researchers should note that the lab-scale operations and performance of the system may significantly differ from the full scale. Therefore, a bench- or full-scale assessment is needed to establish if the proposed system is viable. Also, the researchers propose a technique that involves the addition of coagulants or adsorbents to AnMBR, and I am wondering if they have considered the implications of adding chemicals to the system, as this may have a significant impact on the final product and AD process. Moving forward, the researchers should also consider the toxic shock of the AD process, which is usually common from raw wastewater. Last, in reporting the progress made in the project on slide 21, the researchers indicate that chemical and material consumption in the project increases climate impacts; however, they fail to provide any research data to back up such a claim.
- The project seeks to improve municipal wastewater treatment through the use of membrane bioreactors as well as the conversion of ammonia to hydrogen. The issue of membrane fouling was addressed through the use of a cloth filter membrane. Optimizations achieved lower treatment costs and the potential to commoditize hydrogen as an income source; however, this led to the overall net energy positivity of the approach.
- The project showed strong partner engagement, including a potential host community in Urbana-Champaign, Illinois. In future work, the project team should seek to include a broader range of stakeholders in education and outreach, including local organizations engaged in waste policy. Further, the project should work with Black, Indigenous, and other disproportionately underrepresented groups in STEM to engage and build an understanding of the benefits of this approach to the wastewater treatment industry.
- The goal of this project is to reduce energy usage during the mainstream treatment of municipal wastewater by replacing conventional activated sludge (CAS) with a novel AnMBR design. The investigators proposed to remove ammonia from the wastewater via electrolysis to generate hydrogen gas; the ammonia removal process was augmented by using an ion-exchange process (using clinoptilolite as the ion-exchange medium). The project was well managed, and the results were disseminated to the various stakeholders.
- Treatment efficiency was generally good as far as COD removal, although the investigators were careful to avoid performance comparisons with CAS processes. This treatment process appears to involve lower energy usage compared to CAS, but without a performance comparison…this does not necessarily appear to be a fair comparison. That is, there appears to be a trade-off between process performance and energy usage; in that case, there are other lower energy process designs (e.g., a trickling filter) that are also lower energy users that produce lower effluent quality. The investigators also did not seem to have a solution for the dissolved methane in the treated effluent, which is particularly problematic because this was cited in the previous BETO review process. Finally, a benefit identified by the LCA was the reduced potential due to eutrophication, but this LCA did not seem to incorporate phosphorus removal, which is the more common cause of eutrophication in inland waters. In addition, the LCA compared the proposed

treatment scheme versus a CAS process that was not intended to perform complete nitrogen removal; again, this is an unfair comparison, particularly given that a total nitrogen removal process is typically believed to require less energy than a CAS process (i.e., nitrate is used as the terminal electron acceptor for microbial respiration, thus reducing the oxygen demand by the process).

- Generally speaking, this is really high-quality research, although I think that the researchers are trying to “spin” the work to generate a commercially ready process per the BETO requirements. That is, many people recognize that CAS is a highly energy-intensive process, and these same people have suggested mainstream anaerobic treatment. With this in mind, rigorous and fair-minded LCAs and TEAs could be incredibly valuable because they would identify the specific situations in which mainstream anaerobic treatment would be preferred over conventional aerobic wastewater treatment processes.
- The project demonstrates clear improvement of anaerobic membrane bioreactors and makes additional improvements in the conversion of ammonia (which can inhibit AD) to hydrogen gas by electrolysis. This area of research targets 1%–3% of national energy consumption in order to move WRRFs toward a position of neutral or net-positive energy generation.
- The application of technologies could potentially be deployed at small facilities with a limited budget, in all making a large impact on the creation of bioenergy from smaller organic sources.
- AnMBRs have had limits to their deployment due to the issues discussed by the project leads. Although research targets WRRFs, applicability to other organic waste streams seems to provide an even larger target for further beneficial outcomes for the performer and the government.

PI RESPONSE TO REVIEWER COMMENTS

- Response to Reviewer 1: Ammonia in the CFAnMBR permeate is typically 25–35 mg N/L. This ammonia must be removed from the wastewater prior to discharge, and we have selected an ion-exchange process to do that. Regenerating the ion-exchange media results in an ammonia-laden brine regenerant solution, which is not well suited for fertilizer applications because it is not concentrated enough (~0.1% N) and the salt concentration is too high. Ammonia could potentially be sparged out of this brine solution to provide gaseous ammonia, and the gaseous ammonia could be compressed into liquid (anhydrous) ammonia, which is a viable commercial fertilizer; however, this project was designed to investigate a more novel route to utilize the ammonia brine for hydrogen production by electrolysis. It is possible that H_2 production from ammonia is not the most economic method of removing ammonia from the wastewater stream and that production of a concentrated NH_3 product is more economic. Considering the relatively high-energy and chemical inputs for the ion-exchange/electrolysis step, the University of Illinois group is also pursuing funding sources to research other low-energy, low-chemical-use processes for treating the ammonia-rich permeate (e.g., biological nutrient reduction). The team will continue to work with Aqua-Aerobics on the potential commercialization of the technology for the application of AnMBR and share the final project findings with the company to discuss strategies for achieving this. The team is also working with other cloth filter manufacturers who may be interested in commercialization for this application. The recipient acknowledges that the DEI plan for this project was underdeveloped, as this was not originally included in the scope of the work requested by DOE at the time of this award. The team has since submitted additional proposals with a DEI document with measurable milestones to improve work in this area. The Illinois Sustainable Technology Center is leveraging the DEI resources available to the University of Illinois, which have helped support hiring diverse staff at senior, junior, and student levels. A number of minority-serving institutions in Illinois have been identified for potential collaboration in the greater Chicago area for future work. The applicant does feel that the goals of the project support the goals of the Council on Environmental Quality, which includes environmental justice, and could produce lower-cost, energy-positive wastewater treatment for rural and economically disadvantaged communities, which typically have fewer municipal resources for wastewater treatment. The reviewer mentions the difficulty in overhauling or retrofitting existing large

WRRFs. We agree this is an important target for the development of this technology and have included some information on this in our 2021 BETO Project Peer Review presentation. Basically, we have proposed that existing tankage for aeration and sedimentation can be covered with flexible tops and converted to anaerobic bioreactors with plastic media similar to integrated fixed-film activated sludge processes. Then a cloth filter can be added to the effluent of the converted tankage. Thus, if we can get the hydraulic retention time of the AnMBR process to roughly match the current aerobic treatment processes, a relatively low-cost retrofit option can potentially be achieved that will greatly increase the net energy production of existing WRRFs.

- Response to Reviewer 2: While municipal wastewater is relatively low strength (400–600 mg COD/L), AnMBR helps decouple the hydraulic retention time and solids retention time to provide conditions sufficient for AD to proceed with short hydraulic retention times. By increasing the membrane flux and lowering cleaning energy, the CFAnMBR increases the share of organics treated anaerobically (i.e., increasing net energy produced as biogas) and lowers the energy inputs by reducing or eliminating aeration. Energy balance showing net-energy-positive process was based on our CFAnMBR pilot performance over 2 years, not bench-scale work. The chemicals currently used in the coagulation step are commonly used in coagulation processes used in the WRRF industry for improving effluent quality and are not known to induce toxicity under normal operating conditions. The LCA has incorporated the effect of ferric chloride on reducing phosphorus and its effect on eutrophication potential, and it will continue to explore other effects of the coagulation step on operational parameters. Increased GHG emissions from material and chemical consumption were based on the pilot-scale operation of the CFAnMBR and ion-exchange system, their respective chemical inputs, and the indirect GHG emissions embedded in the production of those materials. This evaluation was performed in the LCA step using widely accepted emissions estimates for these materials. The main GHG contribution is for NaOH, which is used consumptively in the process because electrolysis requires a high pH, and the ammonia removed in this process is a base that must be replaced to maintain a high pH.

- Response to Reviewer 3: The recipient is currently working on the dissemination of the project results to industry and academic sectors through journal articles and conference presentations, including a presentation at the annual Anaerobic Digestion Conference in spring 2022 and presenting at a regional meeting for wastewater operators. The team will consider future work with local or state organizations that work in waste management policy. See response to Reviewer 1 for additional comments regarding DEI and working with historically underrepresented groups.

- Response to Reviewer 4: The TEA/LCA comparisons for the baseline CAS and the proposed D-LEWT process scenarios were developed in CapdetWorks wastewater modeling software such that all the processes achieved 90% COD removal, which the CFAnMBR pilot was able to achieve with a sufficiently high coagulant dosing rate. The reviewer is correct in that the CAS and D-LEWT processes are not comparable in terms of total nitrogen removal; however, this is why the CAS + denitrification scenario was also modeled to more accurately compare the two processes when both are designed to meet the same effluent water quality goals. A separate TEA/LCA scenario has been modeled for the case in which endogenous COD is used for denitrification; however, this scenario was not included in order to simplify the Project Peer Review presentation and comply with the time limits. This scenario was excluded because its results generally fall between the limiting cases of CAS and CAS + tertiary denitrification. In our work, we are trying to match the costs of CAS, which is the predominant current WRRF process, while trying to achieve the better effluent water quality associated CAS + denitrification, which is expected to become prevalent as discharge regulations become more stringent. The reviewer noted that "a total nitrogen removal process is typically believed to require less energy than a CAS process (i.e., nitrate is used as the terminal electron acceptor for microbial respiration), thus reducing the oxygen demand by the process)." There is significant literature showing that plants providing advanced nutrient removal typically use 30%–50% more energy (e.g., Burton, F. L. 1996. "Water & Wastewater Industries: Characteristics & Energy Management Opportunities," CR-10691, Electric Power Research

Institute). Although nitrate may be used as an electron acceptor, it generally requires aeration to first convert ammonia to nitrate, such that there is not a net reduction in the oxygen demand for using nitrate. The LCA slide discussing eutrophication potential may not have been clear, as the differences in eutrophication potential between the five scenarios was only due to lower phosphorus removal due to the coagulation step in the D-LEWT process. The finalized TEA/LCA due at project end will consider all the operational parameters of the pilot-scale system and refine the TEA/LCA for other scenarios for a more comprehensive comparison that addresses the reviewer suggestions. The University of Illinois team intends to begin work on dissolved methane recovery later this year, using external funding from U.S. Army partners and future DOE grants for WRRF decarbonization. Discussions with several commercial degassing equipment manufacturers have determined that vacuum degassing over packed beds is the most promising technology, which will be tested at the pilot scale using permeate from the CFAnMBR.

- Response to Reviewer 5: The recipient agrees that future research and collaborations should include the market potential for higher-strength organic waste streams (e.g., industrial wastewater, food and beverage, agricultural wastewater).

A CATALYTIC PROCESS TO CONVERT MUNICIPAL SOLID WASTE COMPONENTS TO ENERGY

Worcester Polytechnic Institute

PROJECT DESCRIPTION

WBS:	5.1.3.202
Presenter(s):	Mike Timko
Project Start Date:	10/01/2018
Planned Project End Date:	06/30/2023
Total Funding:	$2,497,821

Biofuels and bioenergy have the potential to reduce GHG emissions, improve energy security, and reduce energy price volatility (https://doi.org/10.1016/j.eneco.2005.11.003). Unfortunately, despite significant progress in the past 20 years, the conversion of biomass into transportation fuels is not yet directly competitive with fossil fuels (https://doi.org/10.1016/B978-0-12-407909-0.00030-4). In fact, biomass conversion costs have steadily decreased in the past 10 years, as indicated by successive cost estimates published by NREL, while biomass feedstock costs have remained nearly unchanged (https://doi.org/10.2172/1013269; https://doi.org/10.2172/982937). Reducing the costs of biomass production, transportation, and storage has proven more difficult. As suggested in DOE's Billion-Ton Report (https://www.energy.gov/eere/bioenergy/2016-billion-ton-report), a potential solution to biomass production costs is to use waste feeds that would otherwise require a tipping fee for disposal. MSW, including food waste and green waste (e.g., yard waste), is especially attractive as a feed for bioenergy production. Depending on location and tipping fees, the conversion of MSW to energy diverts it from landfills, where its AD leads to GHG emissions, and the generation of MSW coincides with population centers.

Food waste constitutes approximately 15% of the total mass of MSW. Water constitutes approximately 50% of the total mass of food waste, effectively reducing its energy content relative to other organic components of MSW. Its high water content and variable composition make conversion using pyrolysis and gasification unattractive energetically, as these require energy-intensive drying and result in significant char and tar formation. The HTL process is a great fit for the conversion of waste feedstocks with high water content. This project is designed to tackle the main challenges associated with converting the combined food and green waste feed to fuel product, namely diesel.

The main project objective is to generate bench- and pilot-scale experimental data and models to de-risk the commercialization of a process to convert a combined stream consisting of the food waste and green waste components of MSW into an energy-dense bio-oil and refined lignin stream. Green waste is fed to a solvent-based fractionation process that produces furans from the cellulose and hemicellulose fractions and lignin. The lignin is co-fed with food waste to an HTL process for the production of an energy-dense biocrude. The biocrude undergoes catalytic hydrodeoxygenation and denitrogenating to improve its fuel properties. The component processes are being investigated at the bench scale, and the data are used for operating a continuous HTL system constructed at Mainstream Engineering. Finally, the economics and LCA of the carbon emissions from the overall process will be continuously assessed using standard metrics of energy return on investment and LCOE. The project is split into eight tasks based on the individual expertise with milestones for each task. The main products of the technology are upgraded HTL biocrude and a furan stream to be sold as chemicals. Byproducts will include a gas purge stream, consisting primarily of carbon dioxide; a char stream, with many potential applications; and an aqueous phase containing water-soluble organic compounds produced in the HTL process. The catalytic upgrading process is designed to minimize carbon loss to the aqueous phase, since aqueous-phase carbon represents energy loss and the contaminated aqueous phase must be treated prior to discharge, thereby increasing costs and decreasing overall efficiency. The catalytic hydrogenation step further improves HTL bio-oil properties, specifically heating value, by rejecting oxygen and nitrogen.

The main target markets are the U.S. chemical market and the U.S. diesel fuel market for the upgraded bio-oil product. These markets represent billion-dollar opportunities in both transportation and stationary heat and power. The feedstock of MSW is around 250 million tons per year in the United States. Utilizing the organic fraction (~40%) would significantly divert waste from landfills while providing an inexpensive and renewable feedstock for fuel production. The proposed technology could produce 10%–15% of the annual domestic gasoline usage (assuming 100% material efficiency) or 3%–5% with 25% efficiency.

To date, the team has successfully fractionated two different real green waste streams into lignin-rich and carbohydrate-rich fractions for lignin products and biofuel feedstocks, with the carbohydrate fraction having less than 10% lignin. The team is now finalizing solvent recovery experiments.

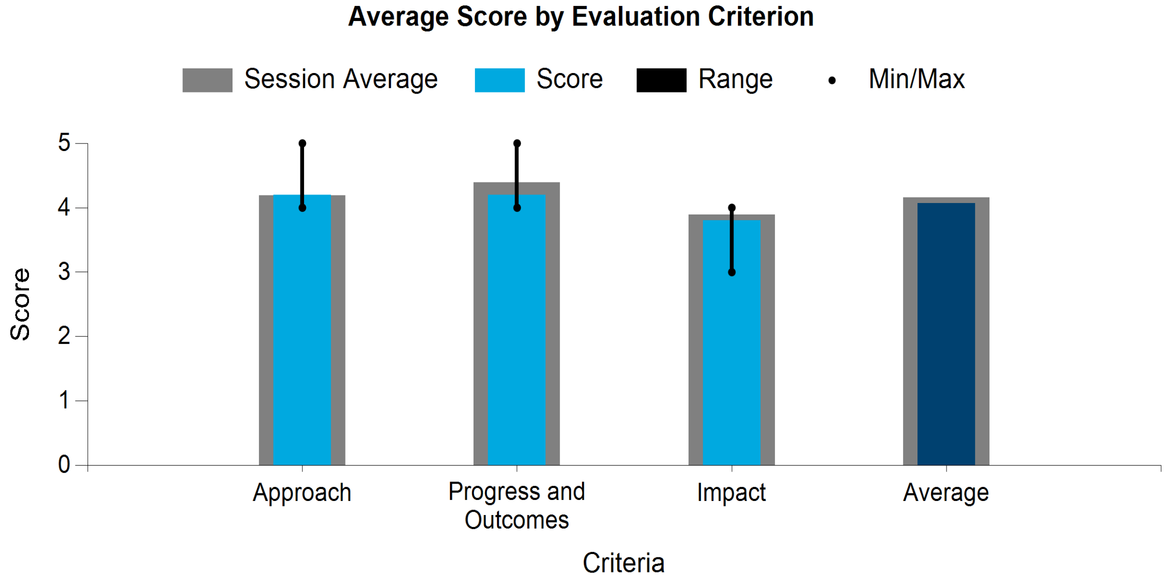
The team has evaluated HTL of many different feeds, including green waste, lignin, food waste, and their mixtures. Food wastes available in cafeterias provide the best HTL performance of these, with energy recovery exceeding 60 wt %. The team has studied interactions between co-fed components in molecular detail, identifying sources of synergy when food waste and green waste are co-fed. The team has developed machine-learning and physics-based models to predict biocrude yields and nitrogen fate.

Catalysts are used to minimize carbon loss to the aqueous phase. The team has evaluated four generations of catalysts to achieve this goal: (1) $CeZrO_x$, (2) inexpensive oxides, (3) Ni-impregnated oxides, and (4) hydroxyapatite. Of these, hydroxyapatite is the most effective at boosting biocrude yields while minimizing costs.

The hydrotreating step required to convert biocrude to diesel fuel can be performed using industrial CoMo or NiMo catalysts. The team has studied Mo_2C as a potential disruptive catalyst to minimize H_2 consumption in the hydrotreating step. Mo_2C is an effective catalyst for hydrodeoxygenation to preserve the carbon content of the biocrude. Conversion to the oxide form remains a challenge.

Continuous HTL tests have been performed with various food waste streams. The team has now completed 45 of 100 hours required for continuous testing. Performance in continuous tests is comparable to that observed in the batch. The team has gained useful experience in formatting real waste streams to ensure pumpability.

Economic and environmental analysis have been performed, with the finding that a 75% food waste and 25% lignin co-feed stream to the HTL process is optimal. This arrangement leads to an MFSP of $2.74/GGE, a 50% reduction relative to the starting point. The energy return on investment is 1.73, which is an acceptable value for a fuel product. The team is actively engaged in patenting these technologies, and the PI recently cofounded a company for commercialization purposes.



COMMENTS

- Hydroxyapatite (catalyst) research for HTL is showing real promise and improvement over standard practice. Clear value in increasing the oil yield from existing feedstocks.
- Curious about the catalyst life and resiliency. Project team is leaning heavily on its low cost and acceptable lifetime/resiliency.
- Less clear of the impact/value of lignin separation because it looks like its oil yields are in the middle. Seems its value is not in HTL yield but in the co-solvent enhanced lignin fractionation (CELF) fraction itself. Lignin separation does increase the yield of bio-oil. The CELF process is more valuable because of the furfural/hydroxymethylfurfural recovery.
- Would also be interested in the resiliency of this process—e.g., what happens if a plastic bag ends up in the stream? If these numbers are real, it seems like just commercializing the CELF process would be valuable on its own.
- Analysis work is generating interesting data and serving as an independent sounding board for the national lab work.
- The biocrude upgrading task appears to be less progressed than many other tasks.
- The team has incorporated DEI activities in real time. Nice inclusion of undergraduates from nontraditional STEM individuals.
- The team recognizes that the state of the industry has moved beyond what is in the FOA, and it is still seeking to push the technology forward.
- The team has spun out River Otter Renewables to commercialize the technology. Positive development that River Otter Renewables is looking to license the technology. Still a lot of bent on the academic literature; it's going to take a lot to commercialize (see PNNL's ongoing difficulties). I'm not saying that this team wouldn't have more success, just noting that investor appetite for this kind of a project has been less than ideal.

- Initial phase of the project was delayed by the pandemic but appears to be back on schedule.
- While the 100-hour run time seems to be within reach, unclear about the learning from the intermediate run times. Could one of the earlier runs be bumped up? Is there some value in marginally adding about 10 hours at a time? Should be looking at longer continuous run time, perhaps not 100 hours.
- The project team is talking but doesn't seem to be coordinating as well as ideal.
- Overview/impact/progress:
    - The researchers investigated a novel, innovative, and widely applicable technique for effectively managing the organic fraction of MSW. The researchers combined green waste fractionation with HTL and catalytic upgrading to produce energy-dense liquid products from MSW. A lot of ingenuity is shown in this project, as the researchers applied the novel technique to a wide array of substrates, including food waste from hospitals and green waste from industries, showing that the technique is widely applicable, as any type of waste can be properly degraded.
    - The project is highly impactful to the urban environment, as it will help curb the menace involved with the indiscriminate disposal of MSW, especially the organic fraction of the waste. It helps in reducing overdependence on landfills, as it serves as a way of treating/managing solid waste while generating renewable energy from the waste. A lot of versatility is shown in the project, as high-quality fertilizer is obtained as one of the end products of the process. Also, the process is designed in such a way that there is phase water/oil separation, and thus the process water can be recycled. The patents, awards, conferences, and publications that have been obtained with this project speak volumes about the originality of the project.
    - The researchers have made tremendous progress toward achieving the goals of the project. Despite the challenges and delays in the project, it is still on track, as most goals have been met. The researchers have been able to produce lignin-rich (>90% lignin) and lignin-free (45 hours time on stream) and obtained greater than 45% energy recovery from food waste.
- Strengths: The researchers show a lot of inventiveness in this technique for converting MSW to biofuel by combining waste fractionation with HTL and catalytic upgrading. Also, the project involves collaboration between researchers from different universities and industry partners who have different kinds of expertise that are being fused together. In addition, there is a logical flow of tasks, as the work from one principal investigator feeds/fits into those of other principal investigators. Another major commendation for this project is the incorporation of scenario-based models.
- Weaknesses: In this study, nothing was shown about the characteristics of the feedstocks used in the process. The researchers should note that the feedstock type/characteristics have a significant effect on the catalysts used and process performance. The researchers should therefore conduct a sensitivity analysis between the catalysts and feedstock type/characteristics. After this sensitivity analysis, the researchers should determine the optimum conditions of the process before moving forward to scaling up the system. Further, the researchers should consider assessing the economic viability/feasibility of using catalysts on a full scale but testing different models. The researchers should also comment on how they plan to handle MSW contaminated with non-biodegradable materials such as plastics, etc. I am worried this may limit the scaling up or commercialization of the system.
- The project investigates the use of HTL to convert food and yard wastes into two products: biocrude and refined lignin. The project appears well managed and is making progress. Among operational strengths is attention to the modularization of HTL components and the minimization of transportation.

- In their next presentation, the researchers should more explicitly address the markets and end uses for lignin.
- The researchers define food and yard waste as abundant and inexpensive; however, they should carefully consider food waste sources and potential for significant contamination with film plastics, as well as plastic containers and packaging (glass, metal, and other contaminants are less of an issue in source-separated organics collection). The researchers used institutional kitchen waste as the test feedstock, but most food waste generated is from residential or food service establishments and may not have the same level of purity. If this process can accept and convert plastic contaminants, then researchers should specify maximum levels and other feedstock requirements. Being able to manage plastic-contaminated biogenic feedstocks will greatly improve the acceptability of this method of treating versus what many small and regional compost operators and the public prefer to do with well-separated food and yard waste: make compost to enrich soils and promote food sovereignty (regardless of energy return on investment [EROI] or other bioenergy metrics commonly applied to compare projects).
- This project is focusing on a catalytic form of HTL to convert MSW to a usable energy source.
- This project has very much benefitted from the TEA in which the researchers have considered various different catalysts with the goal of increasing biocrude yield, increasing char reduction, and reducing the cost per GHG equivalent. The project also has a legitimate effort in DEI, although this was not a requirement. The investigators have also been very successful in promoting their work, both via academic publications and other routes of publicizing their work. The management of the project appears to be excellent (a lot of data sharing) through regular meetings (online and in person) with all project personnel.
- The project is making substantial progress toward the identification of chemical and thermal processing to create biocrude from high-lignin wastes, which would further reduce needs for diverting such wastes to compost facilities or high-energy drying for gasification. Benchmarks exploring new catalysts and treatment options are continuing, with the future development of other catalysts for processing identified chemical contaminants in the remaining project time. Research has established fast, efficient, and adaptable pretreatment possibilities for lignin-containing wastes that are currently difficult to convert to energy, all while creating valuable coproducts for sale and environmental co-benefits.
- Shipping container size of technology could enable the development of completed technology at a lower cost for quick deployment, with a clear path for potential commercialization. Lignin is a large barrier to sorting and processing waste; its beneficial use will provide significant impact and outcomes.

PI RESPONSE TO REVIEWER COMMENTS

- The team appreciates the reviewers' thoughtful comments. The project has not been without its challenges. BETO's consistent support throughout, especially during the pandemic, was critical to our accomplishments. In exciting news, we are happy to report that the company commercializing this technology, River Otter Renewables, has nearly finalized licensing key patents that stem from this BETO-funded work and is in advanced discussions with an early-stage investor and a state incubator. The town of Stow, located in central Massachusetts, is enthusiastically supporting these efforts, especially as the extent of its PFAS contamination problems become increasingly evident. The reviewer comment that the bulk of this project has tended toward the academic is accurate, and seeing the rapid transition to potential commercial deployment is evidence that targeted science can yield tangible results. Responding to every comment is not possible. We pick several recurring or important themes instead.
- Reviewers identified catalyst lifetime as an area for future attention. We agree with this assessment. Initially, we deployed catalysts in the same reactor as the HTL process. Since our early work, we have moved to using two separate reactors, one for HTL and one for catalytic conversion. The two-reactor

system shows promise for extending catalyst lifetime, with an achievable known limit of 200 h based on catalyst endurance testing. While 200 h is less than is typically considered necessary for industrial applications, our focus on inexpensive catalysts allows us to operate economically with catalysts that last less than 200 h. Batch experiments that simulate the two-reactor system have yielded promising results. This summer, we plan to test the catalytic step in a dedicated packed bed reactor. Early results obtained on a collaborator's reactor were promising.

- The relative value of CELF and HTL. The reviewer is correct: Much of the economic value of the process is driven by the furfural products of CELF; however, much of the waste reduction value is driven by HTL. The two technologies are a good fit for one another, especially since the lignin product obtained from the CELF process needs a better end use than combustion to offset heating.
- Biocrude yield must be sensitive to feedstock composition, and the relationship between the two should be studied. The team recognized this early in the project and built a machine-learning model to predict biocrude yields from feedstock composition. That model was published in 2022 and has already been cited 15 times. We are now working on developing a similar model for catalytic HTL. This is a more difficult challenge since the catalyst adds a degree of freedom to the analysis. Ideally, a future study will systematically test a handful of representative catalysts for several different feeds to test the hypotheses that our machine-learning model can generate.
- The fate of plastics should be examined. The waste streams evaluated in this project contained microplastic contaminants, as do all food waste streams. Any yield we report includes those microplastics. For macroplastics, future work can be performed to add different amounts of different types of plastics to a food waste stream to determine the effect on biocrude yield. At low levels (<10 wt %, approximately), plastics are expected to improve biocrude yield, though more severe conditions may be required than we've found optimal for waste streams lacking plastics. In fact, new studies are reporting synergistic interactions between biomass and plastic during HTL. The origin and amount of these synergies is worthy of study in a future BETO project.

DEVELOP AN EFFICIENT AND COST-EFFECTIVE NOVEL ANAEROBIC DIGESTION SYSTEM PRODUCING HIGH-PURITY METHANE FROM DIVERSE WASTE BIOMASS

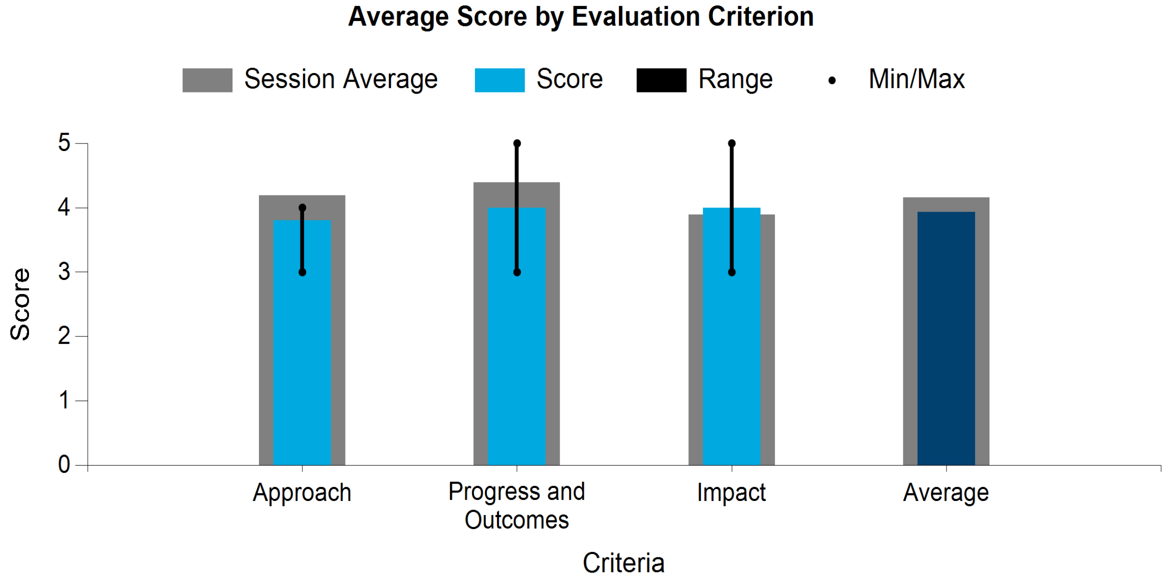
Washington State University

PROJECT DESCRIPTION

WBS:	5.1.3.204
Presenter(s):	Shulin Chen
Project Start Date:	10/01/2019
Planned Project End Date:	09/30/2023
Total Funding:	$2,792,893

The lack of cost-effective AD technology is a major hurdle for wide allocations of this technology for converting organic wastes to RNG. This project aims at developing a novel AD system to increase methane yield, productivity, and purity through process intensification. This system takes the synergistic advantages of innovative process engineering and a high-performing microorganism to (1) overcome the recalcitrance of waste biomass through hydrothermal pretreatment, (2) enhance biological conversion rates by using hyperthermophilic microbial communities, (3) achieve *in situ* purification of biogas through methanogenesis under pressure, and (4) relieve inhibition by recovering ammonia as a fertilizer. This novel system is expected to have a near-term commercialization potential by significantly reducing the cost of biogas-based RNG production. The project team includes Washington State University, PNNL, Regenis LLC, and DVO Inc. The active participation of the industry partners makes it possible to use existing AD systems as baseline technology and accelerate technology transfer and commercialization of the novel technology.

The project is expected to produce significant impacts. The proposed novel AD system offers a new platform to DOE's technology portfolio for the production of RNG from different types of organic wastes. The project results will lead to critical data for advancing the technology from TRL 3 to TRL 5, decreasing the risk factor in commercializing the technology. The progress of the project to date has proven the merit of the concept. The project has passed the go/no-go evaluation. Success in this project will remove several key technical barriers and lead to economic development opportunities by creating value from the immense amount of waste biomass. The project also benefits the federal government, as this effort aligns well with the priorities of several governmental agencies, especially those of BETO.



COMMENTS

- The team seems to be addressing the key elements of commercialization.
- Working with two large AD installers is really critical to getting feedback. Have thought through retrofitting and implementation. Actually seem to be underselling the project's performance, which is refreshing.
- Active engagement of DVO throughout the project.
- The team has been able to model quite low EROI, which should make for large market demand. That said, unfortunately, folks are not necessarily looking for solutions, so you will have to go to them, as opposed to them coming to you.
- Not quite clear why the volume and productivity decreased over the life of this project. Have been able to decrease the volume of reactors; I figure that ultimately reduces the capital expenses without dramatically compromising the productivity of the process.
- Clear improvement in EROI and levelized cost of disposal.
- Was the solid retention time also impacted along with the hydraulic retention time?
- Met the overall project metrics as well as the lesser goals that rolled up into these.
- No elements of DEI outreach.
- Project is only producing biogas, which aligns less with the current focus of BETO on SAF and other difficult-to-electrify transportation.
- Certainly a valuable project in the BETO portfolio.
- Interesting thought on high pressure to force more CO_2 into solution and increase the concentration of methane in the biogas.
- Overview/impact:

  - This project aimed at developing an efficient and cost-effective novel AD system producing high-purity methane from diverse waste biomass. This project investigated the use of an intensified versatile AD process comprising a hyperthermophilic anaerobic acidification process for the rapid conversion of organic wastes to VFA and a thermophilic anaerobic methanogenesis process for expedient transformation of VFAs to high-purity methane.
  - The project has made appropriate progress toward addressing the project goals. It passed the go/no-go evaluation of reducing the LCOE and EROI by 25% of the baseline technology. The project reached all six milestones scheduled for BP1, and only three more milestones remain for BP2.

- Strengths: The researchers did a great job of combining biological and hyperthermal processes without derailing the metabolism of the microorganisms in the AD system. Also, the researchers applied avant-garde molecular biology techniques, such as proteomics and florescence-activated flow cytometry. The project is being carried out using collaboration between academia and industry, thereby providing a means through which the expertise from these two sectors can be leveraged. Further, the industry partners involved in this project are well known for their expertise in designing and building anaerobic digesters.

- Weaknesses: In the process of using hyperthermophilic anaerobic acidification to convert biomass to VFAs, it is expected that other products will be generated from the acidification process. In the flow diagram (slide 3), the researchers do not indicate/mention these products and how they were managed. Further, the researchers suggest the use of hyperthermophilic process; however, I am worried about the costs of operating this energy-intensive system, and this may limit the scaling up or use of the system. It would be great if the researchers could conduct an energy balance and LCA of the system. In slide 13, the researchers present gas production and composition; however, fluctuations can be observed in the gas production, with daily gas production dropping to 0 liters on days 2/25 and 2/26. I am wondering if the researchers could consider repeating the experiments to determine the optimum process conditions of the system before moving to the pilot scale. The researchers should also consider describing the type of organic wastes used in the study, their mixing ratios, and characteristics. This is because the performance of the AD process depends on the characteristics of the feedstock. The waste streams used in the process are manure, biosolids, and food waste; the researchers need to provide more clarity on which type of manure was used and if the results of the project are applicable to other waste materials.

- Recommendations: In the future, I suggest that all the presenters provide a Gantt chart in their PowerPoint presentations tracking the progress of their work against the planned milestones.

- This project is of potential application to the management of manure waste through improved treatment of recalcitrant (fibrous) fractions in feedstock to enhance methane production, with ammonium-derived nitrogen as a recoverable side product. Strengths include building on existing baseline technology, including industry partnership, as well as looking holistically at the whole process. Applicants should build DEI goals into future research through outreach to HBCUs and other institutions serving students unrepresented in agricultural engineering applications, as well as mentoring such students through steps that include job training and higher education. Applicants should continue industry stakeholder engagement to assess feasibility of the modifications to widely used baseline tech in real-world applications.

- The goal of the research was to develop an AD process that could generate a high-methane-content biogas from diverse wastes. The investigators seemed to focus on animal manure as its feedstock, which led to pertinent issues of poor conversion efficiencies of fibrous material and of ammonia inhibition. Three primary activities were to reduce the reactor size, concentrate the feedstock, and alleviate inhibition. The first stage of the process was a high temperature (>60°C) operated at a low pH (5–6). A hydrothermal treatment process was also used. Finally, a thermophilic AD process (T = 50°C, pH = 6.5–

8) was used to generate high-methane (>80%) biogas. The purpose of the first bioreactor was to optimize the hydrolysis of fibrous material, which is believed to be a rate-limiting step. Research goals were generally achieved in that treatment performance, and the methane content was >80% in the biogas.

- The project seemed to lack a rigorous TEA, which I think would be especially helpful. The paradigm of the proposed process design seems to be these unit operations should achieve a goal, which is very different than a rigorous analysis of pertinent variables to optimize the system's performance with respect to carbon conversion, COD reduction, methane content of the biogas, etc. It would be particularly interesting to see how a TEA would rank this process design to compare to other process designs that could achieve similar treatment goals.
- Could industry partnerships be expanded to ensure a diversity of feedstocks and differing AD digester types? Typically, the AD systems employed by the industry partner are of the plug flow variety, which are not conducive to the digestion of diverse feedstocks. Concerned this is a technology gap that impacts the future deployment of this research to all types of digesters.
- Results indicate clear progress toward goals, significantly exceeding targets; however, in order to secure beneficial outcomes for AD, the project needs to diversify the deployment of research to other common AD technologies (lagoon, complete mix, etc.). Refinement of microbial communities offers a path forward toward shared improvements to digest wastes across other AD technologies, yet more information is needed on how hyperthermophilic microbiomes have specific applicability toward diverse waste (food wastes, WRRF) streams.
- Overall, the project is advancing toward the stated goals; however, without more information, it is currently unclear how the results apply toward other AD technologies and specific wastes outside of food waste in concert toward its stated goal of applicability to diverse wastes.

PI RESPONSE TO REVIEWER COMMENTS

- The research team sincerely thanks the reviewers for both their positive and constructive comments for improvements. The responses presented here cover only the constructive comments. The working volume of the anaerobic acidification reactor was reduced to test the effect of reduced hydraulic residence time. As a result, the total volume of gas production was reduced, but the unit volumetric productivity did not. The team has made DEI efforts in training to include female students in the research. More efforts will be made during the results dissemination phase of the project. More specifically, the project team will recruit underrepresented students for the summer of 2024 to work on the pilot system evaluation. The project goal is to produce pure methane that can be compressed for vehicle uses, although not for aviation. Other products from the acidification process will not be recovered. It is not economic to utilize these products because of their relatively small quantity. The research team has conducted an energy balance analysis as a part of the LCOE and EROI calculations. The detailed analysis was not presented due to the time limitation. The research team is continuing the optimization of the bench-scale system. The research team does have the data on the manure/waste characterization. The research team has a Gantt chart for the project schedule and will use it to track the progress. The research team will proactively engage industrial stakeholders during the next phase of the technology scale-up and results dissemination. Although a preliminary TEA was conducted based on the results of the project to date, a more rigorous analysis will be further conducted based on the performance data of the pilot system during the next phase of the research to answer the questions that the reviewer asked.

RENEWABLE NATURAL GAS FROM CARBONACEOUS WASTES VIA PHASE-TRANSITION CO_2/O_2 SORBENT-ENHANCED CHEMICAL LOOPING GASIFICATION

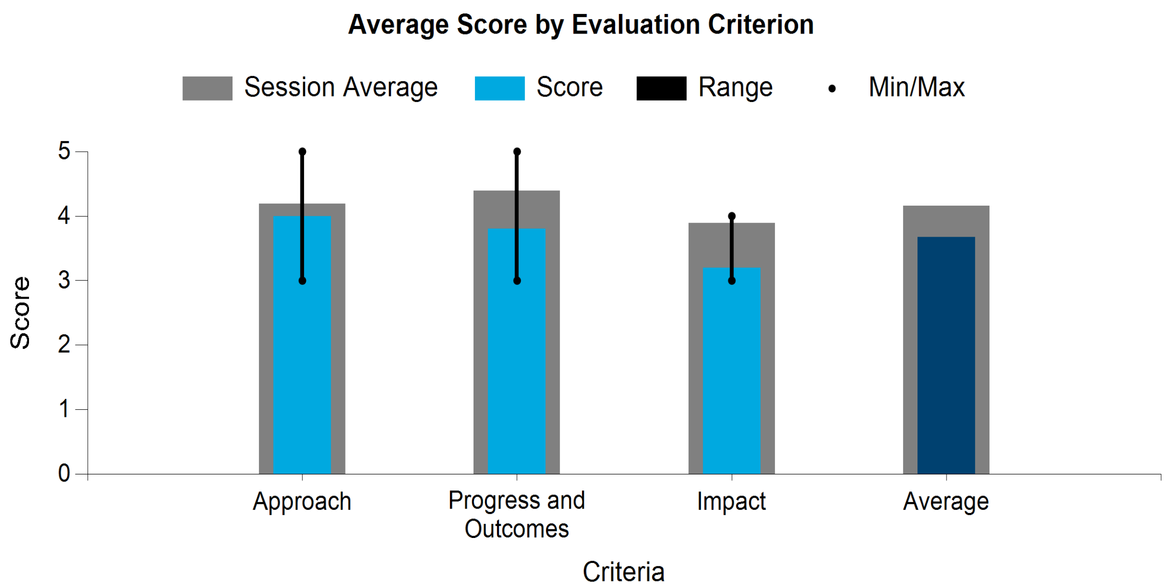
North Carolina State University

PROJECT DESCRIPTION

WBS:	5.1.3.205
Presenter(s):	Fanxing Li
Project Start Date:	10/01/2019
Planned Project End Date:	05/31/2024
Total Funding:	$3,135,560

This project aims to develop and demonstrate a sorption-enhanced chemical looping gasification (SE-CLG) technology that combines biomass gasification, air separation, and syngas conditioning/cleaning into a single circulating fluidized bed (CFB) gasifier. The resulting syngas, with a high H_2:CO ratio, would be ideal for RNG production. This intensified gasification process is facilitated by our recent discovery of unique CO_2 and O_2 phase-transition sorbents (PTSs), which allows dual functionality of air separation and CO_2 capture. As such, it enables sorption-enhanced gasification to produce syngas with a high H_2:CO ratio.

During the first six quarters of this project, the team has successfully demonstrated the functionality and stability of the multifunctional PTSs. Near complete conversions of various tar model compounds and woody biomass particles were achieved in lab-scale reactors, producing syngas with high H_2:CO ratios ideal for methanation reaction. Various sorbents were designed and optimized, showing excellent cyclic stability in the presence of biomass waste ash and under a fluidization environment. A 5-kWh CFB cold model was also designed, constructed, and operated, showing desirable solids circulation rates and stable performance. A hot unit design is subsequently finalized, which will be constructed and demonstrated in Phase II of the project.



COMMENTS

- The team involves an HBCU, which is a great way to incorporate DEI elements and communication into the project.

- Still very early in this project.
- Not clear about the commercialization or the involvement of commercial partners, although the team does appear to be engaged in outreach to these parties.
- Interest from commercial partners in the technology is important and merits more mention. Will be curious to see how the interest plays out.
- Gasification does not tend to be the most common way to address wood waste, so it will be interesting to see the ultimate LCOE and economic metrics.
- Does it matter which part of the wood waste is used? Good that they seem to be pretty agnostic to the construction and demolition waste. Have started doing some characterization of the feedstock.
- Process intensification is a great way to address numerous unit operations and avoid integration.
- Early work shows promise in terms of what the PTS catalyst is supposed to do.
- Project goals are set to show significant improvement in LCOE.
- Have been stepping through the project phases in increasing risk (so sequentially) to minimize challenges.
- Did not discuss risk and contingency plans.
- Have received a quote for the hot reactor, awaiting on a second quote from a different vendor before purchasing.
- Not making fuels and products that are difficult to electrify. Challenge is going to be a lot due to the office's priority shifting away from biogas/natural gas.
- Tested ash at values beyond what you would see in real operation.
- Overview/impact:
    - The researchers assessed the generation of RNG from carbonaceous wastes via phase-transition CO_2/O_2 sorbent-enhanced chemical looping gasification. The researchers applied a novel technique comprising a multifunctional integrated system where mixed oxide-based PTSs are used for biomass gasification with integrated air separation and CO_2 sorption.
    - The project objectives fully align well with the BETO goals, as it serves as a means of generating renewable energy while reducing the release of GHGs into the environment. It is also aimed at reducing the LCOE and increasing the EROI.
    - So far, the project seems to have moderate progress, and a lot still has to be done to develop and validate the equipment that needs to be built for the project.
- Strengths: In this project, the removal of CO_2 occurred through *in situ* capture; thus, there is no need for extra expenses on post-treatment and scrubbing for the removal of CO_2. The presentation shows that the PTS is working properly, and the reactor shows very good performance. Further, the fact that the project involves connections between different experts from different universities and a blended approach to the project makes it worthwhile. Also, the application of different thermogravimetric and mass sorption techniques shows how high the technological expertise of the researchers on this project is. In addition, the buildup of a novel dual fluidized bed gasifier cold model speaks volumes about the ingenuity of the researchers.

- Weaknesses: The project seems to have a lot of phases that are not blended together. Also, the researchers do not provide adequate clarity on how many aspects of the project were conducted. Further, the researchers seem not to have a clear project team communication and management plan. Last, I am wondering if the researchers have considered the limitations of scaling up this system, especially those related to the presence of impurities in the feedstock or feedstock quality.
- Questions: There are many boggling questions with regard to the overall approach for the project. In the first stage of the process, why is torrefaction used as a pretreatment step? Are there other processes that could be looked at for the pretreatment of the biomass? Also, one thing that is not clear is how the authors plan to validate a 35% reduction in LCOE. Further, I am wondering if the researchers could provide more clarification on how the isothermal thermogravimetric analysis test was used to preliminarily test the efficiency of the concept in the project. Another thing that still remains unclear to me is what informed the design of the cold fluidized bed gasifier. It will be good if the researchers could clearly state how the prior experiments they conducted influenced the design of the fluidized bed gasifier. One weakness observed is the catalytic activity for tar removal from the process; can't the tar be recovered and used for the generation of biofuel? I understand that this may be outside the scope of the research study.
- This project addresses the gasification of multiple biomass feedstocks. Among its strengths, it seeks to optimize the efficiency of syngas production and tar removal in a single step. The management and progress on the project appear sound. Further progress will be enhanced by more regular engagement with program partners at other universities and a greater level of engagement with potential use cases through consultation with industry and locality partners. The project also needs to integrate attention to DEI in all stages of project staffing, working proactively with students from the high school through Ph.D. levels in outreach, education, and inclusion on long-term aspects of this project.
- This project was strongly focused on applying fundamental thermodynamics to develop multifunctional mixed-oxide-based PTSs. While I am very pleased that the foundation of this work is in thermodynamics, this poses a particular challenge for this reviewer as far as my ability to understand the technical aspects of this project.
- The management of this project appears to be excellent, with monthly Zoom meetings and numerous in-person meetings with local-ish collaborators. In the future, I urge them to consider a larger, in-person meeting of all the collaborators.
- There is a strong industrial collaborator, and an HBCU (i.e., DEI participant) is involved. The fact that this HBCU is relatively close to North Carolina State University, I believe, increases the chances for impact as far as DEI (i.e., the students at North Carolina A&T are more likely to have a prominent role). The researchers at Yale are responsible for the TEA and LCA
- This project is still early, having yet to reach its first go/no-go milestone. Despite this, there are already substantial results for the speaker to share. Admittedly, though, the scores for "Progress and Outcomes" and "Impact" are likely a little low, simply as an artifact of this project still being relatively new.
- Offers a path to managing construction and demolition wastes, as well as woody biomass, difficult waste streams to mitigate.
- The team indicates active management by selecting members to de-risk forecast issues. Clear diagrams show how each member's work interfaces toward the whole of the project. Interested to hear more about industry partners and the role they fill in creating a circular economy. Concerned about cost inflation of the reactor; how does this compare with existing technologies' TEA? To ensure beneficial outcomes to the performer and government, to what extent are lab wastes applicable to real-world waste streams?

Would significant contamination of streams (chicken waste and/or grit in pine and metals/plastics in construction and demolition waste) negate advances of the research?

PI RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for recognizing the originality of the suggested method and the progress we have made so far while acknowledging that this project is still "relatively new." We are also glad to hear the reviewers acknowledging our DEI efforts in terms of involving an HBCU and their encouragement on furthering our efforts. We agree with the reviewers' concerns over our target product (RNG) but respectfully submit that this target product was required by the original FOA. We also note that the SE-CLG technology we are developing has already shown promise to produce concentrated H_2 or H_2-enriched syngas with varying H_2:CO ratios. The latter can be converted into jet fuels or methanol using commercial technologies. Therefore, SE-CLG can be a platform technology for a variety of renewable products beyond RNG. The feasibility of the SE-CLG and PTS concept was demonstrated through isothermal thermogravimetric analysis, and the preliminary efficiency estimations were based on lab-scale fluidized bed and packed bed data. The design basis for the cold model was established using kinetic measurements from thermogravimetric analysis and lab-scale bubbling fluidized bed experiments. The SE-CLG technology effectively addresses tar, an undesirable biomass gasification byproduct, by converting almost all of it into hydrogen-enriched syngas. In terms of the scalability of SE-CLG and the effect of feedstock impurity, the adopted CFB design offers scalability for commercial-scale applications, and careful attention has been given to impurity considerations. We have tested contaminants at levels well exceeding those in the anticipated industrial operations, and we will continue to assess their impacts during the CFB studies in BP2. We also understand one of the reviewer's comments over "a lot still has to be done" for "the equipment that needs to be built" but respectfully note that the construction and demonstration of the CFB equipment will occur in BP2 according to the statement of project objectives, and currently we are still in BP1. The project progress is fully consistent with the originally proposed objectives, and in several areas, it has exceeded the milestone performance targets. The BP1 work, which focuses on proof of concept, sorbent development, reactor design, and cold model studies, is crucial to de-risk the subsequent BP2 equipment construction and demonstration work. The project will validate the reduction in the levelized cost of electricity through a detailed TEA in BP2, incorporating operational results from the hot CFB unit, preliminary design of the commercial reactor, and vendor-provided cost estimates. Reactor cost inflation will be considered in the TEA, ensuring a comprehensive evaluation of the technology's competitiveness against conventional gasification. In terms of project management and outreach, the project team actively collaborates with industry partners, including a catalyst producer and a large chemical company, while intensifying outreach efforts and engagement with HBCUs. The risk and mitigation aspects were comprehensively considered and addressed in slide 5 of the Project Peer Review presentation.