Proposed Organized Session for the 2023 Annual Conference on Global Economic Analysis
Université de Bordeaux, Bordeaux, France

Availability and Sustainability of Power-to-Liquid Fuels for Aviation

Sustainability Paper:

Paper 4: Sustainability Challenges and Opportunities of Power-to-Liquid Fuels

Authors and their affiliations

Kristin C. Lewis, Volpe National Transportation Systems Center, U.S. Dept of Transportation

Jon A. Obnamia, Transport Canada

Florian Allroggen, Massachusetts Institute of Technology

Farzad Taheripour, Purdue University

Robert Malina, University of Hasselt

Table of Contents

Abstract

Power-to-liquid fuels are considered by many proponents to be a significant improvement in sustainable aviation fuel alternatives to petroleum. Previous papers in this session focused on the potential carbon benefit and land use impacts of these fuels. The scale at which these fuels would be needed to replace a significant portion of fossil-based fuels may lead to additional sustainability challenges that must be addressed to avoid unintended consequences of PtL deployment.

The high PtL requirement for renewable power suggests that PtL fuel production is likely to take place where renewable power generation from sources such as wind and solar is highly available. These locations are also likely to experience water scarcity. However, water is required as a hydrogen source for PtL fuels as part of the renewable and low carbon performance of the fuels. Thus, desalination may become an important source of water for PtL production. Desalination produces significant brine waste that must be disposed of properly to avoid environmental impacts. Therefore, the use of water in the local context is an important determinant of PtL fuel sustainability.

Both renewable power generation and electrolysis for PtL depend on rare earth minerals and other critical raw materials, the sourcing and use of which can have environmental impacts. It is therefore also important that minimization and recycling of such materials be integrated into PtL production pathways.

The International Civil Aviation Organization’s Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) defines a globally applied set of sustainability criteria for

sustainable aviation fuels used in international aviation. To be used in the international aviation sector, PtL fuels will need to be certified as meeting these criteria. The renewable power generation, electrolysis, and water sourcing of PtL fuels should be considered as part of the sustainability certification of these fuels. By applying sustainability criteria consistently and requiring verified/audited reporting of actions, it is possible to systematically reduce the sustainability risks associated with fuel production.

Motivation: Need for sustainability assessment for PtL fuels

Alternative renewable fuels for aviation tend to be more expensive than traditional fuels and require the development and expansion of entirely new industrial and supply chain infrastructure (de Jong, et al., 2015; World Economic Forum, 2020; Brandt, Martinez-Valencia, & Wolcott, 2022) Therefore, the key value proposition of alternative renewable fuels that drives interest is based on the potential for decarbonization and associated improved sustainability performance (Lewis, et al., 2022). The demand for such sustainable fuels is growing rapidly (German Environment Agency, 2022) as the urgency of climate action increases (IPCC, 2023). In addition, using renewable electricity to generate renewable hydrogen and liquid fuels is seen as a method to enhance the output of biofuel processes (Hannula, 2016) and/or to store excess renewable electricity (Koj, Wulf, Linssen, Schreiber, & Zapp, 2018).

However, given the complexity of sustainability, comprising environmental, social, and economic considerations and the tradeoffs among them, sustainability cannot be assured for all instances of fuel production technologies. Therefore, as new fuels enter the marketplace, careful consideration is needed to ensure that the fuels are developed thoughtfully and that sustainability is assessed rigorously to prevent unintended consequences of alternative fuel scale up.

Currently there is significant interest in power-to-liquid (PtL) fuel options, which are considered by many proponents to be a significant improvement in sustainable fuel alternatives to petroleum compared to biomass-based alternative aviation fuels. There are a range of PtL technologies (German Environment Agency, 2022) with varying degrees of enhancement over traditional biofuels in terms of carbon, hydrogen and/or energy source, land use, and carbon intensity.

Previous papers in this session focused on the potential carbon benefit and land use impacts of these fuels. In many cases, PtL fuel technologies are focused on drawing down CO_2 directly from the atmosphere or from unavoidable waste streams. These fuels could be less land-use intensive than biomass-based fuels if they are not reliant on agricultural or forestry for production of feedstocks. (German Environment Agency, 2022). However, the need for extensive renewable power generation to achieve scaled up PtL production may extend competition for land and induce land use change.

Furthermore, beyond carbon and land use change considerations, the scale at which these fuels would be needed in order to replace a significant portion of fossil-based fuels may lead to additional sustainability challenges that must be addressed to avoid unintended consequences of widescale PtL deployment. Currently, efforts are underway to identify any unique sustainability challenges associated with PtL fuels and to develop approaches that can mitigate potential negative impacts (e.g., European Commission's delegated regulation on Renewable Fuels of Non-Biological Origin or RFNBO (European Commission, 2023)).

Analysis of potential negative sustainability implications and key sustainability considerations for PtL fuels

Sustainability evaluations encompass environmental, social, and economic conditions. Some of the key environmental resource areas beyond decarbonization that must be considered include impacts on demand for water and water quality, air quality, soil health, biodiversity/conservation, and impacts from process waste and chemicals. From a socioeconomic perspective, considerations include food security, human and labor rights, and water/resource rights. Any industry that scales up extensively runs the risk of affecting these resource areas of concern, and PtL fuels are no exception. On the other hand, producing sustainable aviation fuels using the PtL technologies could provide local economic development opportunities.

While any of the above resource considerations can be of concern for a new, scaled-up industrial process, specific risk areas are higher when associated with inherent production process conditions. The implications of the high electricity intensity of PtL fuels with regard to carbon intensity [PtL Core LCA session paper reference] and land use impacts [PtL ILUC session paper reference] were outlined in the previous papers for this session. The electricity source can be the largest contributor to the environmental performance of these fuels both from a carbon reduction perspective and other environmental considerations (Koj, Wulf, & Zapp, Environmental impacts of power-to-X systems - A review of technological and methodological choices in Life Cycle Assessments, 2019). The scale of the required systems also raises questions around the temporal supply and demand matching requirements for renewable electricity, both from carbon accounting perspective [Intermittency paper in this session] as well as from a grid stability perspective. The latter is specifically relevant for PtL, which might provide both benefits and disbenefits to the grid: PtL fuel production can act as a stabilizing element through use of excess renewable electricity during high production periods or it can add additional baseload, which increases the need for back-up resources.

The use of rare earth minerals and other critical raw materials are a concern for long-term sustainability both because of their inherent supply insecurity as well as the potential environmental and social effects of the materials themselves and/or their extraction. The electrolysis used for PtL depends on a range of these materials, which may include iridium, platinum, cobalt, tantalum, and nickel (International PtX Hub, 2022). Renewable power infrastructure (wind, PV power plants) also requires consumption of metals such as aluminum, steel, and copper as well as permanent magnets that require rare earth elements. Copper mining in particular is considered to have high potential for freshwater toxicity (Zhang, Bauer, Mutel, & Volkart, 2017). In addition, many of these materials can be difficult to source and subject to geopolitical issues that render the supply chains potentially unstable (Bobba, Carrara, Huisman, Mathieux, & Pavel, 2020). Use reduction and recycling of these materials is strongly recommend to ensure the viability and sustainability of PtL fuels. (International PtX Hub, 2022).

Another known high-risk area for PtL fuels is water use and associated water quality impacts. The U.N. estimates that 2.3 billion people live in water-stressed countries, an issue which is being exacerbated due to climate change (UN-Water, 2021). For biofuels produced from agricultural resources, water use intensity has been raised as a potential issue since their introduction due to the potential unsustainable use of water for irrigation and for fuel production processes, coolant, and other demands (e.g., (Diaz-Chavez, Berndes, Neary, Neto, & Fall, 2011; Gerbens-Leenes, Hoekstra, & Meer, 2009; Domingues-Faus, Powers, Burken, & Alvarez, 2009). Water use intensity comparing conventional fossil-based fuels and biomass-based fuel indicate that water consumption is within the same range within 1.6 to 20.1 liters of water per liter of middle distillate fuel produced if the biomass feedstock is rain-fed (Staples, et al., 2013). On the other hand, irrigated biomass results in an overall water consumption that can be up to 22,600 liters of water per liter of middle distillate or up to three orders of magnitude greater than rain-fed biomass. Efforts have been made to reduce the water use intensity of biofuel production through reduction or elimination of crop irrigation, use of forestry and agricultural wastes and other waste materials, and increased process efficiency (Wu, 2019).

Although water use efficiency may be better for PtL fuels than other alternative and conventional fuels (German Environment Agency, 2022) certain aspects of PtL fuels, particularly the demand for green hydrogen and renewable electricity, may have water use and quality implications as the industry scales up. Green hydrogen production via electrolysis splits water to generate the renewable hydrogen (currently with approximately 73% efficiency for alkaline or PEM electrolysis (IEA, 2020)) coupled with the reverse water gas shift reaction, synthesis gas can then be generated for Fischer-Tropsch fuel production reactions from CO_2 and water (German Environment Agency 2016). Both of these processes are critical for the renewability and carbon benefit on which the value proposition of PtL fuels depends. In addition, the high demand for renewable energy to power the conversion to PtL fuels is both land intensive and tends to be co-located with regions where water scarcity is an issue. (Grahn, et al., 2022). Therefore, the water use intensity of PtL fuels production and potential water quality impacts may pose a substantive issue for many communities and regions.

The International Renewable Energy Agency (IRENA) has suggested that most planned green hydrogen projects will need to source water via desalination (IRENA, 2022) to supply electrolysis because of their likelihood of being in regions of water scarcity. Desalination is itself energy intensive, with the two alternative technologies of reverse osmosis requiring up to 3.5-5 kWh of electricity per m^3 of water desalinated and multi-stage flash desalination requiring up to 80 kWh of heat energy and up to 3.5 kWh of electricity per m^3 of water desalinated (IEA-ETSAP and IRENA, 2012). If desalination needs to be used in tandem with PtL fuel production, this will increase the demand for renewable energy beyond the requirements from electrolysis, feedstock production, and conversion processes.

Desalination can also have implications for localized water quality around the facility due to brine and/or cooling water production and release. For every liter of clean water produced by desalination, approximately 1.5 liters of brine is produced (Jones, Qadir, van Vliet, Smakhtin, & Kang, 2019). This brine is high salinity (sodium chloride) and can also be contaminated with ions such as calcium, magnesium, and sulfate as well as heavy metals in some cases, particularly copper, and biocides and other additives (Omerspahic, al Jabri, Siddiqui, & Saadaoui, 2022). This brine is toxic to organisms, and must be disposed of properly or risk significant environmental harm. There are existing methods for brine disposal and efforts are also being taken to evaluate alternative brine disposal methods that improve upon water recovery, energy efficiency/optimization, and techno-economic feasibility (e.g., zero liquid discharge technologies including membrane and thermal treatment technologies) (Panagopoulos, Haralambous, & Loizidou, 2019).

Thus, water quality and quantity are key concerns relating to PtL fuel production in addition to the land use and carbon implications. Beyond these factors, PtL fuels need to be held to the standards set for all alternative fuels covering the range of sustainability considerations encompassing environmental, social, and economic aspects.

Current requirement for sustainability of PtL SAF

Many regulatory schemes and voluntary programs leverage third-party verified audits for certification in accordance with overarching principles and criteria on sustainable fuel production to ensure sustainability of alternative fuels

Existing regulatory programs with qualification criteria for alternative/renewable fuels and voluntary schemes for ensuring sustainability of fuels and other products depend on the implementation of measures that can limit / mitigate impacts. Regulatory programs such as the E.U. Renewable Energy Directive (EU, 2018) and the U.S. Renewable Fuel Standard (U.S., 2007) obligate certain parties to comply with such sustainability criteria. The International Civil Aviation Organization Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) sets a requirement for carbon neutral growth in international aviation that has been adopted by 107 countries as of 2022 (ICAO, 2022), and only fuels that have been certified to comply with the CORSIA sustainability criteria can be used to contribute to that requirement. Both the EU RED and CORSIA rely upon certification by voluntary Sustainability Certification Schemes (SCSs) to ensure compliance with the required sustainability criteria.

ICAO has adopted a comprehensive set of sustainability criteria for the first phase of the CORSIA program (ICAO, 2022). The criteria were developed as an “umbrella” standard based on existing sustainability principles and criteria developed by existing regulatory programs and non-governmental organizations (e.g., the Roundtable on Sustainable Biomaterials (RSB) and the International Sustainability and Carbon Certification (ISCC)) with extensive stakeholder input and refinement.

The CORSIA sustainability criteria are the only set of sustainability criteria being applied globally across an entire industry. ICAO has defined sustainability criteria for two categories of CORSIA Eligible Fuels (CEF): Sustainable Aviation Fuels (SAF) and Lower Carbon Aviation Fuels (LCAF). The former are waste or renewable-based fuels, and the latter are fossil-based fuels that have at least a lower carbon intensity than conventional petroleum jet fuels. PtL fuels fall within the SAF category.

In the CORSIA pilot phase (from 2021 through 2023) only three criteria under two themes are required, focusing on greenhouse gas emissions reductions on a life cycle basis and the avoidance of disturbing high carbon stock ecosystems. For the “First Phase” of CORSIA (starting 1 January 2024), there are 13 applicable themes for SAF and 19 individual criteria that must be met under those themes. The environmental considerations addressed include: GHG emissions, high carbon stocks, GHG emissions reduction permanence, water use and quality, soil, air, conservation, and wastes and chemicals. Social considerations include human and labor rights, land use and land use rights, and, and economic considerations include local and social development and food security. At the time of writing, RSB and ISCC are two SCS that have been approved by ICAO to provide certification across these sustainability considerations so that CORSIA SAF candidates can be used in CORSIA (ICAO, 2020).

The CORSIA sustainability criteria and associated requirements for SAF vary in their level of prescription with regard to the demonstrations of compliance depending on the criterion/area of concern: in some cases, such as carbon accounting and land use change, very specific metrics and thresholds are prescribed either in the sustainability criteria themselves or in additional documents outlining the requirements associated with them including CORSIA Default Life Cycle Emissions Values for CEF (ICAO, 2021), the CORSIA Methodology for Calculating Actual Life Cycle Emissions Values (ICAO, 2021), the Guidance to Sustainability Certification Schemes for SAF (ICAO, 2021), and the CORSIA Supporting Document "CORSIA Eligible Fuels – Life Cycle Assessment Methodology (ICAO, 2022). In other criteria such as water quality or soil health, the demonstration of compliance is focused ensuring the implementation of best practices and appropriate planning and operating procedures to reduce risk. Social factors are addressed by an attestation by the company in which the SAF is produced, and economic factors are addressed by reporting of measures taken without further judgement by the SCS. These different compliance approaches reflect the challenges of demonstrating compliance in various States with differing expectations and legal requirements.

The CORSIA sustainability criteria serve as a guideline for implementation by SCSs, with multiple approaches potentially allowable by credible SCSs. Sustainability certification schemes can apply to be qualified to certify CORSIA Eligible Fuels using their own approach as long as it is deemed sufficiently rigorous by ICAO. By applying sustainability criteria consistently and requiring verified/audited reporting of actions, it is possible to systematically reduce the sustainability risks associated with fuel production.

In this regard, PtL fuels should be treated as any other SAF under CORSIA. However, there are specific aspects inherent to PtL processes should be taken into account when applying sustainability criteria. These include the high requirement for renewable power, with its potential associated land use changes and sustainability impacts, and the generation of renewable hydrogen and any carbon capture, either from industrial or ambient atmospheric settings. These significant inputs to the PtL process must be addressed in any application of sustainability criteria to these fuels to ensure that their scale up does not lead to detrimental environmental, social, or economic effects.

Discussion and conclusions

The global aviation sector has agreed upon a minimum set of sustainability criteria for SAF in the form of the CORSIA sustainability requirements. Any SAF, including PtL fuels, need to be held to those standard requirements in order to minimize the risk of unsustainable production. However, while the primary focus on PtL fuels has been the value proposition of their potential carbon benefit when produced with renewable fuels, there are other aspects of sustainability that may be uniquely acute for PtL fuels that must be addressed in order to ensure that the industry does not generate unintended consequences for other resources of concern. Given the potential water demand for PtL fuels and the criticality of renewable energy to their value proposition, plus the likely co-location of renewable power generation and water scarcity, the issue of local water availability, quality, and use will be important. Water demand for PtL fuels in water-scarce regions where renewable power generation is high may potentially be supported by desalination, which can lead to issues relating to associated brine production causing water quality and ecotoxicity issues. The need for substantial infrastructure for power generation may include significant mining and materials sourcing that can have both environmental and sociopolitical impacts, and the ability to source these materials may also be influenced by geopolitical considerations. In these regards, there may be additional considerations for evaluating sustainability of PtL fuels that will need to be taken into account for regulatory and voluntary sustainability evaluations.

References

Bobba, S., Carrara, S., Huisman, J., Mathieux, F., & Pavel, C. (2020). *European Commission, Critical materials for strategic technologies and sectors in the EU - a foresight study, 2020.* European Union. doi:10.2873/58081

Brandt, K. L., Martinez-Valencia, L., & Wolcott, M. P. (2022, March). Cumulative Impact of Federal and State Policy on Minimum Selling Price of Sustainable Aviation Fuel. *Frontiers in Energy Research, 10*. Retrieved from https://doi.org/10.3389/fenrg.2022.828789

de Jong, S., Hoefnagels, R., André, F., Raphael, S., Rebecca, M., & Junginger, M. (2015). The Feasibility of Short-Term Production Strategies for Renewable Jet Fuels - a Comprehensive Techno-Economic Comparison. *Biofuels, Bioproducts and Biorefining, 9*(6), 778-800. Retrieved from https://doi.org/10.1002/bbb.1613

Diaz-Chavez, R., Berndes, G., Neary, D., Neto, A., & Fall, M. (2011). Water quality assessment of bioenergy production. *BioFPR, 5*, 445-463. Retrieved from https://doi.org/10.1002/bbb.319

Domingues-Faus, R., Powers, S., Burken, J., & Alvarez, P. (2009). The water footprint of biofuels: a drink or drive issue? *Environ. Sci. Technol., 43*(9), 3005-3010. Retrieved from https://pubs.acs.org/doi/10.1021/es802162x

EU. (2018, December 11). Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). . Brussels, Belgium, European Union.

European Commission. (2023). *Delegated regulation on Union methodology for RFNBOs.* Retrieved from https://energy.ec.europa.eu/publications/delegated-regulation-union-methodology-rfnbos_en

Gerbens-Leenes, W., Hoekstra, A. Y., & Meer, T. v. (2009). The water footprint of bioenergy. *Proceedings of the National Academy of Sciences, 106*(25), 10219-10223. doi:https://doi.org/10.1073/pnas.0812619106

German Environment Agency. (2016). *Power-to-Liquids: potentials and perspectives for the future supply of renewable aviation fuel.* ISSN: 2363-829X. Retrieved from https://www.umweltbundesamt.de/sites/default/files/medien/377/publikationen/161005_uba_hintergrund_ptl_barrierrefrei.pdf

German Environment Agency. (2022). *Power-to-Liquids: A scalable and sustainable fuel supply perspective for aviation.* Dessau-Roßlau: Umwelt Bundesamt. Retrieved from https://www.umweltbundesamt.de/sites/default/files/medien/376/publikationen/background_paper_power-to-liquids_aviation_2022.pdf

Grahn, M., Malmgren, E., Korberg, A. D., Taljegard, M., Anderson, J. E., Brynolf, S., . . . Wallington, T. J. (2022). Review of electrofuel feasibility - cost and environmental impact. *Progress in Energy, 4*. doi:https://doi.org/10.1088/2516-1083/ac7937

Hannula, I. (2016). Hydrogen enhancement potential of synthetic biofuels manufacture in the European context: A techno-economic assessment. *Energy, 104*, 199-212. doi:https://doi.org/10.1016/j.energy.2016.03.119
ICAO. (2020). *CORSIA Approved Sustainability Certification Schemes.*
ICAO. (2021, November). CORSIA Default Life Cycle Emissions Values for CORSIA Eligible Fuels. Montreal, ON, Canada. Retrieved from https://www.icao.int/environmental-protection/CORSIA/Pages/CORSIA-Eligible-Fuels.aspx
ICAO. (2021, March). CORSIA Methodology for Calculating Actual Life Cycle Emissions Values. Montreal, ON, Canada. Retrieved from https://www.icao.int/environmental-protection/CORSIA/Pages/CORSIA-Eligible-Fuels.aspx
ICAO. (2021). *Guidance to Sustainability Certification Schemes (SCS) for application.* Montreal, Canada: ICAO. Retrieved from https://www.icao.int/environmental-protection/CORSIA/Documents/Guidance%20on%20Sustainability%20Themes%203-7.pdf
ICAO. (2022, January). *Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)* . Retrieved from ICAO: https://www.icao.int/environmental-protection/CORSIA/pages/default.aspx
ICAO. (2022). *CORSIA Supporting Document: CORSIA Eligible Fuels - Life Cycle Assessment Methodology, Version 5.* Montreal, Canada: ICAO. Retrieved from https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/CORSIA_Supporting_Document_CORSIA%20Eligible%20Fuels_LCA_Methodology_V5.pdf
ICAO. (2022, November). CORSIA Sustainability Criteria for CORSIA Eligible Fuels. Montreal, ON, Canada. Retrieved from https://www.icao.int/environmental-protection/CORSIA/Documents/CORSIA_Eligible_Fuels/ICAO%20document%2005%20-%20Sustainability%20Criteria%20-%20November%202022.pdf
IEA. (2020). *Task 38 Final Report: Power-to-Hydrogen adn Hydrogen-to-X: System Analysis of the Techno-economic, legal, and regulatory conditions.* IEA. Retrieved from https://www.ieahydrogen.org/download/17/task-reports/3535/task-38-final-report.pdf
IEA-ETSAP and IRENA. (2012). *Technology Brief 112: Water Desalination Using Renewable Energy.* IEA-ETSAP and IRENA. Retrieved from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2012/IRENA-ETSAP-Tech-Brief-I12-Water-Desalination.pdf
International PtX Hub. (2022). *PtX.Sustainability: Dimensions and Concerns.* International PtX Hub. Retrieved March 30, 2023, from https://ptx-hub.org/ptx-sustainability/
IPCC. (2023). *AR6 Synthesis Report: Climate Change 2023.* Interlaken, Switzerland: IPCC. Retrieved from https://www.ipcc.ch/report/sixth-assessment-report-cycle/
IRENA. (2022). *Geopolitics of the Energy Transformation: The hydrogen factor.* Abu Dhabi: IRENA. Retrieved from https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jan/IRENA_Geopolitics_Hydrogen_2022.pdf
Jones, E., Qadir, M., van Vliet, M. T., Smakhtin, V., & Kang, S.-m. (2019). The state of desalination and brine production: A global outlook. *Science of the Total Environment, 657*, 1343-1356. doi:https://doi.org/10.1016/j.scitotenv.2018.12.076
Koj, J. C., Wulf, C., & Zapp, P. (2019). Environmental impacts of power-to-X systems - A review of technological and methodological choices in Life Cycle Assessments.

Renewable and Sustainable Energy Reviews, 112. doi:https://doi.org/10.1016/j.rser.2019.06.029

Koj, J. C., Wulf, C., Linssen, J., Schreiber, A., & Zapp, P. (2018). Utilisation of excess electricity in different Power-to-Transport chains and their environmental assessment. *Transportation Research Part D, 64*, 23-35. doi:https://doi.org/10.1016/j.trd.2018.01.016

Lewis, K. C., Brown, N. L., Goldner, W. R., Haq, Z., Hoard, S., Holladay, J. E., & Wolcott, M. P. (2022). Editorial: The motivations for and the value proposition of sustainable aviation fuels. *Frontiers in Energy Research, 10*. doi:https://doi.org/10.3389/fenrg.2022.1005493

Omerspahic, M., al Jabri, H., Siddiqui, S. A., & Saadaoui, I. (2022). Characteristics of desalination brine and its impacts on marine chemistry and health, with emphasis on the Persian/Arabian Gulf: A review. *Frontiers in Marine Science*. doi:https://doi.org/10.3389/fmars.2022.845113

Panagopoulos, A., Haralambous, K.-J., & Loizidou, M. (2019, November 25). Desalination brine disposal methods and treatment technologies - a review. *Science of the Total Environment, 693*. doi:doi.org/10.1016/j.scitotenv.2019.07.351

Staples, M. D., Olcay, H., Malina, R., Trivedi, P., Pearlson, M. N., Strzepek, K., . . . Barrett, S. R. (2013). Water Consumption Footprint and Land Requirements of Large-Scale Alternative Diesel and Jet Fuel Production. *Environ. Sci. Technol, 47*, 12557-65. doi:dx.doi.org/10.1021/es4030782

U.S. (2007). *Energin Independence and Security Act. Public Law 110-140, 121 Stat 1492.*

UN-Water. (2021). *Summary Progress Update 2021: SDG 6 – water and sanitation for all.* UN. Retrieved from https://www.unwater.org/water-facts/water-scarcity

World Economic Forum. (2020). *Clean Skies for Tomorrow Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation.* Retrieved from https://www.mckinsey.com/~/media/mckinsey/industries/travel transport and logistics/our insights/scaling sustainable aviation fuel today for clean skies tomorrow/clean-skies-for-tomorrow-sustainable-aviation-fuels-as-a-pathway-to-net-zero-aviation.pdf

Wu, M. (2019). *Energy and water sustainability in the U.S. biofuel industry.* Argonne National Laboratory. Retrieved from https://water.es.anl.gov/documents/EW%20survey%20report%20final%20ANL.pdf

Zhang, X., Bauer, C., Mutel, C. L., & Volkart, K. (2017). Life Cycle Assessment of Power-to-Gas: Approaches, system variations, and their environmental implications. *Applied Energy, 190*, 326-338. doi:https://doi.org/10.1016/j.apenergy.2016.12.098