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Sustainable Aviation in Washington State

Connecting Policy, Technology, Infrastructure and Workforce Development Needs

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Executive Summary

For more than a century, Washington State has been at the forefront of innovation in the aviation and aerospace industries. Reaching the emission reduction goals of international bodies, federal and state governments, and the aviation industry will require innovations in technology, infrastructure, and workforce development. As a recognized global leader, Washington is well-positioned to lead decarbonization efforts in aviation.

The aviation and aerospace industries are huge drivers of Washington State's economy. Washington's 134 public-use airports support 407,042 jobs and generate $26.8 billion in labor income and $107 billion[1] in business revenues while Washington's aerospace industry employs 136,000 highly skilled workers and is home to 1,500 aerospace-related companies, generating 70 billion in overall revenue[2]. These industries will be strongly affected by the need to decarbonize, and the transition to clean energy provides a unique economic opportunity for the state to develop and support a thriving sustainable aviation ecosystem.

This white paper, prepared as background for the Washington State Academy of Sciences' 16th Annual Symposium, aims to review the opportunities and challenges of the technology options, their associated infrastructure, and the workforce development needs for Washington State to maintain its leadership role in the new sustainable aviation ecosystem.

What is Sustainable Aviation?

Sustainable aviation is a long-term strategy to collectively reduce aviation's contribution to climate change through innovative technologies and approaches. Aviation is a significant source of carbon emissions and a particularly difficult industry to decarbonize in part because of the unique energy needs of aircraft, the scale and global nature of airline operations, and the complex technical and regulatory hurdles around the globe. According to the Washington Department of Ecology[3], aircraft related emissions represented about 7.5% of the state's total greenhouse gas emissions in 2015. Globally, aviation's contribution to greenhouse gas emissions is around 2%. This percentage is expected to continue to grow as demand for air travel expands in the state and around the globe, and as other sectors decarbonize. In addition, high-altitude emissions have a greater effect on climate than surface emissions, suggesting aviation's global contribution to climate change is higher[4].

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[1] "Aviation Economic Impact Study and Calculator | WSDOT," accessed August 1, 2023, https://wsdot.wa.gov/travel/aviation/aviation-plans-studies/aviation-planning/aviation-economic-impact-study-and-calculator.

[2] Washington State Department of Commerce, "Aerospace & Aviation," Choose Washington State, accessed August 1, 2023, http://choosewashingtonstate.com/why-washington/our-key-sectors/aerospace/.

[3] Air Quality Program, Washington State Department of Ecology, "Washington State Greenhouse Gas Emissions Inventory: 1990-2015, Report to the Legislature," *18-02-043*, 2018, https://apps.ecology.wa.gov/publications/documents/1802043.pdf.

[4] Hannah Ritchie, "Climate Change and Flying: What Share of Global CO2 Emissions Come from Aviation?," Our World in Data, October 22, 2020, https://ourworldindata.org/co2-emissions-from-aviation.

Emission Reduction Goals

In 2021, the Federal Aviation Administration (FAA) published the United States 2021 Aviation Climate Action Plan (ACAP)[5] – setting an objective of achieving net-zero greenhouse gas (GHG) emissions from the U.S. aviation sector by 2050. In 2022, member states of the United Nation's International Civil Aviation Organization (ICAO) agreed to net-zero GHG emissions from aviation by 2050[6]. In 2021, the White House[7] set a goal of achieving at least a 50% reduction in lifecycle GHG emissions from 2005 levels by 2030. The Washington state legislature has also set GHG emission limits[8] – by 2030 the state is required to reduce emissions levels by 45% below 1990 levels, 70% by 2040, and 95% by 2050.

As the aviation industry transitions to being sustainable, it will have to compete for access to sustainable energy sources with other GHG-emitting sources in the transportation sector – such as passenger cars, trucks, ships and trains. To reduce aviation's contribution to GHG emissions, industry will need to pursue all available solutions as no single solution will be sufficient.

Technology Options

To achieve net-zero GHG emissions by 2050, the aviation sector is investing in the development of sustainable aviation fuels (SAFs), aircraft electrification and hydrogen fuel technologies. Although each of these technological solutions will play a role in the sustainable aviation ecosystem, it is unclear what the balance among them will be or how their implementation will evolve over time. Important considerations for these innovative technologies include technology readiness level, difficulty of advancing the technology within the highly regulated aviation sector, net total impact on GHG emissions, scalability, production costs, and other environmental impacts.

Due to the advantages and limitations of each technology, the best use case for each technology within the sustainable aviation ecosystem depends on flight length, transport load, and location. The Aviation Climate Action Plan recognizes that reaching net-zero emissions will require the production of SAFs in the near term and integration of electric and hydrogen-powered aircraft in the longer term. As will be discussed further below, the timing of these transitions depends on the

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[5] Daniel Williams, "United States 2021 Aviation Climate Action Plan," *Federal Aviation Administration*, accessed August 1, 2023, https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf.
[6] William Raillant-Clark, "States Adopt Net-Zero 2050 Global Aspirational Goal for International Flight Operations," ICAO: Uniting Aviation, October 7, 2022, https://www.icao.int/Newsroom/Pages/States-adopts-netzero-2050-aspirational-goal-for-international-flight-operations.aspx.
[7] The White House, "FACT SHEET: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies," The White House, April 22, 2021, https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/.
[8] "RCW 70A.45.020: Greenhouse Gas Emissions Reductions—Reporting Requirements.," accessed August 1, 2023, https://apps.leg.wa.gov/rcw/default.aspx?cite=70A.45.020.

specific aviation markets being considered. Large investments and successful initial testing toward certification are already underway for all three technologies.

Sustainable Aviation Fuels

Sustainable Aviation Fuels (SAF) are biofuels used to power aircraft that have similar properties to conventional jet fuel (Jet A) but are produced from a variety of renewable carbon sources, or feedstocks, instead of from fossil fuels. Compared to jet fuel, 100% SAF has the potential to reduce GHG emissions by up to 94%[9] depending on the feedstock and process by which the fuel is produced. A key advantage of SAFs is that they are drop-in capable, meaning they can be used in existing aircraft and infrastructure because they meet the fuel quality standards set by ASTM International. There are currently seven ASTM-approved pathways[10] to produce fuel that can be blended with Jet A at different ratios ranging from 10-50%, and then used in commercial flights. While two of these pathways could potentially produce drop-in unblended, or 100%, SAF[11], they are cost prohibitive and difficult to scale. One hundred percent SAFs contain fewer aromatic components allowing them to burn cleaner in aircraft engines and result in fewer contrails compared to conventional jet fuel. However, because aromatics are needed to maintain seal compatibility, aircraft may need to be modified to prevent leaks. In 2021, United Airlines flew the world's first passenger flight[12] powered by 100% SAF in one engine, and conventional jet fuel in the other to prove there are no operational differences between the two that could affect aircraft performance.

There are two types of SAFs: biomass-based and Power-to-Liquid (PtL). The former is produced from non-petroleum-derived renewable feedstocks such as the food and yard waste portion of municipal solid waste as well as dedicated energy crops, with production from used cooking oil and fats being the most established pathway. Roughly 1 billion dry tons[13] of biomass can be collected sustainably each year in the United States, enough to produce up to 60 billion gallons of biofuels. This would be more than enough to meet the projected fuel demand of the U.S. aviation industry, but there is significant competition for these resources from other industries. A 2020 report prepared for the Port of Seattle[14] found that the Pacific Northwest region could produce up

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[9] Matteo Prussi et al., "CORSIA: The First Internationally Adopted Approach to Calculate Life-Cycle GHG Emissions for Aviation Fuels," *Renewable and Sustainable Energy Reviews* 150 (October 2021): 111398, https://doi.org/10.1016/j.rser.2021.111398.
[10] "Conversion Processes," ICAO: Environment, accessed August 1, 2023, https://www.icao.int/environmental-protection/GFAAF/Pages/Conversion-processes.aspx.
[11] Susan van Dyk, "Sustainable Aviation Fuels Are Not All the Same and Regular Commercial Use of 100% SAF Is More Complex," *Green Air News* (blog), February 1, 2022, https://www.greenairnews.com/?p=2460.
[12] United Airlines, "United to Become First in Aviation History to Fly Aircraft Full of Passengers Using 100% Sustainable Fuel," PR Newswire, Cision, December 1, 2021, https://www.prnewswire.com/news-releases/united-to-become-first-in-aviation-history-to-fly-aircraft-full-of-passengers-using-100-sustainable-fuel-301435009.html.
[13] Bioenergy Technologies Office, "2016 Billion-Ton Report," Energy.gov, accessed August 1, 2023, https://www.energy.gov/eere/bioenergy/2016-billion-ton-report.
[14] "Potential Northwest Regional Feedstock and Production of Sustainable Aviation Fuel" (Port of Seattle and Washington State University, February 2020), https://www.portseattle.org/sites/default/files/2020-08/PofSeattleWSU2019updated_appendix.pdf.

to 220-290 million gallons of biomass-based sustainable aviation fuel per year, which is about one-third of the fuel dispensed at Seattle-Tacoma International Airport. To meet demand, production of biomass resources will need to be scaled up. However, the environmental costs[15] of scaling up production, such as the many potential impacts of changes to water and land use, will need to be assessed.

The total lifecycle emission reductions[16] of SAFs vary substantially depending on the feedstock. Some SAF pathways barely meet 50% carbon intensity reduction relative to jet fuel while other pathways involving carbon sequestration are carbon negative. The use of corn ethanol is a potential 'net zero' SAF pathway in the U.S. – the CO_2 generated by fermentation is very pure (99.7%) making sequestration possible, although there is some debate about whether it is truly a climate friendly fuel[17]. However, implementing this pathway, or any other biomass-based pathway, at scale in places like Europe does not appear feasible, illustrating how different regions around the globe may rely on different SAF production pathways. In addition, it is unlikely that any single feedstock or production pathway will yield enough SAF to meet all demand. Moreover, the impacts of using 100% SAF on aircraft fuel storage and management systems, as well as engine life, are unclear.

Uptake of SAF has several benefits in addition[18] to lowering GHG emissions from aviation. Biomass derived SAF production may enable the use of agricultural land unsuitable for food crops or repurpose waste streams that would otherwise release large amounts of methane gas, another GHG. In addition, SAFs mixed with jet fuel, in contrast to 100% SAF, can use existing transportation infrastructure. This topic will be discussed further in the next section on infrastructure.

Power-to-Liquid (PtL) derived SAFs[19] are synthetically produced liquid hydrocarbon fuels that involve hydrogen production via electrolysis of water using renewable electricity and a source of climate-neutral CO_2. These fuels can be further upgraded to a jet fuel equivalent with additional processing. If the power used to generate these fuels comes from renewable sources and the carbon is sourced from non-fossil sources, PtL SAFs would significantly reduce GHG emissions, potentially up to 100%, from aircraft[20]. Washington State is well-positioned to generate PtL fuels

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[15] Xin Zhao et al., "Estimating Induced Land Use Change Emissions for Sustainable Aviation Biofuel Pathways," *Science of The Total Environment* 779 (July 2021): 146238, https://doi.org/10.1016/j.scitotenv.2021.146238.
[16] "Life Cycle Emissions of Sustainable Aviation Fuels," ICAO: Environment, accessed August 1, 2023, https://www.icao.int/environmental-protection/pages/SAF_LifeCycle.aspx.
[17] Leah Douglas and Leah Douglas, "U.S. Corn-Based Ethanol Worse for the Climate than Gasoline, Study Finds," *Reuters*, February 14, 2022, sec. Environment, https://www.reuters.com/business/environment/us-corn-based-ethanol-worse-climate-than-gasoline-study-finds-2022-02-14/.
[18] Bioenergy Technologies Office, "Sustainable Aviation Fuels," Energy.gov, accessed August 1, 2023, https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuels.
[19] "Power-to-Liquids, Explained," Airbus, October 28, 2021, https://www.airbus.com/en/newsroom/news/2021-07-power-to-liquids-explained.
[20] Bernd Heid et al., "Clean Skies for Tomorrow: Delivering on the Global Power-to-Liquid Ambition," McKinsey & Company, August 25, 2022, https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/clean-skies-for-tomorrow-delivering-on-the-global-power-to-liquid-ambition.

because 80% of the state's electricity is generated from non-GHG emitting sources (including hydropower and nuclear). Like biomass-based SAFs, PtL SAFs are drop-in capable. Their main disadvantage is that their production cost is 3-to-5 times higher than conventional fossil-based fuels.

SAFs provide a near term pathway toward a sustainable aviation future. However, biomass-derived SAFs are unlikely to completely eliminate GHG emissions, and PtL SAFs have a long development time and scaling challenges, meaning that SAFs are inevitably only part of the solution to achieving net zero GHG emissions.

From a technology perspective, key uncertainties of SAFs include:

- Are there compatibility issues for 100% SAF derived from different sources?
- Can approved SAF pathways be implemented globally?
- How will scaling up biomass-based SAF production impact the environment, production of other biofuels and prices of other products?
- How do we allocate biomass-produced fuels across sectors that are hard to decarbonize?
- How much of U.S. demand can be met through PtL SAF production?

Aircraft Electrification

Electric aircraft use energy-efficient electric motors powered by batteries for propulsion. Electric aircraft are the only option that produce no emissions during operation[21]; however, emissions can be generated by non-renewable sources powering the electric grid. As previously mentioned above, Washington State is well-positioned for electric aviation because it obtains most of its electricity from renewable sources. In 2022, Washington-based startup Eviation demonstrated the potential for an electric commercial commuter aircraft by flying its newly designed all-electric aircraft Alice[22].

Aircraft electrification depends on advances in battery technology, specifically the development of light-weight batteries with high storage capacity. Batteries will be used with power management and distribution systems to produce full power at all stages of flight. Currently, the best available batteries are heavy and far less energy dense (~265Wh/kg) than jet fuel (13,000Wh/kg)[23]. Thus, near-term electric planes will only be able to travel a few hundred miles before needing to land for recharging—making them ideal for regional flights. New rechargeable battery chemistries will be needed to meet the energy density demands of longer range, higher load flights.

[21] Amy Schwab et al., "Electrification of Aircraft: Challenges, Barriers, and Potential Impacts," October 1, 2021, https://doi.org/10.2172/1827628.
[22] Dominic Gates, "First All-New, Electric Commuter Airplane Takes Flight at Moses Lake," The Seattle Times, September 27, 2022, https://www.seattletimes.com/business/boeing-aerospace/first-u-s-all-electric-airplane-takes-flight-at-moses-lake/.
[23] National Academies of Sciences, Engineering, and Medicine, "Electric Propulsion," in *Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions* (Washington, D.C.: National Academies Press, 2016), 51–70, https://doi.org/10.17226/23490.

Competing demand for batteries in electric vehicles may make the raw materials used to make batteries, like lithium or cobalt, difficult to source. Batteries used in aviation that reach the end of their useful life could be repurposed in a secondary application such as grid storage rather than being discarded. It will be important to establish a battery recycling industry to avoid producing a new toxic waste stream.

While certification of any aircraft is complicated, certification of electric aircraft will be particularly challenging because it will require regulators to create new standards for novel designs that establish safety levels consistent with existing standards. Already lengthy certification timeframes, upwards of 3-5 years, are likely to be even longer.

Low operating and maintenance costs as well as the ability of electric aircraft to use shorter runways could enable new connections between regional communities by making it feasible, both economically and structurally, for airlines to serve smaller airports. Moreover, use of electric aircraft for flights under 500 miles would be especially impactful at reducing emissions since takeoff and landing are the most fuel-intense phases of flight.

In Washington State, flights anywhere within the state, as well as to Vancouver, BC or Portland, OR, could be provided by aircraft using today's battery technology. However, these electric aircraft could only carry a small fraction of the passengers/load that existing regional flights are capable of. Nevertheless, this rapidly improving technology may transform the way people and goods move through the air, and if the power source is fully renewable and the power grid can handle the loads, electric aircraft are the only zero-emission option for aviation. Whether the power grid can be sufficiently scaled to ensure that the required power can be delivered and stored at all airports that need it is still an open question that will be discussed further in the next section on infrastructure.

From a technology perspective, key uncertainties of electric aircraft include:

- What amounts of raw materials such as lithium will be needed to scale this technology?
- What battery energy storage densities can be achieved and how will these new technologies be introduced into the aviation market?
- What are the battery technology requirements to maintain fast aircraft turnaround times?
- Will it be possible to increase the aircraft electric power handling capability of the system for larger aircraft?
- How will scaling this technology impact the ground EV industry?

Hydrogen Power

Hydrogen-powered aircraft may be one of the most promising long-term solutions to reduce GHG emissions if efficient hydrogen production, storage, and transportation are developed.

Hydrogen can be used in two ways as a power source for aircraft propulsion. It can be combusted through modified gas-turbine engines or converted into electrical power via fuel cells. Although hydrogen combustion produces no CO_2 emissions, it is known to produce harmful NOx pollutants.

In contrast, hydrogen fuel cells – which, like batteries, generate electricity through an electrochemical reaction – do not generate these pollutants[24]. In 2023, both ZeroAvia[25] and Universal Hydrogen[26] flew regional planes powered by hydrogen suggesting hydrogen powered commercial flights could be on the horizon.

Regardless of whether using hydrogen fuel-cell or combustion-based technology, both must be able to accommodate the safe storage of hydrogen. Hydrogen has roughly three times more energy per weight than jet fuel but takes up to four times the volume. As a result, storage of hydrogen onboard an aircraft is a challenge. To minimize volume, hydrogen must either be stored[27] as a compressed high-pressure gas or a cryogenic liquid. Aircraft design will likely need to change to accommodate hydrogen storage solutions. Additionally, since hydrogen is one of the most flammable fuels and the flame burns invisible to the naked eye, new safety technology will be needed to detect leaks and flames.

From a technology perspective, key uncertainties of hydrogen-powered aircraft include:

- Can the long-term safe hydrogen storage challenge be solved for aircraft?
- If aircraft must be redesigned and newly built to accommodate hydrogen storage, how will this affect reduction of total lifecycle emissions?
- Can high power fuel cells be built as required by larger aircraft?
- Can hydrogen-powered planes be quickly refueled for short aircraft turnaround times?

Besides the technological hurdles, producing clean hydrogen power is expensive. Similar to PtL SAFs, hydrogen has to be produced through electrolysis, and in a sustainable ecosystem it must use electricity produced from renewable sources. Currently, most of the hydrogen produced in the U.S. is generated from natural gas reforming[28] – which is not sustainable. To address this challenge, the Department of Energy is funding regional clean hydrogen hubs[29] across the nation. These hubs will accelerate the use of hydrogen as a source of clean energy by creating networks of

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24 Alastair C. Lewis, "Optimising Air Quality Co-Benefits in a Hydrogen Economy: A Case for Hydrogen-Specific Standards for NO $_x$ Emissions," *Environmental Science: Atmospheres* 1, no. 5 (2021): 201–7, https://doi.org/10.1039/D1EA00037C.
25 ZeroAvia, "ZeroAvia Makes Aviation History, Flying World's Largest Aircraft Powered with a Hydrogen-Electric Engine," PR Newswire, Cision, January 19, 2023, https://www.prnewswire.com/news-releases/zeroavia-makes-aviation-history-flying-worlds-largest-aircraft-powered-with-a-hydrogen-electric-engine-301726022.html.
26 Dominic Gates, "Pioneering Moses Lake Flight Uses Hydrogen to Power Regional Airplane," The Seattle Times, March 2, 2023, https://www.seattletimes.com/business/boeing-aerospace/pioneering-moses-lake-flight-uses-hydrogen-to-power-regional-airplane/.
27 Hydrogen and Fuel Cell Technologies Office, "Hydrogen Storage," Energy.gov, accessed August 1, 2023, https://www.energy.gov/eere/fuelcells/hydrogen-storage.
28 Hydrogen and Fuel Cell Technologies Office, "Hydrogen Production: Natural Gas Reforming," Energy.gov, accessed August 1, 2023, https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming.
29 Office of Clean Energy Demonstrations, "Regional Clean Hydrogen Hubs," Energy.gov, accessed August 1, 2023, https://www.energy.gov/oced/regional-clean-hydrogen-hubs.

hydrogen producers, consumers, and local connective infrastructure. The Pacific Northwest Hydrogen Association (PNWH2)[30], a coalition of entities from Washington, Oregon, and Montana, proposed a regional hub that would produce more than 100 metric tons of green hydrogen per day. Aviation will have to compete with other sectors for the supply of green hydrogen when it becomes available. Notably, even if this green hydrogen were entirely dedicated to aviation, it would only provide about 5% of the fuel needed at SEATAC airport. Also supported by the Department of Energy is the Hydrogen Shot initiative[31], which seeks to reduce the cost of green hydrogen to $1 per kilogram by creating a framework and laying a foundation for green hydrogen deployment in the American Jobs Plan.

Infrastructure Needed to Realize Sustainable Aviation

The transition to sustainable aviation will require new infrastructure to support technological changes in aircraft. Currently, fossil-based jet fuel is produced and distributed from a refinery by either pipeline or barge to off-airport storage. At the airport, fuel is either delivered to aircraft via a hydrant system with pipelines underground or by refueler trucks at smaller, more isolated airports. Although SAFs blended with fossil-based jet fuel can use this infrastructure, 100% SAF cannot, necessitating the creation of new or upgraded infrastructure. Electric and hydrogen-powered aircraft will require substantial infrastructure changes including charging stations at airports, a network of hydrogen production and distribution facilities, and new on-site energy storage options. PtL SAFs, electric aircraft and hydrogen-powered aircraft will all require upgrades to the power grid and investments in renewable energy.

Sustainable Aviation Fuels

As SAF technology begins to mature, understanding the environmental impacts and challenges of scaling up production, as well as addressing how SAFs will be stored, blended, and transported will become increasingly important. For biomass-based SAFs to be used to meet the 2050 net-zero goal, production must be increased by a factor of 10,000 and priced competitively with today's jet fuel. In 2019, only 2.4 million gallons of SAFs were produced in the U.S.[32], which represents 0.01% of the jet fuel used that year. Through the SAF Grand Challenge Roadmap[33], the U.S. Departments of Energy, Agriculture, and Transportation have set a target of producing 3 billion gallons of SAF in the U.S. by 2030 and 35 billion gallons by 2050, which could meet the projected U.S. jet fuel demand.

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[30] "Pacific Northwest Hydrogen Association," Pacific Northwest Hydrogen Association, accessed August 1, 2023, https://pnwh2.com/.

[31] Hydrogen and Fuel Cell Technologies Office, "Hydrogen Shot," Energy.gov, accessed August 1, 2023, https://www.energy.gov/eere/fuelcells/hydrogen-shot.

[32] Kristi Moriarty and Allison Kvien, "U.S. Airport Infrastructure and Sustainable Aviation Fuel" (Golden, CO: National Renewable Energy Laboratory, February 1, 2021), https://doi.org/10.2172/1768316.

[33] U.S. Department of Energy et al., "SAF Grand Challenge Roadmap" (Bioenergy Technologies Office, September 23, 2022), https://www.energy.gov/sites/default/files/2022-09/beto-saf-gc-roadmap-report-sept-2022.pdf.

Unique considerations exist for scaling up SAF production based on the feedstock used. For example, for SAFs derived from food crops considerations include the amount of land that must be allocated or converted to produce those crops, and the associated environmental costs of those land-use changes. Converting grassland or forests to cropland can generate significant amounts of GHG emissions[34] and impact land and water quality. Moreover, if these crops compete with other fuel feedstocks or foods, there may be impacts on the prices of those products for consumers. For SAFs produced from waste streams including municipal waste, wood and paper waste, and used cooking oil, dedicated transportation infrastructure will be needed to direct waste streams to processing facilities instead of landfills. If each source material needs to be processed at separate refineries, it will be important to consider the carbon investment to construct each refinery and transport the materials, and the pay-back time.

While the infrastructure needs for PtL SAFs are different and more costly than biomass-derived SAFs, they are applicable to the development of other technologies in the sustainable aviation ecosystem. Production of PtL SAFs[35] requires renewable electricity to generate hydrogen using water electrolysis and a source of non-fossil CO_2. Greater investments in dedicated non-GHG emitting power plants (solar, wind, or nuclear) are needed to generate enough clean electricity, although Washington state has an advantage with hydropower. Currently, global green hydrogen production accounts for only about 1% of total hydrogen. The U.S. Department of Energy is already exploring the use of existing nuclear plants for hydrogen generation[36]. Unlike biomass-derived SAFs, PtL fuels are sourced from green hydrogen and clean carbon, which means there would be little to no fuel variation between refineries. PtL SAFs will inevitably develop further as SAF uptake and availability of renewable power continue to grow.

Under current regulations set by the Federal Energy Regulatory Commission (FERC)[37], SAFs must be blended with jet fuel at a maximum of 50% for transport by existing pipelines. This limit has been set in part because biofuels can lead to stress cracking of steel pipelines, cause "trailback" contamination of other fuels in the pipeline[38], and damage materials used in seals or gaskets. Uptake of pure SAFs will likely be necessary to significantly reduce aviation GHG emissions, and therefore a new pipeline system specific for biofuels may be needed.

Although up to 50%-blended SAFs can use existing infrastructure, some additional infrastructure will still be needed, such as tanks to store and mix SAFs or mixing equipment to offload SAFs directly into jet fuel storage tanks. Blended SAFs also need to be transported to airports as most are not equipped or certified to blend fuel and many refineries cannot offload fuel delivery into

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34 Zhao et al., "Estimating Induced Land Use Change Emissions for Sustainable Aviation Biofuel Pathways."
35 Heid et al., "Clean Skies for Tomorrow: Delivering on the Global Power-to-Liquid Ambition."
36 Office of Nuclear Energy, "3 Nuclear Power Plants Gearing Up for Clean Hydrogen Production," Energy.gov, November 9, 2022, https://www.energy.gov/ne/articles/3-nuclear-power-plants-gearing-clean-hydrogen-production.
37 Moriarty and Kvien, "U.S. Airport Infrastructure and Sustainable Aviation Fuel."
38 Association of Oil Pipe Lines and American Petroleum Institute, "Ethanol, Biofuels, and Pipeline Transportation," White paper, accessed August 1, 2023, https://www.api.org/~/media/files/oil-and-natural-gas/pipeline/aopl_api_ethanol_transportation.pdf.

airport storage tanks. Moreover, many large airports use hydrant systems to deliver fuel and cannot control the airline or flight to which blended fuels are delivered.

Electrification

To support aircraft electrification, airport infrastructure will need to be reconfigured to provide ample power and charging capabilities. Greater power needs may require the expansion of existing power grids to ensure adequate supply of electricity. Ultimately, adoption of electric aircraft will depend heavily on the development of a network of airports with sufficient electrical power and aircraft charging infrastructure.

Electric aircraft will place new demands on the electric grids powering airports. Some airports may already have sufficient power supplies to meet these new demands, but many airports will not, and will need to upgrade the total capacity of their connection to the main grid. WSDOT's 2022 electric aircraft feasibility study[39] concluded that insufficient power supply from local electric utilities is unlikely to prevent initial adoption of electric aircraft by regional airports in Washington State. However, if aircraft electrification takes off, regional airports will need to work closely with utilities to ensure they have sufficient access to adequate electric supply. Additionally, to provide a large enough market to make electric aircraft economically viable, a sufficiently large network of regional airports across the country, continent and world will need to have these capabilities.

To ensure reliable access to power, airports may consider installing on-site power generation infrastructure which would allow them to operate independently from the main power grid. Increased demand on the power grid from electric vehicles and heating and cooling (HVAC) systems will also need to be considered when evaluating power grid capacity.

Charging infrastructure[40] will be critical to advancing electric aviation. Adoption of electric aircraft at scale will require coordination of charging standards to ensure that aircraft of different size, capability, and manufacturer can utilize airport charging equipment. In addition, this infrastructure will need to be capable of charging electric aircraft quickly between flights. The most prominent charging options being explored are plug-in charging and battery swapping. Battery swapping – the replacement of a depleted battery with a fully charged battery when the plane is on the ground – would reduce aircraft turn-around times and demand on the energy grid but would require FAA support to be feasible. In addition, this option may require more maintenance as battery swaps increase the likelihood of damage to the battery or aircraft. It will also be critical that airports have sufficient power and charging infrastructure to meet the aggregate demand.

Safety and security approval from the FAA will drive both the standardization and implementation of electric aircraft technologies. Assuming that the vehicle technology and certification issues are successfully addressed, the ultimate viability of electric aircraft as a reliable mode of

[39] Steffen Coenen, Daniel Malarkey, and Don MacKenzie, "Washington Electric Airport Feasibility Study" (University of Washington, Department of Civil and Environmental Engineering, December 2022), https://wsdot.wa.gov/sites/default/files/2023-01/Electric-Airport-Feasibility%20Study-December2022.pdf.
[40] Schwab et al., "Electrification of Aircraft."

transportation in Washington State will depend on the development of a network of charging and operations infrastructure[41]. Ensuring the economic viability of electric aircraft production and operation will require expansion of this infrastructure across the nation at a minimum, and maybe across the world.

Hydrogen

With hydrogen-powered planes undergoing their first successful demonstrations, their associated infrastructure needs should be considered now. As previously mentioned, green hydrogen currently accounts for only 1% of the hydrogen produced. Additional infrastructure such as electrolysis facilities powered by renewable energy will be needed to massively scale up production of green hydrogen.

Transporting hydrogen safely and economically will be a logistical challenge. Currently, most hydrogen is produced close to where it is used, so the existing framework for transportation is small. There are 1,600 miles of hydrogen pipeline in the U.S., compared to 190,000 miles of liquid petroleum pipeline. The U.S. Department of Energy is investigating whether natural gas pipelines may be used to deliver pure hydrogen gas[42].

Ideally, liquid hydrogen, as opposed to gaseous hydrogen, would be used as a fuel source to reduce the volume of storage needed, though its energy density is 3.7 times lower than jet fuel. However, liquid hydrogen must be stored at -253 C, resulting in major insulation and active refrigeration requirements, as well as potentially significant boil-off (loss) of the fuel during transfers. Luckily, hydrogen liquification and storage technology already exists since it has been used as rocket fuel for decades, albeit with significant loss rates, and the costs of these systems are significant.

Infrastructure needs may vary depending on how hydrogen fuel is delivered to the fuel tanks of planes. For example, Universal Hydrogen[43] has developed lightweight capsules for green hydrogen storage that can be placed in the fuselage of certain aircraft. The capsules are transported from green hydrogen production sites and loaded onto aircraft using existing airport infrastructure. Another option being pursued by ZeroAvia[44] is the production of liquid hydrogen on-site at airports. This requires both an electrolysis facility to produce hydrogen gas from electricity and water and a liquefaction plant to turn it into liquid hydrogen.

Workforce Development Needs for Sustainable Aviation

The transition to a sustainable aviation ecosystem will require a workforce with the skills necessary to develop, produce, operate and maintain the technologies and infrastructure

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[41] Coenen, Malarkey, and MacKenzie, "Washington Electric Airport Feasibility Study."
[42] Hydrogen and Fuel Cell Technologies Office, "Hydrogen Pipelines," Energy.gov, accessed August 1, 2023, https://www.energy.gov/eere/fuelcells/hydrogen-pipelines.
[43] Universal Hydrogen, "Fueling Carbon-Free Flight," Universal Hydrogen, accessed August 1, 2023, https://hydrogen.aero/.
[44] "ZeroAvia," ZeroAvia, accessed August 1, 2023, https://zeroavia.com/.

described above. Fortunately, Washington state has an aerospace and advanced manufacturing workforce development infrastructure that can be leveraged to train and grow the sustainable aviation workforce, though current production of aviation professionals is well below levels required to support the growth of the industry in its current form, let alone support the transition to sustainability. Washington State's workforce development infrastructure includes a network of skills training programs[45] managed by technical colleges[46], a Center of Excellence for Aerospace and Advanced Manufacturing[47], certificate and university degree programs[48], apprentice programs in industry, and public-private partnerships[49].

One of the biggest challenges to preparing the workforce for the transition to a sustainable aviation ecosystem is that the exact skills gaps are unknown and difficult to predict. Industry will need to work with educators to first identify what skills are needed to support each of these emerging technologies and to what extent are they lacking or underrepresented. They then need to work to close these skills gaps by providing workers with opportunities to gain the appropriate expertise and experience. For areas needing enhanced training in the sustainable aviation ecosystem, will Washington State's current infrastructure be able to produce the necessary workforce?

The aerospace community also has a unique opportunity to use the transition towards sustainable technologies to inspire the next generation to pursue aerospace careers as a means of helping the environment. Inspiring increased interest in aerospace careers is critically important for growing the aviation workforce in Washington State.

Sustainable Aviation Fuels

Because SAFs can to a large extent be deployed with existing engine systems and airport fuel management infrastructure, the primary workforce impact relates to whether the workforce can scale up SAF production, either biomass or PtL, to the levels required[50]. As SAF production is still a nascent industry, SAF supply chains – which encompass feedstock production, collection, and distribution to SAF production facilities; conversion of feedstock to fuel; and transport of finished fuel to the infrastructure required to fuel aircraft – are not yet mature, may differ by region and will likely require significant financial resources to establish. Regional workforces with the technical

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[45] Edmonds College, "Washington Aerospace Training & Research Center," accessed August 1, 2023, https://watrcenter.edmonds.edu/default.html.
[46] Washington State Board for Community and Technical Colleges, "Aerospace in Washington State," accessed August 1, 2023, https://www.sbctc.edu/colleges-staff/programs-services/aerospace/.
[47] Aerospace and Advanced Manufacturing, "Education & Pathways," Center of Excellence for Aerospace and Advanced Manufacturing, accessed August 1, 2023, https://www.coeaerospace.com/education-pathways.
[48] "University of Washington College of Engineering," UW College of Engineering, accessed August 1, 2023, https://www.engr.washington.edu/node/3209.
[49] "Pacific Northwest Aerospace Alliance," Pacific Northwest Aerospace Alliance (PNAA), accessed August 1, 2023, https://www.pnaa.net/.
[50] Brett Oakleaf et al., "A Roadmap Toward a Sustainable Aviation Ecosystem" (National Renewable Energy Laboratory, August 8, 2022), https://doi.org/10.2172/1881303.

expertise necessary to support the entire supply chain will be critical. Ultimately, regional production of SAFs will only be possible if the workforce capacity exists in that region.

Electric Aviation

The workforce for the electric aircraft industry[51] will have different requirements than today's aircraft industry. However, electric aircraft workforce development can build on existing workforce development programs through the addition of new modules within current programs and the creation of electric aviation-focused trainings in industries involved in the development, production, operation and maintenance of electric aircraft. Connecting with electric aviation startups, which comprise nearly half of all companies in this space, will also be crucial for integrating electric aircraft into workforce development. Electric aircraft offer the potential to help the aviation industry meet the anticipated surge in demand for pilots by making flight training more affordable due to reduced costs.

Overview of workforce development needs for an electric aircraft ecosystem	
Development	- Expand educational programs to produce more individuals with expertise in electronics, electric motor and power systems, semiconductors, automation technologies and sophisticated design programs.
Production & Operation	- Grow technical college programs and learning facilities at airports to train workers in the production and operation of electric power systems and specialty aircraft components. - Increase renewable power and grid distribution workforce to support the overall electric energy needs.
Maintenance	- Provide additional training for mechanics and operators to service electric power systems and specialty aircraft components. - Expand the renewable energy production and grid maintenance workforce.

Hydrogen-powered aircraft

Developing, producing, operating and maintaining a hydrogen-powered aviation ecosystem will require a workforce with skills that do not exist in the aviation sector today[52]. Technicians and engineers will need to be trained in the areas of hydrogen fuel systems and storage, hydrogen gas turbines, electrical systems and fuel cells. Researchers with expertise in materials science and

[51] WSP, Kimley Horn, and PRR, "Washington Electric Aircraft Feasibility Study," *WSDOT Aviation Division*, November 2020.
[52] Bethany Hall, Eliot Burrows, and Katy Milne, "Workforce to Deliver Liquid Hydrogen Powered Aircraft," White paper (United Kingdom: Fly Zero Aerospace Technology Institute, March 2022).

chemistry will be needed to develop novel materials, understand the effects of hydrogen on materials, design and validate hydrogen combustion setups, and model and support system design. In addition, a large expansion of the green hydrogen production, storage and distribution workforce will be required.

Overview of workforce development needs for a hydrogen-powered aircraft ecosystem	
Develop	- Expand educational programs to produce more individuals with expertise in the effects of hydrogen on materials, hydrogen combustion setups, novel material applications, advanced electrical motors and thermal management. - Train more engineers with systems and automation expertise to develop refueling solutions, hydrogen detection and fire suppression systems.
Production/Operation	- Develop technical college programs to provide technicians with knowledge of fuel cell products and how to safely handle and store liquid hydrogen. - Increase renewable power and grid distribution workforce to support the overall electric energy needs.
Maintain	- Develop training programs for mechanics to learn how to work with liquid hydrogen and vacuums and provide them with an understanding of the integration between fuel cell and electrical system on aircraft. - Expand the renewable energy production and grid maintenance workforce.

In 2021, WA Governor Jay Inslee signed House Bill 1170[53], the Building Economic Strength Through Manufacturing (BEST) Act, into law. In addition to providing a framework to add 300,000 new manufacturing jobs over the next ten years, the law tasks the WA Department of Commerce with appointing a workforce innovation lead to coordinate needs identified by leads in the manufacturing, clean technology, and aerospace sectors.

[53] "HB 1170 - 2021-22," Washington State Legislature, accessed August 1, 2023, https://app.leg.wa.gov/billsummary?BillNumber=1170&Year=2021&Initiative=false.

Regardless of which path sustainable aviation takes – whether it be SAF, electric or hydrogen, or likely a mix of all – addressing workforce development needs will be essential to bringing the emission reduction benefits of each technology to bear.

Key questions for Workforce Development:

- To what extent can the existing workforce development infrastructure accommodate the changes in skills and experience needed for workers in the sustainable aviation ecosystem?
- How do we create a flexible curriculum to prepare for the blend of technologies that will be used in the sustainable aviation ecosystem?
- How do we support the growth of sustainable aviation across Washington state?
- How do we more effectively partner with Tribal Nations and Colleges to feed the aviation workforce? How do we ensure that workforce development programs are equitable?

The Landscape in Washington State

Washington State is committed to advancing the state's climate resilience and to that end is actively working to support and grow the state's sustainable aviation ecosystem. Washington is home to several startups pursuing SAF, electric aircraft, and hydrogen-powered aircraft (Table 1).

In April, Governor Inslee signed Senate Bill 5447[54] into law, creating policy and per-gallon incentives for the production and use of SAF. This legislation subsidizes production of sustainable aviation fuel by up to $2 per gallon on top of the clean energy subsidies embedded in the federal Inflation Reduction Act, helping to bring down the cost of SAF so that it is priced competitively with jet fuel. Also signed into law in the 2023 session, House Bill 1216[55] accelerates permitting and environmental review for constructing clean energy plants. This legislation aims to ensure that new clean energy projects happen in an efficient, sustainable, and equitable manner.

Following passage of this legislation, Silicon Valley startup Twelve and Dutch company SkyNRG announced plans to scale production of SAF in the state. Twelve broke ground[56] on a new facility in Moses Lake in July where they will produce fuel using renewable electricity, water and waste biomass CO_2. Roughly 100 construction workers will be needed to build the plant and 20 full-time "green jobs" to operate it. SkyNRG's project[57], which has not yet announced a location, is expected

[54] "SB 5447 - 2023-24," Washington State Legislature, accessed August 1, 2023, https://app.leg.wa.gov/billsummary?BillNumber=5447&Year=2023&Initiative=False.
[55] "HB 1216 - 2023-24," Washington State Legislature, accessed August 1, 2023, https://app.leg.wa.gov/billsummary?BillNumber=1216&Initiative=false&Year=2023.
[56] Dominic Gates, "Sustainable Aviation Fuel Startup Breaks Ground on Moses Lake Plant," The Seattle Times, July 12, 2023, https://www.seattletimes.com/business/boeing-aerospace/sustainable-aviation-fuel-startup-breaks-ground-on-moses-lake-plant/.
[57] Dominic Gates, "New $800M Sustainable Aviation Fuel Plant Planned for Washington State," The Seattle Times, May 18, 2023, https://www.seattletimes.com/business/boeing-aerospace/new-800m-sustainable-aviation-fuel-plant-planned-for-washington-state/.

to produce about 30 million gallons of SAF per year, requiring an investment of between $600 million and $800 million. Construction of the facility will provide roughly 600 jobs with 100 permanent jobs needed for operation.

Increasing SAF production capacity in the state will be important for the state to meet its emission reduction goals. The Port of Seattle, which manages Seattle-Tacoma International Airport, has a goal of fueling all flights with at least a 10% blend of sustainable fuels by 2028[58].

To further research, development and adoption, the state has supported several industry-led consortiums through its Innovation Cluster Accelerator Program. The Sustainable Aviation Technologies and Energies (SATE)[59] cluster is researching opportunities in aviation fuels, electric aircraft and new propulsion technologies. The Consortium for Hydrogen and Renewable Generated E-Fuels (CHARGE)[60] is specifically exploring the use of hydrogen in difficult to decarbonize sectors including aviation.

As previously mentioned, Washington State is part of a broader coalition that has applied for up to $1 billion in funding from the Department of Energy to build a clean hydrogen hub in the Pacific Northwest. If funded, this could potentially bring tens of thousands of jobs to the state. The coalition proposed to create a regional network of clean, renewable hydrogen suppliers and end-users for hard-to-decarbonize sectors, such as aviation, heavy-duty transportation, maritime, agriculture, and industrial operations. Regardless, Washington-based ZeroAvia, which is developing a hydrogen-electric aircraft, recently announced[61] it will expand the workforce at its Everett facility to roughly 150.

Table 1. Select companies working in sustainable aviation in Washington State

Company/ Location	Technology Area	Focus
Mercurius Biorefining Inc / Ferndale	SAF	Sustainable aviation fuel from cellulosic waste biomass
NESTE / Seattle	SAF	Sustainable aviation fuel supplier
SkyNRG / TBD	SAF	Sustainable aviation fuel supplier
Twelve / Moses Lake	SAF	Aims to make sustainable aviation fuel from biomass waste

58 "Sustainable Aviation Fuels," Port of Seattle, accessed August 1, 2023, https://www.portseattle.org/page/sustainable-aviation-fuels.
59 "Clusters: Meet the Innovation Clusters," *Washington State Innovation Cluster Accelerator* (blog), accessed August 1, 2023, http://icapwashingtonstate.org/cohort-1.
60 "Consortium for Hydrogen and Renewably Generated E-Fuels," Joint Center for Deployment & Research in Earth Abundant Materials, accessed August 1, 2023, https://info.jcdream.org/charge.
61 Dominic Gates, "WA Wins E-Fuel and Hydrogen Power Pledges at Paris Air Show," The Seattle Times, June 19, 2023, https://www.seattletimes.com/business/boeing-aerospace/washington-state-announces-e-fuel-and-hydrogen-power-wins-at-paris-air-show/.

Insitu / Bingen	Hydrogen	Boeing company producing unmanned aircraft system (UAS or drones) powered by liquid hydrogen
ZeroAvia / Everett	Hydrogen	Developing hydrogen-electric aircraft that uses a combination of hydrogen fuel-cells and lithium-ion batteries
Eviation / Arlington	Electrification	Developing an all-electric aircraft named Alice for commuter and cargo flight applications that will be able to carry 9 passengers a maximum range of 290 miles using 260 Wh/kg battery cells
MagniX / Everett	Electrification	Produces electric motors for electric aircraft
Zeva Aero / Tacoma	Electrification	Developing aircraft with electric vertical takeoff and landing

Conclusion

Tackling decarbonization in the aviation ecosystem is a formidable challenge, but is achievable with innovation in aviation technologies, infrastructure and workforce development. Each technological solution – SAFs, aircraft electrification and hydrogen fuel technologies – has different benefits and challenges (Table 2) suggesting that pursuit of all solutions is the best path forward.

Although the transition to a sustainable aviation ecosystem is driven by the need to address climate change, it provides new research opportunities, opens new markets, and creates new jobs. Washington State is well-positioned to lead the U.S. into the next era of sustainable aviation given its commitment to mitigating climate change and the size and economic importance of the aviation sector in the state. Though there is much work to be done, the aviation industry has already demonstrated significant progress. Reducing aviation's climate impact is within reach.

Table 2. Summary of Sustainable Aviation Technology Options

Technology	Benefits	Challenges
Sustainable Aviation Fuels	- Reduced emissions compared to jet fuel - Engine and infrastructure compatibility - Flexibility due to multiple production pathways	- Doesn't completely eliminate emissions - Emission reduction varies depending on SAF pathway - Cost 2-5X more than jet fuel - Production needs to be massively scaled up

Electric	- No emissions during operation - Electric motors are highly reliable and more efficient than traditional combustion engines - Lower operating costs - Potential to increase access to regional airports	- Low battery energy storage density restricts aircraft size and flight duration - Scaling systems to high power for larger aircraft - Major changes to airport infrastructure including charging infrastructure - Scaling power grid to meet demand particularly at regional airports
Hydrogen	- No emissions when used with fuel cells - Only NOx emissions when used in gas-turbines	- Low energy storage density of hydrogen restricts aircraft size and flight duration - Requires rigorous testing and lengthy certification processes - Complex transportation and safety technology needed - Green hydrogen production currently very expensive

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