Project 001(A) Alternative Jet Fuel Supply Chain Analysis

Washington State University

Project Lead Investigator

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- FAA Award Number: 13-C-AJFE-WaSU-023, 026
- Period of Performance: October 1, 2021 to September 30, 2022
- Tasks:
    1. Prepare and assess design cases.
    2. Evaluate the most promising biorefinery concepts for alternative jet fuel (AJF) production.
    3. Supplement and maintain the current inventory of biorefinery infrastructures that are useful for the production of AJF, as identified in the conversion design cases.
    4. Perform a community social asset assessment.
    5. Refine and deploy facility siting tools to determine regional demand and to identify potential conversion sites to be used in regional analyses.
    6. Perform a refinery-to-wing stakeholder assessment.
    7. Conduct a supply chain analysis.
    8. Provide analytical support for regional Commercial Aviation Alternative Fuels Initiative (CAAFI) and U.S. Department of Agriculture (USDA) jet fuel projects.

Project Funding Level

This project has received $1,091,455 in FAA funding, $1,091,455 in matching funds, and state-committed graduate school contributions for four PhD students. Faculty time for Michael Wolcott, Manuel Garcia-Perez, and Xiao Zhang contributes to the cost share.

Investigation Team

- Michael Wolcott, WSU, Project Director/P.I. (Tasks 3,5,7,8)
- Christina Sanders, WSU, Co-Project Director/Co-P.I.
- Season Hoard, WSU, Co-Project Director/Co-P.I.
- Manuel Garcia-Perez, WSU, Co-Project Director/Co-P.I. (Tasks 1,2,7)
- Xiao Zhang, WSU, Co-Project Director/Co-P.I. (Tasks 1,2)
- Ji Yun Lee, WSU, Co-Project Director/Co-P.I.
- Michael Gaffney, WSU, Faculty (Tasks 4,6)
- Kristin Brandt, WSU, Staff Engineer
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- Lina Pilar Martinez Valencia, WSU, Graduate Student/Postdoctoral Research Associate

- Anamaria Paiva, WSU, Graduate Student
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Collaborating Researchers

- Burton English, University of Tennessee
- Edward Yu, University of Tennessee
- Scott Turn, University of Hawaii
- Florian Allroggen, Massachusetts Institute of Technology
- Kristin C. Lewis, Volpe Center

Project Overview

As part of an effort to realize an "aviation system in which air traffic will move safely, swiftly, efficiently, and seamlessly around the globe," the FAA set a series of goals and supporting outcomes, strategies, and performance metrics (Hileman et al., 2013). The goal entitled "Sustaining our Future" outlines several strategies collectively aimed at reducing the environmental and energy impacts of the aviation system. To achieve this goal, the FAA set an aspirational goal for the aviation industry to utilize one billion gallons of AJF by the year 2018. This goal was created according to economic, emissions, and overall feasibility perspectives (Richard, 2010; Staples et al., 2014). In the past year, the goals for U.S. AJF use have been updated with the Sustainable Aviation Fuel (SAF) Grand Challenge that by 2030 the United States will produce and use three billion gallons of AJF, with an increase to 35 billion gallons in 2050 with a minimum reduction of 50% in lifecycle greenhouse gases (White House, 2021).

Most approaches to supply chain analyses for AJF optimize feedstock-to-refinery and refinery-to-wing transportation logistics (Bond et al., 2014). One of the greatest barriers to large-scale AJF production is the high capital of greenfield facilities, which translates to risk in the investment community (Huber et al., 2007). The cost of cellulosic ethanol plants ranges from $10 to $13 per gallon capacity (Hileman & Stratton, 2014); moreover, the additional processing steps required to convert the intermediate to a drop-in AJF could increase this cost to more than $25 per gallon capacity (Hileman, 2014).

Motivated by the realities of converting these initial commercialization efforts into second-generation AJF, researchers have considered alternative conversion scenarios, including the transitioning of existing facilities (Brown, 2013). The conversion of existing refineries to produce renewable diesel and AJF is underway at both the Martinez and Rodeo refineries in California (Marathon, 2022; Phillips 66, 2022). Research on approaches for achieving the SAF Grand Challenge goals for AJF consumption has relied on "switching" scenarios, in which existing and planned capacities are used to produce drop-in fuel (Malina, 2012). These approaches require the identification of existing industrial assets, similar to refinery conversions, that can be targeted for future AJF production. Thus, siting becomes not only an exercise for optimizing feedstock transportation but also a necessary task for aligning this critical factor with the existing infrastructure, markets within regions, and the appropriate social capital for developing this new industry (Henrich et al., 2007; Seber et al., 2014).

To date, all published AJF supply chain analyses have been limited to stand-alone jet fuel production technologies that do not generate bioproducts. Hence, future studies must consider the potential techno-economic and environmental benefits of using the existing industrial infrastructure and the production of co-products with respect to the development of jet fuel production scenarios.

Design cases of stand-alone AJF production facilities will be used in supply chain evaluations. Social asset modeling is not well developed, and efforts are likely to be hampered by difficulties in quantifying social assets when compared with improved environmental performance or reductions in AJF costs, which may be better observed by optimizing economic and environmental constraints. However, the community characteristics of a potential site must be considered when determining preferred locations for a new biorefinery. Community resistance or enthusiasm for the AJF industry can strongly influence the success or failure of a facility (Martinkus et al., 2014; Rijkhoff et al., 2017). Thus, community social asset modeling efforts conducted within this project, such as those based on the Community Asset and Attribute Model (CAAM), will inform disciplinary applications and advances. Clearly, social factors can have substantial effects, either positive or negative, on project adoption and implementation, particularly in high-technology or energy-related projects (Lewis et al., 2012; Martinkus et al., 2012; Mueller et al., 2020). The consideration of social factors in site selection and implementation decisions can maximize positive social support and minimize opposition and social negatives, thereby substantially promoting the success of a project. In this regard, the CAAM originally piloted in the Northwest Advanced Renewables Alliance project was designed to provide a quantitative rating of select social factors at the county level (Martinkus et al., 2014).

Focusing on regional supply chains, this research aims to identify the key barriers that must be overcome to meet AJF targets. We will address this overall goal by developing tools to support the AJF supply chain assessment performed at the Volpe Center. Our efforts will provide facility siting analyses that assess conversion design cases combined with regional supply chain assets and social capacity assessments for communities to act collectively toward development goals. Finally, a refinery-to-wing stakeholder assessment will support modeling and accounting of AJF distribution for downstream fuel logistics.

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Task 1 - Prepare and Assess Design Cases

Washington State University

Objectives

In previous years, our team has worked toward completing reviews and final reports of design cases for six stand-alone AJF technologies (Table 1) and four relevant industries (sugarcane, pulp and paper, corn ethanol, and petroleum refineries). The status of each stand-alone AJF techno-economic analysis (TEA) and report is shown in Table 1. The results on pyrolysis and alcohol-to-jet (ATJ) pathways have been published in the referenced peer-reviewed journals. The work conducted from October 1, 2021 to September 30, 2022 focused on the following tasks:

1. Complete a detailed analysis of a "catalytic hydrothermolysis pathway for jet fuel production," including two publications.
2. Conduct a detailed analysis of a new AJF pathway for hydrothermal liquefaction (HTL) processing.
3. Conduct TEA on the integration of lignin co-product technologies in the ATJ pathway to determine the potential for reducing fuel costs.
4. Develop a new case report focusing on a technology review, an evaluation of lipid conversion processes (hydroprocessed esters and fatty acids [HEFA], catalytic hydrothermolysis [CH], SBI, Forge, Tyton, and decarboxylation), and new technologies for the production of alternative lipids (HTL and sugar-to-lipid).
5. Prepare manuscripts for publication.

Table 1. Evaluated stand-alone alternative jet fuel (AJF) technologies.

	Literature review and design report date	Publications	Techno-economic analysis (TEA) model
Pyrolysis	Literature review based on a design report, 138 pages (2017)	*Energy Fuel 33*, 4683, 2019; *Fuel Process Technology 195*, 106140, 2019	A standardized TEA is complete and available for use by university partners.
Alcohol-to-jet (ATJ)	Literature review based on a design report, 28 pages (2015)	*ChemSusChem 11*, 3728, 2018	A standardized TEA is complete and available for use by partners.
Synthetic kerosene and synthetic aromatic kerosene (SK-SKA)	Literature review based on a design report, 36 pages (2015)	Manuscript based on the case design report in preparation	This work was based on a Sasol process, on which we have not found any significant development since 2016. Because of a lack of adequate process information/data on SK-SKA production from renewable feedstock, we are not able to build a reliable TEA.
Direct sugar-to-hydrocarbon (DSHC)	Literature review based on a design report, 88 pages (2017)	*Biomass and Bioenergy 145:105942*, 2021	A standardized TEA is complete and available for use by partners.
Virent BioForming process	Literature review based on a design report, 46 pages (2015)	*Biomass and Bioenergy 145:105942*, 2021	A standardized TEA is complete and available for use by partners.
Catalytic hydrothermolysis (CH)	Literature review based on a design report, 35 pages (2018)	*Renewable and Sustainable Energy Reviews 115:111516*, 2021 *Data in Brief 39:107514*, 2021	A standardized TEA is complete and has been posted on the WSU repository.
Gasification Fischer Tropsch (GFT)	No literature review conducted	*Biomass and Bioenergy 145:105942*, 2021	A standardized TEA is complete and available for use by partners.
Microchannel GFT (microGFT)	No exhaustive literature review written; capital costs found in the open literature for microchannel FT deemed unreliable	Capital cost results deemed unreliable	A standardized microGFT TEA was completed; however, the cost information is considered unreliable.
Hydroprocessed esters and fatty acids (HEFA)	No literature review conducted	*Biomass and Bioenergy 145:105942*, 2021	A standardized TEA is complete and available for use by partners.

Research Approach

Background

We have conducted a detailed literature review and prepared design case reports on six AJF pathways, including pyrolysis, ATJ, synthetic kerosene, direct sugar-to-hydrocarbon (DSHC), Virent BioForming, and CH. We have also collected data from the literature to conduct TEAs for these pathways. The results from these design cases were applied in the development of supply chains and the identification of synergisms that may eventually lead to the construction of integrated AJF production systems that take advantage of the infrastructure in a given region. An analysis of the locations of existing infrastructure demonstrated that the United States can be divided into regions according to the dominant biomass. Thus, we believe that the generation of advanced biorefinery concepts focused on petroleum refineries, pulp and paper mills, sugarcane mills, and corn ethanol mills is a viable approach for evaluating the synergism among AJF pathways, existing infrastructure, and co-products. We can then compare the biorefinery concepts developed for each technology to identify the most promising approach, which can subsequently be used in supply chain analyses.

Stand-alone design case reports were generated by reviewing relevant research in the academic literature and public information provided by commercial entities developing the corresponding technology. The published manuscripts were subjected to an industrial expert review. The reports provide details regarding the processes involved in each conversion pathway and outline the technology readiness and particular barriers to implementation. Publicly available information regarding the commercial processes and research literature will provide a foundation of information to be used in modeling efforts. In cases lacking detailed process engineering information, new models will be built to estimate the parameters needed to complete assessments such as techno-economic modeling and supply chain modeling. Aspen Plus primarily generates process models and details, including mass balances, energy balances, energy requirements, and equipment size and cost. These results will also provide the basis for a comparative analysis of design cases, which will identify the key advantages and markets for each technology.

Each design case has the following components:

- Feedstock requirements
- Companies developing/commercializing the technology
- Current locations of units in the United States and worldwide
- Block and flow diagram of the technology
- Unit operations and process conditions (reactor type, separation unit type, catalysts, product yield, and jet fuel yield)
- Properties of the produced jet fuel
- Identification of potential intermediates
- Current and potential uses of wastes and effluents
- Developed co-products
- Potential methods for coprocessing intermediates, wastes, and co-products by using existing infrastructure (e.g., petroleum refineries or pulp and paper mills)
- Preliminary TEA
- Technological challenges and gaps

We have submitted technical reports and supplementary Microsoft Excel files with mass and energy balances and TEAs for the pathways listed below. Furthermore, we have conducted a strategic analysis to identify the overall weaknesses of the technologies under study. All files are available on shared drives for the Project 01 team members.

- Pyrolysis-bio-oil hydro-treatment concept (hydro-treated depolymerized cellulosic jet): The TEA is complete.
- ATJ: A manuscript with information on the mass and energy balances and the TEA has been published.
- Gasification Fischer Tropsch (GFT): Two design cases have been prepared for biomass gasification. The first case focuses on microreactors, and the second design case is applicable to technology based on larger, standard reactors (reviews on the TEAs for GFT and microGFT have been completed). However, the limited reliability of the microreactor capital costs hinders the value of the practical impact of our microreactor TEA study. The TEAs are available for use by partners.
- HEFA: A stochastic TEA was created in MATLAB and was confirmed to match the completed, deterministic TEA when the assumptions and costs match (deterministic TEA review completed). The TEA is now available for use.
- CH: The TEA is complete.

Major progress has been made on the analysis of corn ethanol, sugarcane, and petroleum refinery infrastructure that could support jet fuel production. A manuscript on the conversion of corn ethanol mills was published in *Biomass and Bioenergy*. Two additional manuscripts repurposing either sugarcane mills or petroleum refineries to reduce AJF production costs were also published.

We have worked with the Pacific Northwest National Laboratory and completed a case design report on HTL for AJF conversion.

A summary manuscript reviewing several lipid conversion pathways, including SBI, Forge, Tyton, decarboxylation, and coprocessing, entitled "Lipid and Bio-processing Technologies: An Insight into Bioconversion Potential of Process Intensification and Continuous Flow-Through Reaction (PICFTR), Lipid to Hydrocarbon (LTH) and TYTON Bioenergy" has been prepared.

Milestones

A Microsoft Excel file with TEAs for all AJF technologies has been completed, and design cases for the corn ethanol and sugarcane industries have been completed. A detailed analysis entitled "Catalytic Hydrothermolysis Pathway for Jet Fuel Production" has been completed, and a manuscript entitled "Jet Fuel Design Case: Hydrothermal Liquefaction Case Design Report" has been published. A summary report entitled "Lipid and Bio-processing Technologies: Process Intensification and Continuous Flow-Through Reaction (PICFTR), Lipid-to-Hydrocarbon (LTH), Tyton, Decarboxylation and Coprocessing" has been produced, and corresponding manuscripts have been prepared for publication.

Major Accomplishments

A manuscript entitled "Economic Analysis of Catalytic Hydrothermolysis Pathway for Jet Fuel Production" has been published in *Renewable and Sustainable Energy Reviews*, and a TEA dataset on the CH pathway for jet fuel production was published in *Data in Brief* in 2021. A manuscript reporting on a preliminary TEA of biorefinery lignin for fine chemical production was published in *Green Chemistry* in 2021. We have also updated two draft manuscripts: "Hydrothermal Liquefaction Case Design Report" and "Lipid and Bio-processing Technologies: An Insight into Bioconversion Potential of Process Intensification and Continuous Flow-Through Reaction (PICFTR), Lipid to Hydrocarbon (LTH) and TYTON Bioenergy." A manuscript entitled "Comparison of Techno-economic and Environmental Performance of Alternative Jet Fuel Production Technologies" has been prepared, reviewed, and updated in preparation for FAA review. We intend to submit these manuscripts to the FAA for review within the next four months. We are working on the construction of a TEA for lignin extraction and utilization in a biorefinery process (NREL, 2018).

We have assisted the International Civil Aviation Organization (ICAO), Committee on Aviation Environmental Protection through participation in the Fuel Task Group and the Long-Term Aspirational Goal task group. An Excel spreadsheet of publicly announced, global AJF producers has been updated, and work with ICAO for integrating the historical portion of these data with their database is ongoing. In addition, a separate U.S. database that does not include ICAO-specific assumptions and data is being maintained to assist in tracking progress toward meeting the SAF Grand Challenge goals.

Six Excel spreadsheet-based TEAs have been published on the WSU repository site to make these tools publicly available for analyses. These TEAs include HEFA, ATJ, FT with both solid and gaseous feedstocks, FT feedstock preparation, pyrolysis, and CH. The TEAs are being used by other ASCENT member universities and interested industry and government parties.

Data generated from the design cases have been made available to 01A partners to assist with supply chain analysis and techno-economic modeling by improving the conversion and cost figure database values. Evaluations of the effects of process variations in the chemical properties of the generated products are being used to provide insight into the challenges that will be faced when AJFs are blended into commercial jet fuel.

Publications

Peer-reviewed journal publications

Brandt, K., Camenzind, D., Zhu, J. Y., Latta, G., Gao, J., & Wolcott, M. (2022). Methodology for quantifying the impact of repurposing existing manufacturing facilities: Case study using pulp and paper facilities for sustainable aviation fuel production. *Biofuels, Bioproducts and Biorefining*, *16*(5), 1227–1239. https://doi.org/10.1002/bbb.2369

Brandt, K. L., Martinez-Valencia, L., & Wolcott, M. P. (2022). Cumulative impact of federal and state policy on minimum selling price of sustainable aviation fuel. *Frontiers in Energy Research*, *10*, 828789. Doi: 10.3389/fenrg.2022.828789

Eswaran, S., Subramaniam, S., Geleynse, S., Brandt, K., Wolcott, M., & Zhang, X. (2021). Dataset for techno-economic analysis of catalytic hydrothermolysis pathway for jet fuel production. *Data in Brief*, *39*, 107514. Doi: 10.1016/j.dib.2021.107514

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Tanzil, A. H., Brandt, K., Wolcott, M., Zhang, X., & Garcia-Perez, M. (2021). Strategic assessment of sustainable aviation fuel production technologies: Yield improvement and cost reduction opportunities. *Biomass and Bioenergy*, *145*, 105942. Doi: 10.1016/j.biombioe.2020.105942

Outreach Efforts

During the preparation of design case reports, we have closely interacted with industrial companies, including Gevo, LanzaTech, Sky Energies, and Agrisoma (now NuSeed). These companies have also helped us review reports and draft manuscripts. Our results have been presented to the FAA and CAAFI. Six harmonized TEAs have been posted on the WSU Research Repository for public use. We have also made several presentations to graduate and undergraduate students.

- Wolcott, M., Brandt, K. SAF Grand Challenge A Path to 3-billion Gallons by 2030. SAF Summit & CAAFI Biennial General Meeting. (2022)
- Brandt, K; Tanzil, AH; Martinez-Valencia, L; Garcia-Perez, M; Wolcott, MP; Pyrolysis techno-economic analysis, v. 2.1. Washington State University (2022)
- Brandt, K; Wolcott, MP; Fischer Tropsch feedstock pre-processing techno-economic analysis, v. 2.1. Washington State University (2022)
- Brandt, K; Tanzil, AH; Martinez-Valencia, L; Garcia-Perez, M; Wolcott, MP; Fischer Tropsch techno-economic analysis, v. 2.1. Washington State University (2022)
- Brandt, K; Tanzil, AH; Martinez-Valencia, L; Garcia-Perez, M; Wolcott, MP; Hydroprocessed esters and fatty acids techno-economic analysis, v. 2.1. Washington State University (2022)
- Brandt, K; Geleynse, S; Martinez-Valencia, L; Zhang, X; Garcia-Perez, M; Wolcott, MP; Alcohol to jet techno-economic analysis, v. 2.1. Washington State University (2022)
- Brandt, K; Eswaran, S; Subramaniam, S; Zhang, X; Wolcott, MP; Catalytic hydrothermolysis techno-economic analysis, v. 2.1. Washington State University (2022)

Awards

None.

Student Involvement

Several graduate students (Sudha Eswaran, Kelly Nguyen, Abid Hossain Tanzil, Anamaria Paiva, and Lina Martinez) and one undergraduate student (Kitana Kaiphanliam) participated in the creation, editing, and updating of design cases for stand-alone AJF technologies, relevant existing infrastructure, and lignin co-products.

Plans for Next Period

We will focus on the following areas and plan to submit three to five manuscripts on lignin co-product analyses and AJF technology analyses. The following are the proposed manuscripts to be completed this project year:

1. Continue to support ICAO work through participation in the Committee on Aviation Environmental Protection's Fuel Task Group.
2. Lipid and Bio-processing Technologies: Process Intensification and Continuous Flow-Through Reaction (PICFTR), Lipid-to-Hydrocarbon (LTH), Tyton, Decarboxylation, and Coprocessing.
3. The Opportunity for Lignin Co-Products to Improve the Economics of Sustainable Aviation Fuel Production.

References

National Renewable Energy Laboratory. (2018). *Process Design and Economics for the Conversion of Lignocellulosic Biomass* *to Hydrocarbon Fuels and Coproducts: 2018 Biochemical Design Case Update* (Publication No. NREL/TP-5100-71949). https://www.nrel.gov/docs/fy19osti/71949.pdf

Task 2 - Evaluate the Most Promising Biorefinery Concepts for AJF Production

Washington State University

Objectives

Continuation from previous years

We have completed our evaluation of biorefinery scenarios for AJF production using corn ethanol, sugarcane, and pulp and paper mills and petroleum refineries.

We will conduct detailed TEAs on the integration of lignin co-product technologies and the ATJ pathway to determine the potential for reducing fuel costs.

Research Approach

Background

In this task, we used the design cases for existing infrastructure, AJF production technology, and identified co-products to generate new biorefinery concepts for petroleum refineries, pulp and paper mills, sugarcane mills, and corn ethanol mills. The results from this effort will allow us to identify and select the most commercially feasible biorefinery concepts. Major technical gaps or barriers to the commercialization of each biorefinery concept will also be determined from the results of this study.

The integration of process technologies will be assessed with an approach similar to that for the stand-alone design cases. The integration concepts will be developed by pairing stand-alone cases with these concepts to evaluate the economic and environmental advantages of the integration approaches. Over this period, we have conducted detailed analyses of ATJ conversion and integration with pulp mill operations. We have also investigated the potential contribution of lignin co-products to the overall process economy.

A dry-grind corn ethanol mill with a capacity of 80 million gallons of ethanol per year was studied to evaluate potential biorefinery scenarios for AJF production. Similarly, we used a sugarcane mill with a sugarcane processing capacity of 12,444 million tons per day that produces raw sugar, molasses, surplus bagasse, and surplus electricity. The petroleum refinery used as the base case processes 120,000 barrels per day of crude oil. Five AJF technologies were studied: Virent's BioForming, ATJ, DSHC, fast pyrolysis, and GFT. A standardized methodology was adopted to compare the biorefinery concepts for a dry-grind corn ethanol mill, sugarcane mill, and petroleum refinery in several integration scenarios with six jet fuel production scenarios. For all cases, we estimated the minimum fuel selling price and greenhouse gas emissions.

A manuscript on the integration of ATJ technologies with pulp mill infrastructure was published. Three additional manuscripts were published with results for corn ethanol mills, sugarcane mills, and petroleum refineries.

Use a p-graph to generate and rank biorefinery concepts utilizing a database of SAF's technological pathways built from a data base of unitary operations created by our team.

Major Accomplishments

Building on the ATJ pathway analyses, we have analyzed the integration of the ATJ process within the pulp, corn ethanol, sugarcane, and petroleum refinery infrastructure. A manuscript entitled "Pulp Mill Integration with Alcohol-to-Jet Conversion Technology" has been published in *Fuel Processing Technology*. Economic models and life cycle assessments have been applied to select the most promising biorefinery concepts for corn ethanol, sugarcane, pulp and paper, and petroleum refineries. A manuscript on corn ethanol was published in *Biomass and Bioenergy*. A manuscript on integration with petroleum refineries was published in *Frontiers in Energy Research*, and a manuscript analyzing the integration of AJF with sugarcane mills was published in *Fuel*.

A manuscript entitled "Synthesis and Techno-Economic Analysis of Pyrolysis-Oil-Based Biorefineries Using P-Graph" was published in *Energy and Fuels*.

Publications

Peer-reviewed journal publications

Tanzil, A. H., Brandt, K., Zhang, X., Wolcott, M., Silva Lora, E. E., Stockle, C., & Garcia-Perez, M. (2022). Evaluation of bio -refinery alternatives to produce sustainable aviation fuels in a sugarcane mill. *Fuel*, *321*, 123992. doi: 10.1016/j.fuel.2022.123992

Tanzil, A. H., Brandt, K., Zhang, X., Wolcott, M., Stockle, C., & Garcia-Perez, M. (2021). Production of sustainable aviation fuels in petroleum refineries: Evaluation of new bio-refinery concepts. *Frontiers in Energy Research*, *9*, 735661. doi: 10.3389/fenrg.2021.735661

Tanzil, A. H., Zhang, X., Wolcott, M., Brandt, K., Stöckle, C., Murthy, G., & Garcia-Perez, M. (2021). Evaluation of dry corn ethanol bio-refinery concepts for the production of sustainable aviation fuel. *Biomass and Bioenergy*, *146*, 105937. doi: 10.1016/j.biombioe.2020.105937

Pinheiro Pires, A. P., Martinez-Valencia, L., Tanzil, A. H., Garcia-Perez, M., García-Ojeda, J. C., Bertok, B., Heckl, I., Argoti, A., & Friedler, F. (2021). Synthesis and techno-economic analysis of pyrolysis-oil-based biorefineries using p-graph. *Energy & Fuels*, *35*(16), 13159–13169. doi: 10.1021/acs.energyfuels.1c01299

Geleynse, S., Jiang, Z., Brandt, K., Garcia-Perez, M., Wolcott, M., & Zhang, X. (2020). Pulp mill integration with alcohol-to-jet conversion technology. *Fuel Processing Technology*, *201*, 106338. doi: 10.1016/j.fuproc.2020.106338

Outreach Efforts

None.

Awards

None.

Student Involvement

Graduate students (Senthil Subramaniam, Kelly Nguyen, Abid Hossain Tanzil, Lina Martinez Valencia, and Anamaria Paiva) have received training in this project. An undergraduate student, Kitana Kaiphanliam, funded under a National Science Foundation Research Experience for Undergraduates grant, assisted in building techno-economic models for co-product production scenarios.

Senthil Subramaniam, who has been supported by this project, graduated with a PhD degree from WSU (December 2020).

Kelly Nguyen, who has been supported by this grant, graduated with a Master’s degree from WSU (May 2020).

Abid Hossain Tanzil submitted and defended a PhD dissertation during the fall 2020 semester.

Plans for Next Period

During the next period, Dr. Zhang’s team will focus on lignin manuscripts and corresponding TEAs. Dr. Garcia-Perez’s team will work to generate new biorefinery systems using p-graphs.

Task 3 - Supplement and Maintain the Current Inventory of Biorefinery Infrastructures that are Useful for AJF Production, as Identified in the Conversion Design Cases

Washington State University

Objective

This task requires periodic evaluation of the databases to add new facilities or update the status of closed facilities in each category to ensure that the geospatially specific assets are current.

Research Approach

The use of existing infrastructure assets is a key component of retrofit approaches for advances in this industry. To differentiate between the relative values of various options, the specific assets must be valued with respect to their potential use within a conversion pathway. Regional databases of industrial assets that might be utilized by a developing AJF industry have been assessed on the national level. These baseline databases have been compiled from a variety of sources, including industry associations, universities, and news outlets. These databases will be expanded, refined, and validated as the conversion design cases indicate additional needs for regional analyses.

Milestones

National databases have been compiled, geolocated, validated, and shared for biodiesel, corn ethanol, energy pellet, pulp and paper, and sugar mill production. We have evaluated the databases as necessary to add new facilities or change the status of closed facilities in each category, to ensure that the geospatially specific assets are current.

The geospatial infrastructure data were converted for use in supply chain resiliency models. Tools were updated for transportation cost modeling, which should lead to future improvements.

Major Accomplishments

National databases have been compiled, validated, and shared with the 01A teams. All metadata are available for use in regional analyses.

Publications

None.

Outreach Efforts

None.

Awards

None.

Student Involvement

None.

Plans for Next Period

None.

Task 4 – Perform a Community Social Asset Assessment

Washington State University

Objective

The objective of this task is to update CAAM with available data and strategically apply it to additional U.S. regions.

Research Approach

Based on the Community Capitals Framework, we created the CAAM model, which provides quantitative indicators of four social assets: social, cultural, human, and political capital. The CAAM provides quantitative proxy measures of qualitative concepts for initial site-selection assessments. Variations of the model have been applied to the Pacific Northwest, Idaho, Montana, Colorado, and Wyoming. Manuscripts on applications of the CAAM have been published in *Community Development*, *Politics and Life Sciences*, *Biomass & Bioenergy*, and *Frontiers in Energy Research*. The CAAM model is being updated with current data with plans to apply it to other regions and contexts.

Milestone

CAAM benchmark measures have been applied to the Bioenergy Alliance Network of the Rockies (BANR) region.

Major Accomplishments

The collaboration with the BANR social science team and application of the CAAM to Colorado and Wyoming have been completed. These efforts resulted in a publication in *Frontiers in Energy Research*. Additionally, the CAAM team published a manuscript in *Frontiers in Energy Research* that reviews social science applications in sustainable aviation research.

Publications

Peer-reviewed journal publications

Boglioli, M., Mueller, D. W., Strauss, S., Hoard, S., Beeton, T. A., & Budowle, R. (2022). Searching for culture in "cultural capital": The case for a mixed methods approach to production facility siting. *Frontiers in Energy Research*, *9*, 772316. doi: 10.3389/fenrg.2021.772316

Anderson, B. J., Mueller, D. W., Hoard, S. A., Sanders, C. M., & Rijkhoff, S. A. M. (2022). Social science applications in sustainable aviation biofuels research: Opportunities, challenges, and advancements. *Frontiers in Energy Research*, *9*, 771849. doi: 10.3389/fenrg.2021.771849

Outreach Efforts

None.

Awards

None.

Student Involvement

None.

Plans for Next Period

We will update the CAAM with the latest U.S. data.

Task 5 - Refine and Deploy Facility Siting Tools to Determine Regional Demand and Potential Conversion Sites to be Used in Regional Analyses

Washington State University

Objective

This task's objective is to develop tools for siting potential conversion facilities. Two primary tools are needed for this task: a generalized tool to site initial locations that meet the needs of a specific conversion facility type and a second tool to select optimal conversion facility sites from the initial set of locations.

Research Approach

We began developing a geospatial siting pre-selection (GSP) tool in early 2019. This tool is a Python-based script that automates ArcGIS to produce points representing locations that suit the needs of a conversion facility. The GSP tool uses a combination of buffer and cost datasets. Buffer datasets ensure that a candidate is sited in proximity to the necessary infrastructure, such as roads, rails, and natural gas pipelines. Because the candidate set generated by using only buffers will be very large, cost datasets have been added to distinguish candidates from each other. Cost datasets represent geospatially variable costs including electricity, natural gas, and transportation. In early 2020, a graphic user interface was added to the GSP tool to make it more user-friendly. An additional script was developed in 2022 to model the transportation cost inputs for the GSP tool based on the local density of feedstock, the maximum feasible travel distance from the facility for feedstock collection, and regional road characteristics. This script also includes a rudimentary user interface.

The Many Step Transshipment Solver (MASTRS) is another Python-based script that models large supply chains across multiple levels by building and solving mixed-integer linear programming problems. The model starts with feedstock spread across many locations and then models the distribution and conversion of feedstock into biofuels and other co-products through multiple levels of intermediate facilities that may include temporary storage, pre-treatment, and fuel production, before new products are sent to their destinations. Intermediate facilities may include existing facilities or new candidate facilities that are generated by the GSP tool. The MASTRS output shows the flow of materials throughout the supply chain and the most cost-efficient capacities and locations for new facilities.

The modeling combination of GSP and MASTRS scripts has been implemented for several regional supply chains. MASTRS was first implemented with the Pacific Northwest oilseed-to-jet-fuel supply chain in 2018. Since 2019, GSP and MASTRS scripts have been used together for two supply chain models for both the production of jet fuel from forest residuals and lumber production byproducts in the Pacific Northwest. The first supply chain model uses single-stage conversion at integrated biorefineries, and the second supply chain model is a multi-stage model with distributed pre-processing facilities.

Milestones
The GSP and MASTRS tools have undergone continual development to become more practical. Along with the expansion of tool capabilities, substantial improvements have been made regarding tool accessibility for new potential users.

Major Accomplishments
None.

Publications
None.

Outreach Efforts
None.

Awards
None.

Student Involvement
None.

Plans for Next Period
We plan to begin the process for publishing manuscripts that define the GSP and MASTRS tools. We will continue implementing the GSP and MASTRS tools in regional supply chain analyses and will complete the BANR supply chain analysis.

Task 6 - Perform a Refinery-to-Wing Stakeholder Assessment
Washington State University
The full report for this task is provided in the report for Award No. 13-C-AJFE-PSU-002.

Objective
We will extend the stakeholder assessment to a limited sample of informed stakeholders in the remaining sections of the country to provide insight into market and industry dynamics, with the aim of optimizing successful outcomes.

Research Approach
A national survey of airport management, fixed base operators, aviation fuel handlers, and relevant airlines to assess opinions on factors impacting the adoption and diffusion of AJF was completed in 2019. Unfortunately, low response rates impacted data collection and analysis.

Milestones
None.

Major Accomplishments
None.

Publications
None.

Outreach Efforts
None.

Awards
None.

Student Involvement
None.

Plans for Next Period
We plan to complete an updated publication based on national results.

Task 7 - Conduct a Supply Chain Analysis
Washington State University, Volpe

Objective
WSU and Volpe have each developed modeling tools that apply transshipment optimization to model the geospatial layout of developing supply chains. A comparison of these tools would be useful to identify the strengths and weaknesses of each.

The objective of Task 7 is to develop tools for supply chain risk and resilience assessment. To achieve this objective, WSU has developed a theoretical framework that assesses the resilience of a supply chain system subjected to various risk factors. In addition, by working closely with the Volpe Freight and Fuel Transportation Optimization Tool (FTOT) team, WSU has developed FTOT supply chain resilience (FTOT-SCR) tools.

Research Approach
Focusing on the use of woody-biomass-to-jet-fuel conversion via fast pyrolysis and the upgrading of a supply chain centered in the northern Rockies, a series of comparison studies was conducted by using optimization tools from Volpe and WSU. Each modeling approach was required to determine sites for new pyrolysis depots and upgrading refineries. Forest production data were provided by the land use and resource allocation (LURA) model from the University of Idaho. Pyrolysis depot locations were selected by candidate generation tools included in each approach, and existing petroleum refineries were used as candidates for upgrading refineries. Cities, ports, and airport hubs throughout the U.S. West Coast and Rocky Mountain regions were used as markets for road transportation fuel, bunker fuel, and jet fuel.

Probabilistic Wildfire Risk Assessment
A new probabilistic framework was proposed to quantitatively assess wildfire risk to a supply chain network. This framework provides rigorous probabilistic descriptions of wildfire ignition likelihood and growth, the interaction between supply chain components and wildfire, consequent component damage, and network-level performance reduction. The framework has been designed to systematically account for uncertainties throughout all phases of risk assessment. The framework first develops a wildfire occurrence estimation model by combining historical fire records with weather data and estimates the occurrence times and locations of fire ignitions through Monte Carlo simulation. The growths of all ignitions are then simulated based on weather conditions, topography, and fuel properties. For each simulated fire, the component-level physical damages and losses of functionalities are calculated based on vulnerability analyses and are subsequently incorporated into supply chain analysis to capture risk propagation throughout the network. In this manner, wildfire-caused supply chain disruptions can be quantified in terms of the post-wildfire unmet demand ratio, total supply chain cost, and total transportation time. This framework can be used as a planning tool to evaluate network performance subject to a set of what-if scenarios and assess the effect of pre- and post-wildfire risk mitigation measures.

Multi-Component Resilience Assessment
As part of this task, the team completed the development of a quantitative resilience assessment framework for a supply chain system exposed to multiple risk factors consisting of two stages: multi-risk assessment and multi-component resilience assessment. The first stage identifies the key risk factors that may affect supply chain performance over the planning horizon and combines their effects by generating a set of plausible scenarios. In the second stage, a new multi-component resilience index is proposed to measure (a) hazard-induced cumulative loss of functionality, (b) opportunity-induced cumulative gain of functionality, and (c) non-hazard-induced cumulative loss of functionality. The proposed resilience index is divided into these three measurable components to render each component more manageable and to facilitate decisions regarding the effective combination of various resilience-enhancing strategies. Finally, a hypothetical forest-residuals-to-SAF supply chain system in the Pacific Northwest region has been introduced to illustrate the proposed framework. This framework can provide

decision-makers with information on the key risk factors that should be mitigated to enhance supply chain resilience. Such information can be further used to determine cost-effective resilience-enhancing solutions.

Milestones

The team completed the development of both theoretical and FTOT tools for supply chain risk and resilience assessment. The FTOT-SCR tool is now available for use, and a manuscript detailing the theoretical procedure for this FTOT-SCR tool has been submitted. A manuscript on probabilistic wildfire risk assessment for a supply chain network was published in September 2022 in the *International Journal of Disaster Risk Reduction*.

Major Accomplishments

The WSU MASTRS and Volpe FTOT were compared for siting analyses in the BANR region. Similar and differing modeling assumptions were identified, and the appropriate model for a given objective was determined.

The team completed the development of both theoretical and FTOT tools for supply chain risk and resilience assessment.

Theoretical framework: The team presented the theoretical framework and a corresponding case study at the ASCENT meeting in February 2022 and submitted a manuscript on multi-component resilience assessment. A conference paper that applied this theoretical framework to a transportation network was presented at the *13th International Conference on Structural Safety and Reliability*, Shanghai, China (Zhao et al., 2022a).

FTOT tool: The FTOT-SCR tool has been released and is now available on a GitHub fork of the main FTOT-Public repository. Upon completion, the team presented this FTOT-SCR tool at the FTOT Users' Group meeting in April 2022. In addition, the team has utilized the FTOT-SCR tool in other studies and has published these findings (Zhao et al., 2022b)

The team completed the development of a probabilistic wildfire risk assessment framework for a supply chain network. A manuscript and conference paper were published as part of this subtask (Ma et al., 2022; Ma and Lee, 2022).

We published a review on the selection and cost estimation of commercially available equipment involved in the collection and adequation of feedstock. The publication includes aggregated information regarding equipment cost, energy consumption, efficiency, feedstock storage, and transportation systems. Five feedstock types for producing AJF were studied: (a) agricultural residues and grasses, (b) forest residues, (c) urban wood waste, (d) oilseeds, and (e) fats, oils, and greases.

Publications

Ma, F., Lee, J. Y., Camenzind, D., & Wolcott, M. (2022). Probabilistic Wildfire risk assessment methodology and evaluation of a supply chain network. *International Journal of Disaster Risk Reduction*, *82*, 103340. Doi: 10.1016/j.ijdrr.2022.103340

Ma, F., Lee, J.Y. (2022). "Probabilistic wildfire risk assessment for a supply chain system." *Proceedings of the 13th International Conference on Structural Safety and Reliability*, Shanghai, China, September 2022.

Martinez-Valencia, L., Camenzind, D., Wigmosta, M., Garcia-Perez, M., & Wolcott, M. (2021). Biomass supply chain equipment for renewable fuels production: A review. *Biomass and Bioenergy*, *148*, 106054. Doi: 10.1016/j.biombioe.2021.106054

Zhao, J., Lee, J.Y. (2022a). "Multi-component resilience assessment framework for transportation systems." *Proceedings of the 13th International Conference on Structural Safety and Reliability*, Shanghai, China, September 2022.

Zhao, J., & Lee, J. Y. (2022). Effect of connected and autonomous vehicles on supply chain performance. *Transportation Research Record: Journal of the Transportation Research Board*, 036119812211154. Doi: 10.1177/03611981221115425

Outreach Efforts

None.

Awards

None.

Student Involvement

Dane Camenzind, MS in Environmental Engineering, WSU, graduated in September 2019 and is currently employed by WSU as an operations research engineer.

Jie Zhao, PhD in Civil Engineering, WSU, graduated in August 2022 and is currently a postdoctoral scholar in the Department of Civil and Environmental Engineering at WSU.

Fangjiao Ma, PhD candidate in Civil Engineering, WSU, successfully passed his preliminary examination.

Plans for Next Period

We will utilize regional supply chain tools to assess forest residuals for SAF using pyrolysis methods, as described below for Task 8.

The team will complete the development of (a) a comprehensive machine-learning-assisted wildfire risk assessment tool for a supply chain network and (b) a robust, adaptive decision-making framework for a supply chain system. The team also plans to submit two manuscripts for publication.

Task 8 - Provide Analytical Support for Regional CAAFI and USDA Jet Fuel Projects

Washington State University

Objectives

We will develop a readiness-level tool to assess the status of regional SAF production projects and will use supply chain and stand-alone design cases to support the USDA BANR project in TEA and supply chain analysis. This regional Community Agricultural Project (CAP) focuses on the use of softwood forest salvage feedstock for fuels via a catalyzed pyrolysis conversion pathway.

We will assess the regional feedstock, conversion pathways and fuel minimum selling price (MSP) for SAF manufactured in the northwest United States. The aim of this work, requested by the Port of Seattle, is to determine whether the Seattle-Tacoma International Airport can attain its 10% SAF goal by using SAF manufactured in the region from regional feedstock.

Research Approach

We will develop readiness-level tools for regional projects to assess the status of developing fuel projects and to identify critical missing components. This tool will be similar in form to the CAAFI Feedstock and Fuel Readiness Levels tool and will be used to assist CAAFI in understanding the stage of development for projects of interest and to assess critical gaps. In addition, we will assist the regional USDA BANR team in deploying TEA and supply chain analysis for their project. This effort will focus on the use of softwood forest salvage feedstock in a thermochemical conversion process to produce fuels and co-products.

The facility siting tools discussed in Task 5, i.e., GSP and MASTRS, have been implemented for the BANR supply chain and Port of Seattle project. The most recent model runs included feedstock and markets in an 11-state region including the West Coast and intermountain regions. Feedstocks include forest residue from logging operations, mill residues from lumber production, and beetle-killed timber. The model results generated by MASTRS will help determine the relationships between facility location, fuel MSP, and conversion facility revenue.

The Port of Seattle project required a detailed feedstock survey for forest residuals, municipal solid waste, and lipids. Forest residuals were quantified with the LURA model for Oregon, Washington, Idaho, and Montana. Regional landfills were identified and located, scales were determined, and the remaining lifetimes were assessed to determine the most viable biorefinery location. The composition of municipal solid waste in the region was determined, as well as a method and the related costs for sorting the material to match the SAF conversion pathway. Lipids were separated into two major categories: (a) waste fats, oils, and greases and (b) vegetable oil. Each feedstock was quantified and then paired with a compatible SAF conversion pathway to determine the SAF MSP by using ASCENT-developed TEAs.

A financial model that uses a system dynamics approach was conceptualized and developed. The model analyzes the effects of policies on the financial performance of projects to produce SAF. This model can perform both deterministic and stochastic analyses. A case study was developed based on the production of SAF from municipal solid waste in the United States and the U.S. Northwest for regional deployment.

Milestones

We are making progress in the use of supply chain and stand-alone design cases to support the USDA BANR project in TEA and supply chain analysis. Additionally, we have supported the BANR team in creating TEAs for the technologies under consideration.

The Port of Seattle analysis and report have been completed, submitted, and presented.

A review entitled "Supply chain configuration of sustainable aviation fuel: review, challenges, and pathways for including environmental and social benefits" was published in *Renewable and Sustainable Energy Reviews*. A companion manuscript that analyzes the effect of policies that incentivize CO_2e reductions on the financial performance of AJF projects was submitted to the *Journal of Cleaner Production*.

Major Accomplishments

We have collaborated with the USDA BANR project team and attended their annual meeting to coordinate analyses. We currently await their completion of dead wood estimates to complete the supply chain analysis. Moreover, analyses with previous forest-residue data have been successfully modeled.

The Port of Seattle feedstock and SAF assessment was completed, presented to the Port of Seattle, and released to the public.

Publications

Peer-reviewed journal publications

Martinez-Valencia, L., Garcia-Perez, M., & Wolcott, M. P. (2021). Supply chain configuration of sustainable aviation fuel: Review, challenges, and pathways for including environmental and social benefits. *Renewable and Sustainable Energy Reviews*, *152*, 111680. doi: 10.1016/j.rser.2021.111680

Martinez-Valencia, L., Peterson, S. Brandt, K., King, A., Garcia-Perez, M., Wolcott, M. Impact of services on the supply chain configuration of sustainable aviation fuel: The case of CO_{2e} emission reduction in the U.S. (*Submitted to Journal of Cleaner Production*)

Outreach Efforts

Martinez, L., Brandt, K., Camenzind, D., Wolcott, M. ASCENT Supply Chain Tools. SAF Summit & CAAFI Biennial General Meeting. June 2, 2022.

Awards

None.

Student Involvement

Dane Camenzind, MS in Environmental Engineering, WSU, graduated in September 2019 and is currently employed by WSU as an operations research engineer.

Lina Martinez, PhD candidate in Biosystems Engineering, WSU graduated in April of 2022 and now works for WSU as a postdoctoral research associate.

Plans for Next Period

- Analysis of the BANR region is underway and will be completed in 2022.
- The Port of Seattle report will be adapted for peer-reviewed publication.