Project 080(B) Hydrogen and Power-to-Liquid Concepts for Sustainable Aviation Fuel Production

Massachusetts Institute of Technology

Project Lead Investigators

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University Participants

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- P.I.: Dr. Florian Allroggen
- FAA Award Number: 13-C-AJFE-MIT, Amendment Nos. 091, 101, 115, 124, 128, 133, 136, and 143
- Period of Performance: October 1, 2021, to August 31, 2027
- Tasks (during current reporting period, October 1, 2024, to September 30, 2025):
    4. Develop methods for assessing the economic and environmental impacts of promising sustainable aviation fuel (SAF) production pathways
    5. Apply models to analyze the economic and environmental footprint of SAF production pathways
    6. Analyze the prospects of direct air capture (DAC) of atmospheric carbon dioxide (CO_2) to provide a carbon source for SAF production

    Note: additional tasks to be reported separately by Washington State University

Project Funding Level

The Federal Aviation Administration (FAA) provided $950,000 in funding; $950,000 matching funds were committed. Sources of matching funds are approximately $264,100 from MIT, plus third-party in-kind contributions of $101,000 from Savion Aerospace Corp., $213,000 from NuFuels LLC, and $371,900 from Earth Force Technologies.

Investigation Team

Florian Allroggen (P.I.), Tasks 4, 5, and 6
Niamh Keogh (Research Scientist), Tasks 4, 5 and 6
Tae Joong Park (graduate research assistant), Tasks 4 and 5
Tara Housen (graduate research assistant), Task 6

Project Overview

The aviation industry is under pressure to diversify its energy supply. The use of SAF is considered one of the most promising approaches to meet the industry’s targets. To date, no comprehensive assessment exists which analyzes how different carbon sources, hydrogen sources, and conversion processes can be combined to make SAF with lowest costs and highest benefits. The goals of this research project are to (1) evaluate the strengths and weaknesses of hydrogen production and power-to-liquid (PtL) concepts in comparison to current SAF production pathways, (2) assess how hydrogen production and PtL production can be integrated with existing production and distribution infrastructure, and (3) analyze the effects these technologies could have on the current production of SAF (e.g., impacts, cost). The MIT team has focused on assessments of how existing SAF pathways can be optimized from an impact perspective, including costs. The team primarily investigates electrification of SAF production as a possible evolution path.

Task 4 - Develop Methods for Assessing the Impacts of Promising SAF Production Pathways

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Objective

The objective of this task is to define a method for assessing the economic and environmental impacts of promising fuel production pathways. For this purpose, the ASCENT Project 080(B) team developed techno-economic assessment (TEA) and life-cycle assessment (LCA) models. The TEA model calculates the minimum selling price of a specific fuel. The LCA model computes its atmospheric impacts. Because the exact process layout and process characteristics (e.g., mass and energy balances, capital expenditures, operating expenditures) of novel fuel production pathways are subject to uncertainty, sensitivity studies will be conducted. Through this approach, we obtain insights into the range of impacts associated with electrified SAF production pathways.

Research Approach

Electrification of SAF production can be seen as a spectrum in terms of electricity use, where conventional SAF and PtL use the least and most electricity, respectively. Electricity-enhanced fuels are another class of fuel production process which fits in between the two endpoints. Such electricity-enhanced SAF production processes use up to ten times more electricity than conventional SAF per unit energy of fuel output but require up to 81% less electricity than PtL. The modeling chain used to explore the impacts of electrifying the conventional SAF production process is outlined using three feedstock and fuel conversion combinations (hence referred to as pathways). These pathways are corn grain ethanol-to-jet (ETJ), hydroprocessed esters and fatty acids (HEFA) soybean, and HEFA tallow. The team reconstructed the process specifications utilizing data from the calculation of United States (U.S.)-based LCA values for each pathway under the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) (ICAO, 2022). These process models are based on older versions of the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET®) model. More specifically, the team used the GREET 2022 (Rev. 1) (Argonne National Laboratory, 2022a), GREET 2022 Aviation module (Argonne National Laboratory, 2022b), and International Civil Aviation Organization (ICAO)-GREET 2019 (Argonne National Laboratory, 2022c) to reconstruct the processes. The replicated baseline impact values are 3–8 g carbon dioxide equivalent (CO_2e)/MJ lower than the respective CORSIA values, largely due to assumed efficiency improvements since the original CORSIA analyses; the remaining differences are attributable to a variety of smaller changes in more recent versions of GREET vs. older GREET versions.

Figure 1 shows the electrification strategies used for this study. All direct combustion of carbonaceous fuels in the primary supply chain are replaced with onshore wind electricity with battery storage, inclusive of embodied emissions (15.7 g CO_2e/kWh) (Argonne National Laboratory, 2022a). Embodied emissions of electricity refer to emissions from the material sourcing, component manufacturing, construction, maintenance, and decommissioning of the power generation facility. This includes all heating energy used in natural gas (NG), liquefied petroleum gas, diesel, residual oil, coal, biomass, and landfill gas boilers (Argonne National Laboratory, 2022a) being substituted with resistance heating electric boilers (Engineer Live, 2021). All existing electricity use from the U.S. grid is replaced with onshore wind electricity with battery storage. In farming, off-road equipment (tractors) (Lagnelöv et al., 2021), irrigation units (Husker Power Products, 2023), pumps (Honda, 2023), and generators powered by diesel, gasoline, and NG are replaced with equivalent electric units (U.S. Department of Energy, 2023). For material inputs such as fertilizer, herbicide, and insecticide use, where there is no direct combustion in the primary jet fuel supply chain, the secondary supply chain (i.e., inputs into fertilizer production) is electrified. This includes ammonia (NH_3) produced from electrolytic hydrogen (H_2), electrified transportation of inputs (battery trucks [Tesla Semi, 2023], rail [Popovich et al., 2021], and NH_3 fuel cell–powered ocean tankers and barges [Korberg et al., 2021]), and electrified off-road mining equipment (battery trucks [Henrio et al., 2023] for phosphoric rock hauling for monoammonium phosphate [$NH_4H_2PO_4$]). H_2 from proton exchange membrane (PEM) electrolysis powered by wind replaces H_2 from steam methane reforming in the HEFA process. Carbon capture and sequestration (CCS) is deployed for the biogenic CO_2 released during the ethanol (EtOH) fermentation process. Feedstock, intermediates, and jet fuel transport and distribution are also electrified; the aforementioned vehicle electrification strategies are applied accordingly. No mode change is assumed.

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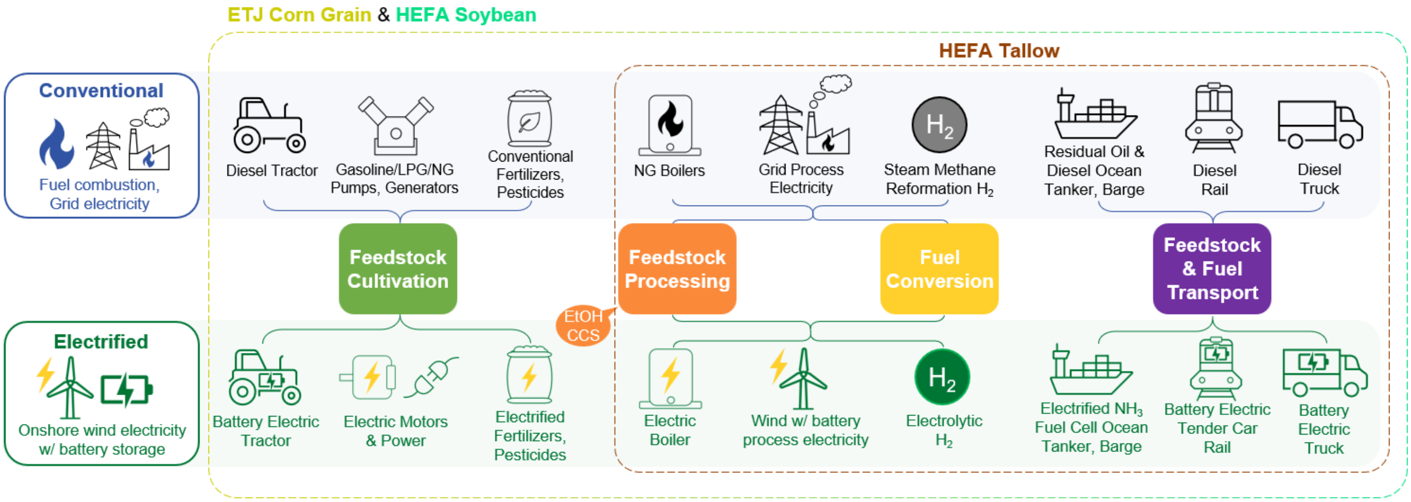

Figure 1. Strategies for reducing the impact of the ethanol-to-jet (ETJ) corn grain, hydroprocessed esters and fatty acids (HEFA) soybean, and HEFA tallow pathways, using electrification. Electrolytic hydrogen is produced via proton exchange membrane (PEM) (low temperature) electrolyzer from onshore wind electricity with battery storage, replacing "gray" electrolytic hydrogen (H_2) from steam methane reformation using natural gas (NG). Note: this is a simplified schematic, not an exhaustive analysis of every element of the lifecycle assessment. LPG: liquefied petroleum gas.

Milestone

- Presented the updated modeling approach to the FAA and other stakeholders.
- The methodology has been documented in a paper draft which will be submitted for publication.

Major Accomplishment

The focus of this year's efforts was on understanding how this method can be expanded to other pathways. The team aimed to select pathways which would provide the most insight into optimizing conventional SAF via electrification and appropriately apply the previously developed electrification method to these pathways (HEFA soybean, HEFA tallow).

Publications

A paper outlining the methods and process modifications is in preparation.

Outreach Efforts

Presented at the ASCENT Spring 2025 Meeting and a poster presentation at the ASCENT Fall 2025 meeting.

Student Involvement

During the reporting period, TJ Park (MIT graduate student) worked on this task. The student developed the structure to analyze electrified variants of existing SAF pathways. This included data gathering from the literature for energy, emissions, and cost data of electrified alternatives to SAF production steps and subsequent adaptation for use in LCAs and TEAs. The student also reconstructed existing LCA and TEA models to replicate baseline values and modified the models to suit the electrification study.

Plans for Next Period

Publish the methods and data for this task.

References

Argonne National Laboratory. (2022a). *GREET: The greenhouse gases, regulated emissions, and energy use in Transportation Model*. U.S. Department of Energy. https://www.energy.gov/eere/bioenergy/articles/greet-greenhouse-gases-regulated-emissions-and-energy-use-transportation

Argonne National Laboratory. (2022b*). Energy systems and infrastructure analysis – GREET aviation module*. https://greet.es.anl.gov/greet_aviation

Argonne National Laboratory (2022c). *ICAO-GREET model*. https://greet.anl.gov/greet_icao

Engineer Live. (2021, December 10). *The move to electric boilers*. Engineer Live. https://www.engineerlive.com/node/20952

Henrio, M., van der Ende, O., Motta, G., & Ray, R. K. (2023). *Mining electrification could double their electricity demand*. McKinsey & Company. https://www.mckinsey.com/industries/metals-and-mining/our-insights/electrifying-mines-could-double-their-electricity-demand

Honda. (2023). *Honda IGX800 engine*. https://www.hastingshonda.co.nz/power-equipment/honda-igx800/

Husker Power Products. (2023). *NGE 14.6L spec sheet*. Husker Power Products. https://www.huskerpowerproducts.com/assets/site/specsheets/irrigation/psi-14.6l-nglpg-specsheet.pdf

ICAO. (2022). *CORSIA eligible fuels – life cycle assessment methodology (CORSIA supporting document)*. International Civil Aviation Organization (ICAO), Montreal, Canada. https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/CORSIA_Supporting_Document_CORSIA%20Eligible%20Fuels_LCA_Methodology_V5.pdf

Korberg, A. D., Brynolf, S., Grahn, M., & Skov, I. R. (2021). Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. *Renewable and Sustainable Energy Reviews*, *142*. https://doi.org/10.1016/j.rser.2021.110861

Lagnelöv, O., Dhillon, S., Larsson, G., Nilsson, D., Larsolle, A., & Hansson, P.-A. (2021). Cost analysis of autonomous battery electric field tractors in agriculture. *Biosystems Engineering*, *204*, 358–376. https://doi.org/10.1016/j.biosystemseng.2021.02.005

Popovich, N. D., Rajagopal, D., Tasar, E., & Phadke, A. (2021). Economic, environmental and grid-resilience benefits of converting diesel trains to battery-electric. *Nature Energy*, *6*(11), 1017–1025. https://doi.org/10.1038/s41560-021-00915-5

U.S. Department of Energy. (2023). *Determining electric motor load and efficiency*. https://www.energy.gov/eere/amo/articles/determining-electric-motor-load-and-efficiency

Tesla. (2023). *Tesla Semi*. https://www.tesla.com/semi

Task 5 - Analyze the Footprint of SAF Production Pathways

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Objective

The objective of this task is to provide harmonized assessments of different SAF pathways. During the reporting period, the ASCENT Project 080(B) team analyzed the implications of different measures, including using renewable electricity and hydrogen, in selected CORSIA-eligible SAF pathways. In addition, the costs of these strategies and the impact abatement costs were calculated to provide a holistic view of the impacts associated with SAF electrification.

Research Approach

Figure 2a shows the impact reduction potential of electrifying the ETJ corn grain, HEFA soybean, and HEFA tallow SAF pathways. Differences in GREET 2011 and 2022 (Argonne National Laboratory, 2022), partially attributed to decreases in methane (CH_4) impact factors in newer NG boilers and efficiency improvements throughout the process, result in new baselines of 82.7 g CO_2e/MJ, 62.9 g CO_2e/MJ, and 18.9 g CO_2e/MJ, for ETJ corn grain, HEFA soybean, and HEFA tallow, respectively. All reduction measures considered (see Figure 1), the lifecycle impact of the electrified ETJ corn grain, HEFA soybean, and HEFA tallow fuel are estimated at 16.8 g CO_2e/MJ (82% reduction), 37.1 g CO_2e/MJ (44% reduction), and 1.2 g CO_2e/MJ (95% reduction), respectively. For ETJ corn grain and HEFA soybean, the remaining impacts include those from farming (corn: 9.8 g CO_2e/MJ, soybean: 11.4 g CO_2e/MJ) - the majority of which is attributed to nitrous oxide (N_2O) emissions from nitrogen fertilizer use in the soil with direct mitigation options currently in an experimental phase (Itakura et al., 2013) - and induced land use change (ILUC) emissions (25.1 g CO_2e/MJ). There may be reduction opportunities with cover crops, double cropping, and sustainable land management practices which remain an area of research. HEFA tallow has a 95% reduction in greenhouse gas (GHG) emissions, as there are no remaining emissions, given that tallow is considered a byproduct of the animal slaughtering process, and thus the feedstock cultivation stage is outside the system boundary of the LCA.

Figure 2b shows the cost changes associated with the electrification strategies. For ETJ corn grain, the two largest impact reduction mechanisms, CCS in corn fermentation and electric heat for jet upgrading, incur the largest cost increases. In total, there is a 34% cost penalty ($0.55/L) for implementing electrification throughout the ETJ corn grain supply chain. However, the fuel after electrification qualifies for SAF and H_2 credits. If 40B (SAF) and 45V (H_2) tax credits are assumed to be directly applied without amortization, the new minimum selling price (MSP) after credits is 16% higher than the baseline, with the credits partially mitigating the cost increases associated with electrification. For HEFA soybean, electrically produced farm chemicals add the most cost to the fuel MSP, due to the complexity of the existing supply chain for phosphate fertilizer production. The HEFA soybean fuel MSP increases 24% due to electrification, while the SAF and H_2 credits reduce the cost penalty of electrification to 7% over the HEFA soybean baseline. For HEFA tallow, electrified rendering is the measure with the highest cost impact, and the fuel MSP rises 22% with all electrification measures implemented. The SAF and H_2 credits apply to both the baseline and electrified HEFA tallow pathway, and electrification can reduce the fuel MSP by 14%.

Figure 2c shows the abatement costs of each electrification step applied independently, and a value for the electrified fuel with all steps applied. Since the CORSIA default LCA value for the U.S. corn ETJ process is above that of fossil jet, there is no impact abatement; thus, there is no associated abatement cost. Instead, the updated GREET value (Argonne National Laboratory, 2022) is used as the basis for calculating the baseline abatement costs. Every electrification method results in a reduction of abatement cost. This shows that the reduced impact outweighs the cost increase from electrification. For HEFA soybean, not every electrification strategy results in an abatement cost reduction. For example, the cost increase from utilizing electrified fertilizers outweighs the associated impact reductions, resulting in an abatement cost increase. However, with electrification of the entire supply chain, the abatement cost is reduced 34% from the baseline, and by 49% after credits. Abatement cost for electrified HEFA tallow SAF increases 16% from the baseline, as the impact of the baseline is already low, and thus the maximum possible impact reduction is limited, compared to the cost increase from electrification.

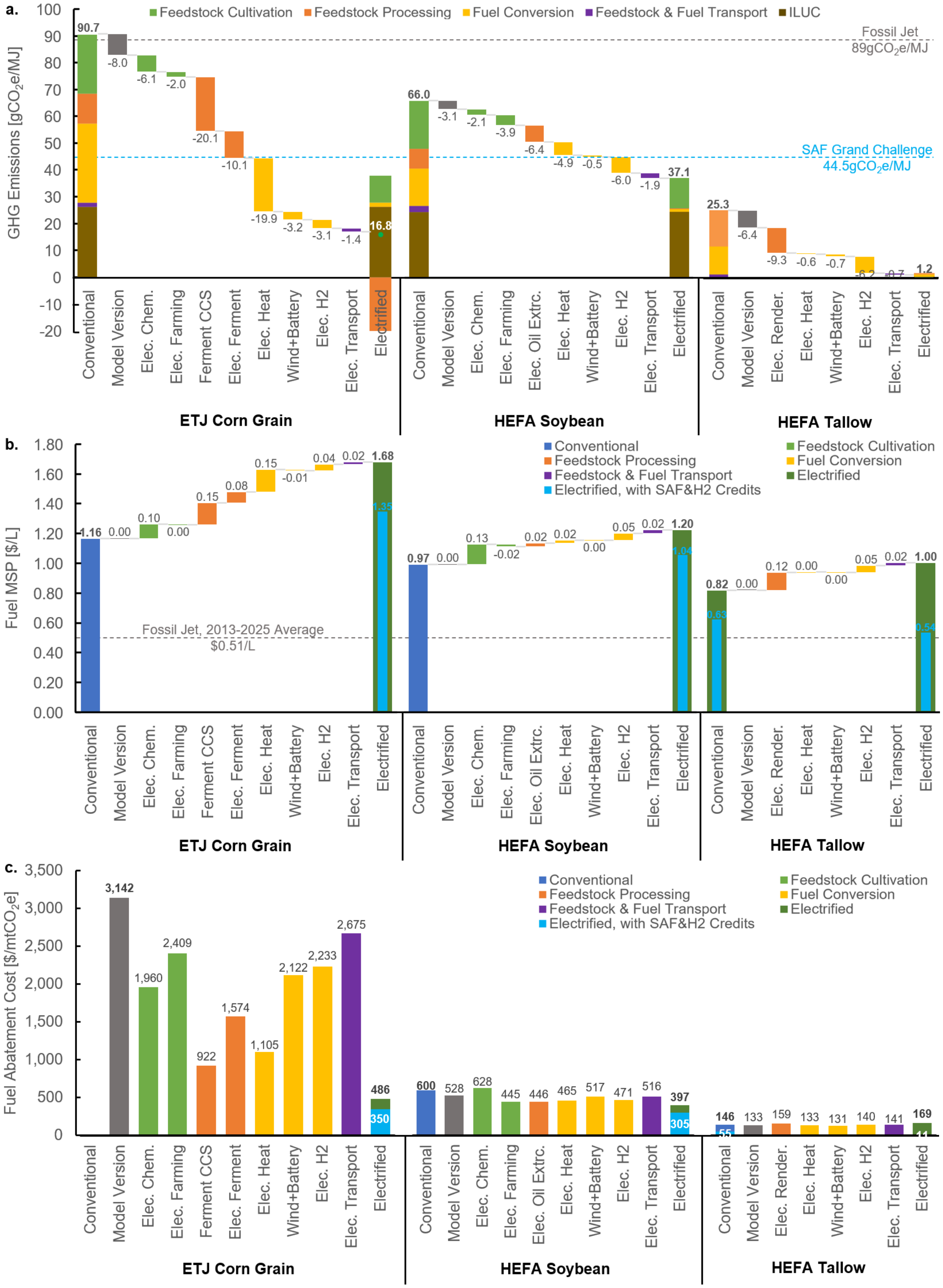

Figure 2. (a) Greenhouse gas (GHG) emissions reduction potential jet fuel supply chain from ethanol-to-jet (ETJ) corn grain, hydroprocessed esters and fatty acids (HEFA) soybean, HEFA tallow via electrification. (b) Minimum selling price (MSP) impacts from fuel electrification, in $2017USD/L. (c) Abatement cost of electrification strategies. Model Ver.: differences in

calculation of CORSIA U.S. baseline value using GREET 2022 (Argonne National Laboratory, 2022); Elec. Farming: electrified farming, including equipment, fertilizer, input material transport; Ferment CCS: Carbon capture and sequestration (CCS) of biogenic carbon dioxide (CO_2) from ethanol fermentation; Elec. Ferment: electrified fermentation, including resistance heating; Elec. Heat: electric heating; Wind+Battery: onshore wind electricity with battery storage replacing U.S. grid electricity in fuel conversion; Elec. H2: electrolytic proton exchange membrane H2; Elec. Trans: battery electric trucks, rail, and ammonia fuel cell powered ocean tankers and barges; Elec. Oil Extr.: electrified oil extraction, including resistance heating; Elec. Render.: electrified tallow rendering, including resistance heating; ILUC: induced land use change (remains constant); SAF: sustainable aviation fuel.

Milestone

Finalized the analysis.

Major Accomplishment

Summarized results and prepared for publication.

Publications

A paper summarizing the results is currently under preparation.

Outreach Efforts

Presented results during the Spring and Fall 2025 ASCENT meetings.

Student Involvement

During the reporting period, TJ Park (MIT graduate student) worked on this task. The student performed the LCA and TEA of the baseline and electrified ETJ corn grain, HEFA soybean, and HEFA tallow pathways for SAF production. The student calculated the change in abatement cost for each electrification strategy applied independently, as well as all strategies combined. The student included the impact of SAF and hydrogen credits on the minimum selling price and abatement cost of the fully electrified processes.

Plans for Next Period

Publish the results for this task.

References

Argonne National Laboratory. (2022). *GREET: The greenhouse gases, regulated emissions, and energy use in Transportation Model*. U.S. Department of Energy. https://www.energy.gov/eere/bioenergy/articles/greet-greenhouse-gases-regulated-emissions-and-energy-use-transportation

Argonne National Laboratory. (2011). *GREET: The greenhouse gases, regulated emissions, and energy use in Transportation Model*. U.S. Department of Energy.

Itakura, M., Uchida, Y., Akiyama, H., Hoshino, Y. T., Shimomura, Y., Morimoto, S., Tago, K., Wang, Y., Hayakawa, C., Uetake, Y., Sánchez, C., Eda, S., Hayatsu, M., & Minamisawa, K. (2013). Mitigation of nitrous oxide emissions from soils by Bradyrhizobium japonicum inoculation. *Nature Climate Change*, *3*(3), 208–212. https://doi.org/10.1038/nclimate1734

Task 6 - Analyze the Prospects of Direct Air Capture of Atmospheric CO_2 to Provide a Carbon Source for SAF Production

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Objectives

The objective of this task is to evaluate the current and future costs of liquid and solid DAC through component-based learning curves. These projections were utilized to compare two pathways for decarbonization of aviation with DAC:
(1) DAC with carbon capture and sequestration (DACCS) to offset emissions from continued use of fossil Jet A fuel, and
(2) production of PtL fuels with DAC as a carbon source. The economic and environmental impact of these pathways were evaluated under various technology and cost assumptions in the near-term and long-term.

Milestone

- Finalized the results as described in the report for the previous period of performance.
- Finalized a paper and submitted for publication.

Major Accomplishments

Submitted paper for publication.

Publications

Housen, T., (2024). *Climate impact analysis of direct air capture deployment* [Master's thesis, Massachusetts Institute of Technology]. MIT Libraries. https://hdl.handle.net/1721.1/155419

Outreach Efforts

None.

Student Involvement

None.

Plans for Next Period

None.