



Sustainable Aviation in Washington State

Connecting Policy, Technology, Infrastructure and Workforce Development Needs

WASHINGTON STATE ACADEMY OF SCIENCES

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Preface

The 16th Annual Symposium of the Washington State Academy of Sciences featured a topic of critical importance to both Washington State and the world: sustainable aviation.

Making aviation sustainable embodies all the challenges and opportunities posed by climate change. People need and want to fly, cargo needs to be transported, and the demand for air travel will continue to increase as the world economy grows. But aviation is already responsible for 2 percent of global emissions of carbon dioxide, and that percentage will increase as other sectors of the economy decarbonize. Reducing and then eliminating the emission of carbon dioxide from aircraft will be essential if the world is to achieve the goal of stabilizing atmospheric levels of greenhouse gases.

Washington State has its own goals to reduce greenhouse gas emissions, but the state also needs to sustain its economic vitality. More than 130,000 jobs and over \$70 billion in revenue depend on the continued success of the various elements of the aviation ecosystem in Washington State. That ecosystem involves not just airplanes but airports, the production of fuel, and the transportation of fuel to airplanes. It involves not just the operation of aircraft but their successful development, production, and maintenance. Furthermore, aviation encompasses regional, national, and international transportation needs, and each of these market segments has its own challenges and opportunities.

In moving toward a sustainable future for aviation, both Washington State and the world have options, but every option requires that actions be taken now. That requires providing answers to many difficult technical and policy questions, including:

- · What is the appropriate balance between the various sustainable aviation propulsion options?
- How will this balance change as technologies mature?
- What fraction of sustainable fuel production should be allocated to each sector of transportation, including aviation, trucking, rail, automobiles, and shipping?
- What fraction of sustainable fuel production should be allocated to each sector of the economy given the competing needs of society?
- What will be the impacts of scaling up the production, distribution, and storage of different sources of energy?
- Where will Washington and the world get the skilled workforce to develop, produce, operate, and maintain all the various elements of the new sustainable aviation ecosystem?

To examine these and many other questions, the symposium, which was held on August 17, 2023, at the Museum of Flight in Seattle, was organized around three interconnected topics. After a keynote address that introduced the overall issues (summarized in Chapter 2), a panel of presenters looked at the three specific technologies being developed to forge a sustainable future for aviation: sustainable aviation fuels, electrification, and hydrogen power (Chapter 3). The following panel discussed the broader changes in the aviation infrastructure required to enable the safe and economically sustainable implementation of sustainable aviation technologies (Chapter 4). A second keynote address and subsequent panel then looked at the workforce development needed to inculcate the skills that people will need to develop, produce, operate, and maintain the technologies and infrastructure sustainable aviation will demand (Chapter 5). Boxed "Key Takeaways" at the end of Chapters 2–5 capture the main observations and recommendations made by the presenters. In a networking session held at the conclusion of the symposium, leaders of the aviation industry and Washington State's government commented on prospects for the future (Chapter 6). It was an insightful, forward-looking, and inspiring event that left the more than 150 attendees energized and optimistic.

I would like to thank the sponsors of the symposium, the Aerospace Futures Alliance, the Museum of Flight, and Clean Fuel Washington. Thanks are also due to the co-organizers of the symposium, the Aerospace Future Alliance, the Joint Center for Aerospace Technology Innovation, the Washington State Department of Commerce, and the Museum of Flight. The executive director of the Washington State Academy of Sciences, Donna Gerardi, and her staff did a stellar job of organizing and conducting the symposium. The Washington State Academy of Sciences, an independent nonprofit organization of more than 375 members who are nationally recognized for their scientific and technical expertise, is to be commended not only for its annual symposiums and other meetings but for its overall mission, the application of science and technology in the service of Washington State.

With its historical leadership in the aviation sector, Washington State has an unequaled opportunity to lead the way toward a sustainable aviation future. By helping the planet decarbonize, what happens in Washington State will make a difference around the world.

Roger Myers Symposium chair and past president Washington State Academy of Sciences

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1. Transitioning to Sustainable Aviation

A Vision for Sustainable Aviation

In his keynote address at the Washington State Academy of Sciences' 16th annual symposium, "Sustainable Aviation in Washington: Connecting Policy, Technology, Infrastructure, and Workforce Development Needs," Richard Wahls, mission integration manager for the Sustainable Flight National Partnership at NASA's Aeronautics Research Mission Directorate, laid out a vision for sustainable aviation. It should:

Grow to meet demand and improve the quality of life for more people worldwide.

Be environmentally friendly and broadly recognized for its value to society.

Be safe, clean, quiet, efficient, economical, operable, and marketable.

Sustainability is often discussed in environmental terms, Wahls pointed out, but sustainability also has to be economic and societal. In each of these three areas, a mission needs to be met while other goals are simultaneously achieved (Figure 1-1). "The unique value of air transportation comes from its payload, speed, range, and relative cost," said Wahls. "If we have to make compromises that take away from that unique value proposition of air transportation, then we haven't won. We need to make sure we can keep doing the missions we are doing now and the ones we need to be doing in the future."



FIGURE 1-1 Sustainability implies meeting societal, economic, and environmental objectives. Source: NASA.

Wahls also provided a list of the needs a sustainable aviation future must satisfy:

- **Safety** –Safety comes first and cannot be compromised.
- Economics —A sustainable aviation future has to be economically favorable for the entire aviation ecosystem while maintaining the United States' global competitiveness.
- Environmental friendliness Aircraft need to produce less emissions and be cleaner throughout their production, use, and disposal lifetimes; they also need to be quieter in flight.
- Efficiency Aircraft need to draw on resources as efficiently as possible, including the value of time.

- **Marketability** Sustainable aviation needs to provide the value that only aviation can provide.
- **Operability** Sustainable aviation needs to be consistent with safe, efficient operations in the global airspace.
- Energy future—Sustainable aviation needs to be consistent with the future economy-wide mix and use of energy sources.
- Timely The aviation ecosystem needs to safely accelerate change because the planet will not wait.

THE CHALLENGE

U.S. carriers performed almost 9 million flights worldwide in 2022, and U.S. airlines transported 24 million tons of freight that year, Wahls observed.¹ The aviation industry's total contribution to U.S. economic activity was \$1.9 trillion in 2019, and in 2021 it had a \$51.5 billion positive manufacturing trade balance. It also was responsible for 2.1 million aerospace/ defense jobs in 2021, with 575,000 in aeronautics and aircraft.

The commercial airline industry is very difficult to enter, and over the past three decades only five companies have delivered more than 100 commercial jets in a single year: Boeing, Airbus, McDonnell Douglas, Bombardier, and Embraer, though the Chinese company COMAC is becoming significant and expects further growth, especially since the Chinese market represents about 20 percent of the projected commercial aircraft market. In 2018, six companies delivered a total of 1,728 commercial jets, although Boeing and Airbus currently account for almost all the commercial jets being produced. Both Boeing and Airbus have projected a need for approximately 40,000 new airplanes in the next 20 years, even though all companies combined have never produced 2,000 aircraft in a year. "We're going to need to be able to produce aircraft faster, and they're going to need to be better," Wahls said.

Energy is the lifeblood of the aviation industry; it "feeds everything." Reducing dependence on fossil fuel is therefore the underlying challenge driving change across the entire energy sector. Subsonic commercial airliner operations dominate aviation's climate impact and will remain the backbone of domestic and international longhaul air transportation. Thus, those aircraft are the key to a sustainable aviation future. At the same time, small aircraft may provide growing value relative to other modes of transportation at the regional and local levels while also serving as technology incubators for larger aircraft.

The aviation sector is hard to decarbonize and has unique impacts that extend well beyond the flights themselves from "source to tank" as well as from "tank to wake," as Wahls put it. Aircraft impact local air quality and cause disruptions because of noise. In addition, aviation is a source of radiative effects from emission of carbon dioxide and from non-carbon emissions. In particular, aircraft create contrails, which may have had a greater warming impact on the planet to date than the carbon dioxide the industry has so far released into the atmosphere.² However, contrails would cease to exist if flights stopped, whereas carbon will remain in the atmosphere for centuries. As a result, the warming

¹ Data are available from the U.S. Department of Transportation's Bureau of Transportation Statistics at https://www.bts.gov.

² D.S. Lee, D.W. Fahey, A. Skowron, M.R. Allen, U. Burkhardt, Q. Chen, S.J. Doherty, S. Freeman, P.M. Forster, J. Fuglestvedt, A. Gettelman, R.R. De León, L.L. Lim, M.T. Lund, R.J. Millar, B. Owen, J.E. Penner, G. Pitari, M.J. Prather, R. Sausen, and L.J. Wilcox. 2021. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment 244:117834.

from carbon emissions will become increasingly greater than that from contrails. They are "two different problems with two different timescales, and we need to be working on them both," Wahls observed. In addition, some contrails are cooling while others are heating, and contrail formation is influenced by engine technology, fuel composition, and atmospheric conditions. Focused research in these three areas could inform flight operations decisions and reduce the negative effects of contrails.

Transportation represents 29 percent of U.S. greenhouse gas emissions, and aviation is 8 percent of transportation (Figure 1-2). That means aviation is responsible for 2.3 percent of U.S. greenhouse gas emissions. But other transportation sectors will be easier to decarbonize than aviation, which will cause aviation's relative contributions to the problem to grow.

At the same time, the electrification of other sectors presents great opportunities for aviation. Ground vehicles use about 140 billion gallons of gasoline a year, much of which consists of 10 percent ethanol. If all ground vehicles were electrified, as much as 14 billion gallons of ethanol would become available to produce sustainable aviation fuel for air travel, which is about half the fuel currently needed for aviation in the United States.



FIGURE 1-2 Aviation accounts for 8 percent of greenhouse gas emissions in the transportation sector, which is itself responsible for 29 percent of U.S. emissions. *Source: Environmental Protection Agency*.

MANAGING THE TRANSITION

The goal of sustainable aviation is to halt aviation's contribution to global warming without suppressing flight demand—"none of this flight shaming," said Wahls. "We want the value of aviation to be available to everyone everywhere." Sustainable aviation should stride to avoid reliance on carbon offsets in other sectors while remaining a viable and valued cornerstone of transportation. Aviation has to

consider its effects on air quality, noise, and the disposal of products, including the batteries that would be involved in electric aircraft.

Of the three possible pathways to a sustainable aviation future—sustainable aviation fuels, electrification, and hydrogen—the greatest near-term opportunity for aviation is sustainable aviation fuels, according to the U.S. National Blueprint for Transportation Decarbonization.³ The United States also has a Sustainable Aviation Fuel Grand Challenge, which calls for the United States to produce 3 billion gallons of sustainable aviation fuel per year by 2030 and 35 billion gallons per year by 2050, with the latter amount meeting the entire projected liquid fuel needs for U.S. aviation in that year.⁴ Progress toward these goals has been accelerating in this decade, Wahls said, and recent incentives established by legislation are likely to further speed this progress.

Electricity and hydrogen offer longer term opportunities. For example, the **U.S. National Clean Hydrogen Strategy and Roadmap** calls for the production of 10 million megatonnes of clean hydrogen produced by renewable forms of energy by the year 2030, 20 million megatonnes by 2040, and 50 megatonnes by 2050. In 2050, 2 to 6 megatonnes would be set aside for sustainable aviation fuels.

The United States has an Aviation Climate Action Plan that calls for U.S. aviation to achieve net-zero greenhouse gas emissions by 2050.⁵ The plan points out that aviation emissions would nearly double by 2050 on the current trajectory. But airline fleet renewal with current technologies, the use of new aircraft technologies, improvements in aviation operations both in the air and on the ground, and uptake of sustainable aviation fuels could combine to achieve the goal of net zero (Figure 1-3). Wahls added that achieving this goal will require that sustainable aviation fuels be produced "at scale and as cheaply as we possibly can as soon as we possibly can."



FIGURE 1-3 Fleet renewal, new technologies, operations improvements, and the use of sustainable aviation fuels could enable U.S. aviation to achieve net-zero emissions by 2050. *Source: Aviation Climate Action Plan.*

 $[\]label{eq:starses} 3 \quad \mbox{Available at https://www.energy.gov/eere/us-national-blueprint-transportation-decarbonization-joint-strategy-transform-transportation.}$

⁴ Available at https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuel-grand-challenge.

⁵ Available at https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf

THE ROLE OF NASA

NASA-which has a primary federal role in developing technologies and improving operations and a supporting role related to sustainable aviation fuels-has a two-pronged approach for sustainable aviation. To elevate technology readiness, NASA leads the Sustainable Flight National Partnership, which is seeking to cultivate the best ideas from industry and academia to advance sustainable aviation.⁶ A major goal for the partnership, said Wahls, is getting technologies across what he called the technology readiness valley of death, "where it becomes expensive to do integrated testing to find out all the finer details so that the people in industry-like the people here in Boeing who make the decisions on what products to do-have enough confidence to adopt something radically different, or even simply different." The Sustainable Flight National Partnership has chosen a series of demonstrations intended to bridge this gap so that decisions can be made by the end of this decade for products that may appear in the 2030s.

The partnership is also casting a very wide net for zeroemission concepts and technologies that are more distant, and it is funding concept studies and technology development that will be needed in the 2040s and beyond. Many of these innovative ideas would require fundamental changes in the aviation infrastructure, but the need to change the infrastructure "doesn't mean you shouldn't be exploring and researching these ideas now—they're just not as visible and high profile as the big demonstrators."

The Sustainable Flight National Partnership is working on advanced engine technologies to reduce emissions, integrated trajectory optimization, advanced airframe efficiency, quicker manufacturing rates, and the use of 100 percent sustainable aviation fuels. Specific technologies under development include electrified gas turbine aircraft propulsion, the use of composites to reduce weight, improvements in aerodynamic efficiency, including the development of transonic truss-braced wings, and increases in efficiency through integrated aircraft design.

As a specific example, Wahls pointed to a January 2023 agreement that NASA made with Boeing to design, build, test, and fly an advanced airframe configuration demonstrator aircraft with technologies that could dramatically reduce fuel burn and carbon dioxide emissions. Boeing's Transonic Truss-Braced Wing configuration uses a high-aspect-ratio, thin, truss-braced wing design to reduce drag and improve fuel efficiency, with the first flight scheduled for 2028 (Figure 1-4). NASA is making a \$425 million direct investment along with facilities and labor valued at approximately \$125 million over seven years. With \$725 million in funding from Boeing and other industrial partners, the project is spending more than a billion dollars in total. "In the commercial aviation world, we haven't seen anything like this since Boeing in the 1950s with the Dash 80."



FIGURE 1-4 NASA's support of subsonic airliner technologies seeks to ensure that U.S. industry continues to lead the next half century of aviation. *Source: NASA.*

NASA is also supporting demonstrations involving operations that are designed to contribute to the goal of net zero. For example, the Digital Information Platform seeks to optimize operations and reduce emissions through digital services. "They're already saving fuel during the demonstration in the active live fleet in Texas, and the system is going to be expanded to look at oceanic routes, including some work on contrails," said Wahls.

In response to a question about differences between the truss-braced wing design and blended wing designs, Wahls noted that the Department of Defense is supporting a large-scale blended wing body demonstrator project. It builds on decades of NASA research, and "we'll learn a lot" from this next effort, he said.

⁶ More information is available at https://www.nasa.gov/directorates/armd/sfnp/.

THE NEED FOR ACTION

Time is of the essence, Wahls said. "2050 is only 27 years away, and the climate is not waiting." Given the development cycle of new aircraft, just one or perhaps two new kinds of commercial aircraft could be put in service during that period. Furthermore, the current fleet and infrastructure have substantial inertia. With about 25,000 airliners in operation today and another 40,000 in growth and replacement expected over the next 20 years, the size of the fleet could nearly double by 2050, especially as people in developing countries fly more. The aircraft being delivered today will be in service for 20 or 30 years, as will the ones being delivered over the next five years and beyond, and all will require a certain kind of fuel and its associated infrastructure. "If we keep studying and studying and don't do anything, we're not going to have impact," he said. "We have to be doing things now."

Aircraft designs and changes in the energy infrastructure will need to be consistent not just nationally but globally. "If one part of the world decides hydrogen is the answer and another part of the world decides something else, how can I fly an airplane from one part of the world to the other?" As aviation technologies are developed, a possibility is that two or even three parallel energy infrastructures will take shape. If so, they would have to operate together for decades, because tens of thousands of airplanes cannot be abandoned if electric or hydrogen-powered aircraft are adopted. In addition, if electric or hydrogenpowered aircraft are adopted for regional transport, how will aviation change overall? Will cleaner aircraft be used on short routes while conventionally fueled or SAF aircraft fly longer routes? Will hub-and-spoke systems give way to new travel configurations? "There are a lot of implications that we should all be thinking about."

The challenge of realizing a sustainable aviation future will require that multiple, often interdependent, solutions be developed across technology, operations, and energy domains, Wahls concluded. No silver bullets exist, but NASA is maturing and demonstrating the most promising solutions for application in the 2030s and beyond.

Key Takeaways

- Sustainability must be measured not just in environmental terms but in economic and societal terms as well.
- A sustainable aviation future must be safe, economic, environmentally friendly, efficient, marketable, operable, consistent with our energy future, and timely.
- Sustainable aviation fuels (SAFs) offer the greatest near-term opportunity for aviation while electricity and hydrogen offer longer term opportunities that can be phased into regional markets.
- Airline fleet renewal, the use of new aircraft technologies to reduce fuel consumption, improvements in aviation operations, and uptake of sustainable aviation fuels could combine to achieve the goal of net-zero greenhouse gas emissions from aviation by 2050.
- The proper allocation of sustainable carbon across different sectors of the economy, including the various transportation sectors (trucking, shipping, rail, etc.), to ensure that all are financially and environmentally sustainable will need to be assessed.
- Just one or perhaps two new kinds of commercial aircraft could be put in service before 2050, so change has to happen very quickly.

2. Propulsion Technologies

Exploring the Major Sustainable Energy Sources for Aircraft

The first panel of the symposium examined the three major energy sources for powering sustainable aircraft: sustainable aviation fuels (SAFs), electricity, and hydrogen. The setting of the symposium was appropriate, said the panel's moderator Anna Oldani, manager of the Sustainable Aviation Fuel Program at the Federal Aviation Administration. Seattle's Museum of Flight is full of aircraft *"that probably were thought to be crazy at the time, but people persisted, . . . they worked through the problems."* Aviation today is effective and safe, said Oldani, but *"we have to do better for the environment. . . . It's important that we try things, because a lot of times we don't know everything until we try it."*

SUSTAINABLE AVIATION FUELS

SAFs are built on a molecular backbone of carbon, and this carbon can come from many sources, said Joshua Heyne, director of the Bioproducts, Sciences, and Engineering Laboratory at Washington State University and co-director of the WSU-Pacific Northwest National Laboratory Bioproducts Institute. One source is carbon-based waste such as used cooking oil, municipal solid waste, sewage sludge, or woody and agriculture residues. Another is purpose-grown crops such as oil seeds and corn ethanol. A third is the use of renewable forms of power to produce liquid fuels, such as the use of energy to capture carbon from the air and convert it to fuels.

Aircraft have many redundant systems that facilitate safety, but they have just one fuel. This fuel dictates the engine operating conditions, which determines the aircraft specifications, which shapes the airline of which the aircraft is a part. "Fuel is the core of all this," Heyne said.

Because of its critical importance, any SAF needs to be equivalent to or better than the product that it is replacing in every dimension. All SAFs approved to date are drop-in, meaning they can substitute for part of conventional fuels at particular ratios, can be used across a fleet, and are compatible with the existing infrastructure. Engines, aircraft, and infrastructures do not "see" any difference between an approved SAF and a conventional fuel, said Heyne.

All approved SAF blends are currently equivalent to Jet A/A-1 fuel. If a SAF blend were not equivalent to Jet A/A-1, the fuel would require its own fuel specification, it would have to be handled separately, and the aircraft and engine would require certification to that fuel.⁷

SAFs have been studied for decades as ways of using non-traditional carbon resources to produce aviation fuel. As a result of this long history, different pathways exist to produce different kinds of SAFs, and variation exists among pathways and even among producers for the same pathway. Well-established and documented processes exist to commercialize a novel SAF process, and SAFs are subject to an extensive and rigorous suite of testing prior to approval.

SAFs also have a connection to contrails, Heyne observed. Some kinds of SAF produce less soot, which can act to seed ice crystal formation and form contrails. Research is examining whether SAF composition could reduce contrails and persistent cloudiness via soot reduction.⁸ A major

⁷ Stephen Kramer, Gurhan Andac, Joshua Heyne, Joseph Ellsworth, Peter Herzig, and Kristin C. Lewis. 2022. Perspectives on fully synthesized sustainable aviation fuels: direction and opportunities. Frontiers in Energy Research 9:782823. https://doi.org/10.3389/fenrg.2021.782823

⁸ Christiane Voigt, Jonas Kleine, Daniel Sauer, Richard H. Moore, Tiziana Bräuer, Patrick Le Clercq, Stefan Kaufmann, Monika Scheibe, Tina Jurkat-Witschas, Manfred Aigner, Uwe Bauder, Yvonne Boose, Stephan Borrmann, Ewan Crosbie, Glenn S. Diskin, Joshua DiGangi, Valerian Hahn, Christopher Heckl, Felix Huber, John B. Nowak, Markus Rapp, Bastian Rauch, Claire Robinson, Tobias Schripp, Michael Shook, Edward Winstead, Luke Ziemba, Hans Schlager, and Bruce E. Anderson. 2021. Cleaner burning aviation fuels can reduce contrail cloudiness. Communications Earth & Environment. 2:114. https://doi.org/10.1038/s43247-021-00174-y

current research question is how to achieve a 100 percent drop-in fuel that would minimize contrail formation.

In addition, with SAFs, the lifecycle emissions of a fuel depend on how its sustainable carbon element is produced, whether biogenically or through atmospheric carbon capture. While both pathways will require significant renewable sources of energy, atmospheric carbon capture will require far more power than biogenic production. Furthermore, even with extensive use of SAFs, achieving a net-zero aviation industry will sometimes require sequestering carbon

ELECTRICITY

While drop-in SAFs could meet the fuel needs of the majority of the commercial aircraft fleet, said Scott Cary, the lead of the Ports and Airports Program in the Energy Systems Integration Directorate at the National Renewable Energy Laboratory, they emit carbon that will persist in atmosphere for centuries. Battery-powered electric aviation using renewable electricity is the only option with zero emissions from aircraft operation.

The diversity of the aviation fleet is a major consideration in the potential of electric aircraft. In addition to the 20,000 to 30,000 large commercial aircraft that are flying, so are more than 200,000 smaller general aviation aircraft in the United States, which have shorter ranges and smaller payloads. These smaller aircraft, as well as the smaller regional aircraft in the commercial fleet, are excellent candidates to be replaced by aircraft that either use more electricity or are fully electric, Cary observed.

The major constraint on electric aircraft is weight. A gallon of kerosene or SAF contains roughly four times more energy than does an equally heavy battery. Nevertheless, some applications are already being electrified, such as drones, and commercial companies are making great progress in starting the transition to regional electric aircraft. In addition, significant investments are being made in battery technologies, which may enable electrification of larger aircraft, though electrifying large passenger aircraft is still well out of reach.

The infrastructure needed to deliver electricity to aircraft is a major issue (as discussed in more detail in the following chapter). The widespread use of electricity in aviation would require that much more renewable electric power underground to compensate for emissions that cannot be avoided, Heyne pointed out.

In response to a question about using more exotic feedstocks like cashew nut shell liquid, which has a high concentration of aromatics that can be problematic from like a sooting perspective, Heyne noted that work is ongoing to get new SAF pathways qualified. The aromatics concentration is an important consideration in this work, he added, with regard to both processing costs and sooting.

be delivered to airports. However, greater electrification could also improve the efficiency of existing airport systems, said Cary.

Already, several types of small electric aircraft have been certified for flight, and larger regional electric aircraft are expected to be certified in the near future. For example, a European company is working on a 30-seat aircraft powered by electric propulsion that would use sustainable aviation fuel as a secondary energy source. "There is a market in terms of the general aviation community and in niche markets," said Cary. At the same time, researchers are continuing to work on higher energy density batteries and higher thrust motors that will expand the opportunities for electric aircraft.

The choice of fuel will affect the organization of the aviation system, Cary noted. The use of regional electric aircraft may spark a transition away from the hub-and-spoke model to a more point-to-point model. This depends as well on what other forms of transportation are being used for regional trips, whether cars, trains, or buses, and the time, effort, and expense associated with different modes of travel and different combinations of those modes.

In response to a question, Cary observed that an important issue is whether the batteries used in electric-powered aircraft can be recycled for other purposes. Also, battery technologies are changing quickly, and future batteries may be more recyclable in addition to being better for aircraft propulsion. Through its ARPA-E program, said Cary, the Department of Energy is pushing to determine what is possible in terms of battery energy density. For example, the department's 1K Challenge is trying to get battery energy densities from their current level of 300 to 450 watthours per kilogram to a future level of 1,000 watt-hours per kilogram, compared with jet fuel at about 1,200 watt-hours per kilogram. This would make electric aircraft much more competitive from a range and payload perspective with SAF or conventional fuels. "It's a drastic jump," he said, but it has motivated researchers to think through the problem and seek solutions.

HYDROGEN

Hydrogen contains 2.8 times the amount of energy per unit weight compared with jet fuel, so it offers an opportunity to reduce the weight of the fuel onboard the airplane. The downside is that it takes more volume to store hydrogen, whether in the form of a compressed gas or a liquid kept below 20 degrees Kelvin (which is equivalent to -424 degrees Fahrenheit). As a high-pressure compressed gas, hydrogen takes up seven to eight times the space of the jet fuel containing an equivalent amount of energy, and as a superchilled liquid it takes up four times as much space as jet fuel. "You're going to need more space on the airplane to store the fuel—that's the bottom line," said Jonathan Gladin, senior research engineer and chief of the Propulsion and Energy Division at the Georgia Institute of Technology.

Large tanks of hydrogen could not fit into the wings of aircraft as with the fuel tanks of modern jets. Rather, they would have to be contained within or attached to the fuselage in some way, either in the back of the aircraft or split between the front and the back to avoid large changes in the center of gravity as the hydrogen is burned (Figure 2-1). Putting tanks in the fuselage would displace passengers or cargo, which would reduce capacity. Adding to the length of the fuselage would increase weight and drag, requiring more energy to fly. Tanks for liquefied hydrogen need associated subsystems such as chilling systems and pumps to get the hydrogen to a high pressure for use in a combustion engine. Health monitoring equipment is also necessary since hydrogen is very prone to leaking and can permeate into materials. Tanks could be made swappable, so that an empty one can be removed and a full one inserted, which would reduce the amount of time needed to fuel a plane with hydrogen. However, swappable tanks would incur a weight penalty due to smaller tank sizes, and safety considerations come into play with any tank configuration. A compressed gas tank requires less volume because the gas is at high pressure, but that typically increases the weight and cost of the tank to ensure its safe use. In general, though small hydrogen-powered aircraft should be able to fly the same ranges as smaller planes today, larger planes are likely to have shorter ranges than today's longrange aircraft, said Gladin.



FIGURE 2-1 Tanks for hydrogen could be located in the rear of an airplane or split between the fore and aft sections of the fuselage.

Tank weights can be compared by measuring how much the hydrogen in a tank weighs and dividing by the total weight of a full tank, a measure known as the gravimetric index. Gravimetric indexes for compressed gas tanks range from 1 to 10 percent, though 10 to 20 percent is possible. For example, a compressed hydrogen tank designed for the Toyota Mirai automobile has a gravimetric index of five percent. In that case, a 37-gallon tank holds 10 pounds of hydrogen. One company has designed a very high pressure 850-bar tank that achieves a gravimetric index of 17 percent, which could be applicable for short-range or regional aircraft if it passes the safety certification process.

Cryogenic liquid tanks have a lower design pressure and occupy two to three times less volume than compressed gas tanks. This results in gravimetric indexes that can range from 50 to 70 percent, with the index increasing with the size of the tank. Foam or vacuum insulation have been used in the past to keep hydrogen below 20 degrees Kelvin, but lower cost and more effective materials are needed. Issues include the strength and compatibility of materials at low temperatures and the large number of fueling cycles that tanks must undergo for commercial aircraft, which makes durability a concern. Tank geometries are also a major consideration so that tanks can conform to aircraft structures while remaining aerodynamic and safe.

On an airplane, hydrogen can either be burned in an engine with air or it can be passed through a fuel cell to make electric power. The benefit of using combustion for propulsion is that it can make use of existing, mature, and widespread gas turbine technologies with a high ratio of power to weight five times that of fuel cells, depending on size. Hydrogen, and especially cold hydrogen, could provide significant synergies in terms of leaner burns and cooling opportunities. Combustion has been the generally preferred technology in studies of hydrogen use for large commercial aircraft.

The downside of using combustion is that it produces nitrogen oxides and water vapor, both of which are greenhouse gases, with the relative amount of each depending on design choices. New combustor and injector designs are required that do not rely on pre-mixing. Fuel delivery, potential leakages, and other issues raise safety concerns, and the technology scales poorly at small sizes.

The benefit of using fuel cells for propulsion is that they produce only water vapor emissions and have relatively high efficiency—50 to 60 percent, depending on design choices. They scale well to small sizes, maintain relatively high power at altitude, and can be used as an auxiliary power unit (APU) to provide energy for functions other than propulsion. The downside of fuel cells is that they generally are heavy and require a variety of thermal management, air compression, and other systems. They also tend to be expensive and have lower durability than other forms of propulsion, issues that are both subjects of ongoing research.

The amount of emissions from a hydrogen-powered aircraft depends on assumptions about the associated infrastructure and on how the hydrogen is produced. Also, hydrogen-powered aircraft would produce contrails, since engine exhaust cooling in the presence of water vapor causes saturation and ice formation. Hydrogen produces water vapor but no soot, and the benefits from eliminating soot have been estimated to outweigh the increase in water vapor, Gladin said.

Multiple regional flight demonstrations of hydrogen-powered fuel cell aircraft have been conducted and are being planned for the future. Furthermore, a roadmap exists to produce fuel cell energy densities of 3 to 3.5 kilowatt-hours per kilogram by 2050, which would make all-fuel-cell single-aisle aircraft theoretically possible, though they would be very heavy.

Key Aircraft Propulsion Technology Takeaways

SAF blends, which are the most promising near-term replacements for conventional jet fuel, are subject to extensive and rigorous testing to ensure that they can be used safely in existing aircraft. Though the weight of batteries is a major limitation on the size of electric aircraft, battery-powered electric aviation using renewable electricity is the only option with zero emissions from aircraft operation.

- Hydrogen-powered aircraft would produce only water vapor emissions during operation, but hydrogen fuel tanks take up more space than conventional fuel tanks and would require modifications of aircraft designs.
- Both electric and hydrogenpowered regional and general aviation aircraft are being certified for flight, though with significant range and payload limitations. More advanced battery and hydrogen storage systems will be needed to increase the range of these options.

3. Infrastructure Challenges

Assessing the Key Hurdles to Implementation

To introduce the infrastructure challenges facing sustainable aviation, the moderator of the second panel at the symposium, Melinda Pagliorello, managing director of Airports Council International–North America, offered a generalized perspective from North American airports.

First, airports have priorities that require sustained investments. Their top priorities are to provide competitive air service and manage costs per passenger. Large hubs face such issues as airport staffing shortages, people experiencing homelessness, and accessibility challenges. With regard to greenhouse gas emissions, the highest carbon emissions for airports are usually related to the heating and cooling of terminals.

The airlines that fly into a given airport also have priorities related to their business models, such as whether that airport serves as an airline's hub or a final destination. At the same time, aircraft fly to different airports, which raises the question of the critical mass of airports needed to support the sustainable aircraft of the future.

Airport infrastructure is aging, even as the electricity grid is subject to increasing demands. As just one example, airports are already struggling with the electrical infrastructure to meet the needs of rental car companies, much less the needs of electric aircraft. According to an estimate from the Airports Council International, airports have \$150 billion in unmet infrastructure needs.⁹ Federal and state funding will be critical in meeting these needs, Pagliorello said.

Forecasting energy demands is a system-wide challenge for U.S. airports. They have to decide what to build today but also how to remain flexible as they transition to meet future needs. The energy management issues that arise include infrastructure requirements, vehicle electrification, facility management, legal/regulatory considerations, stakeholder engagement, and new kinds of staffing skills and knowledge that will be needed.

Airports carry out extremely complex operations in spaceconstrained envelopes, Pagliorello observed, and new infrastructure generally has to fit into those spaces. For example, the fuel infrastructure for hydrogen-powered aircraft may require just as much space as a conventional fuel farm but on the opposite side of the airport. Furthermore, airports need to continue operating while new infrastructure is installed. Solving such problems will require outside-the-box thinking even as airports continue to "operate within the box," said Pagliorello. "Airports are not plain white sheets of paper."

THE INFRASTRUCTURE FOR SAFs

The production and delivery of fuels to aircraft has been optimized over many years, but SAFs would not be produced and transported to airports in the same way. "There are differences all along the supply chain that need to be addressed," said Michael Wolcott, regents professor and director of the FAA Aviation Sustainability Center (ASCENT) at Washington State University. Despite these differences, the delivery of SAFs to aircraft will need to be done in collaboration with the oil industry and the existing infrastructure, "because that's not going away in the near future."

⁹ See https://airportscouncil.org/wp-content/uploads/2023/03/2023ACI-NAInfrastructureNeedsReportOnePager.pdf.

The International Civil Aviation Organization (ICAO), through Washington State University and its partners in ASCENT, maintains a dashboard of facilities, both existing and announced, for the production of sustainable aviation fuels (Figure 3-1).¹⁰ The dashboard includes 206 facilities that currently are producing about 71 billion liters per year of SAFs. About half of these are in the United States, both by count and production volume, and that percentage is growing because of incentives put in place by the federal government, the airline industry, and major corporations that rely on air travel. Of the announced future facilities, past experience suggests that somewhere between 40 percent and 60 percent will eventually come online.





About 36 percent of the production announcements are for the hydrotreated esters and fatty acids (HEFA) pathway, which converts waste fats, oils, and greases into SAFs using hydrogenation. However, not enough waste lipids are currently available to meet feedstock demands for the announced production plans, said Wolcott. If SAFs are instead produced using readily available agricultural feedstocks like soy, questions arise about the overall carbon intensity of the process, since the lifecycle emissions of agricultural products could be high. Novel second cropping techniques, such as growing oil seeds in the wintertime, could make agricultural products more viable, but that would require significant changes in the agricultural sector, and "farmers want to see a market in place before they make their cropping decisions."

Biomass gasification, such as the conversion of biomass to syngas, has not been commercially demonstrated on a large scale. Facilities "are starting to come on stream," said Wolcott, "but there's still technology risk associated with that."

¹⁰ Available at https://www.icao.int/environmental-protection/GFAAF/Pages/Production-Facilities.aspx.

Great hope surrounds power-to-liquid technologies that would extract carbon dioxide from the atmosphere or from the waste stream of a factory and convert it to fuel. However, those technologies will require large amounts of renewable energy, which also will be in high demand from other parts of the transportation sector and from other sectors of the economy.

Initially, carbon will likely be sourced from biomass to reduce reliance on scarce supplies of renewable electricity. Eventually, better power-to-liquid technologies will be devoted to renewable energy production. Both the production of SAFs from wastes and biomass and power-to-liquid technologies involve extracting carbon from the atmosphere, converting it to a hydrocarbon, and returning the carbon to the atmosphere when the hydrocarbon is burned. "We need to think of these as sister technologies producing the same product," said Wolcott. "It's just a matter of how we get the carbon." One reason HEFA technologies are popular is that they produce fuels with the lowest prices of all current SAFs. However, those prices are still approximately four times the prices of conventional fuel, Wolcott observed. The missing factor is that SAFs abate the costs imposed by adding fossil fuel-derived carbon dioxide to the atmosphere. "When we enacted the Clean Air Act, when we enacted the Clean Water Act, it didn't come free, and decarbonizing is not going to come free either," said Wolcott. The federal government, state governments, and companies will all help cover these additional costs. In Washington, for example, Microsoft, through its Climate Innovation Fund, is providing leadership in supporting the production of SAFs.

For all forms of SAF production, new technologies that lower costs are needed, Wolcott said. For example, the world has abundant supplies of waste cellulosic feedstock from wood, agriculture, and other sources, but yields of SAFs from these materials are low. "We need technological advances on those aspects."

THE INFRASTRUCTURE FOR HYDROGEN

Hydrogen is a non-drop-in fuel that is compatible with neither existing aircraft or the current infrastructure serving the aviation industry. "The first question you might ask is, why bother?" observed Florian Allroggen, executive director of Aerospace Climate and Sustainability at the MIT Laboratory for Aviation and the Environment. "Why rethink the infrastructure? It sounds costly. It sounds complicated. It will take a lot of time."

The answer is hydrogen's promise, Allroggen said. Hydrogenpowered aircraft would have no direct carbon dioxide emissions and very low overall emissions if hydrogen is produced via electrolysis with renewable electricity. Also, hydrogen production has a higher energy conversion efficiency than does power-to-liquid production, and the higher gravimetric energy density of hydrogen reduces energy consumption, though the lower volumetric energy density increases drag and the structural weight of the airframe.

However, hydrogen as an aviation fuel poses major production and logistics challenges. The first is the scale required to produce hydrogen for the aviation sector. The electrical energy required to produce liquid hydrogen for the air travel that took place at each of the world's 20 most energy intensive airports in 2019 would be between 5 and 13 gigawatts annually. That is the equivalent of the output of two large nuclear power plants for each airport. "I'm not trying to argue that we should build nuclear power plants to solve this problem. This is just to give you a sense of scale."

Similarly, to make all the liquid hydrogen projected to be needed for aviation in the year 2050 would require an investment of between \$700 billion and \$1.7 trillion just for the fuel infrastructure.¹¹ Such an investment represents twice the combined revenue of Boeing and Airbus annually, Allroggen observed. "For the aviation industry, this is a ginormous number."

The second challenge is how to structure the supply chain for a hydrogen-powered aviation system. Transporting liquefied hydrogen by pipeline is not feasible, so tank trucks or railcars would be necessary. But supplying the Paris airport with hydrogen equivalent to the energy that it used in 2019 would require about 1,000 tanker truck deliveries per day, "so it's

¹¹ World Economic Forum. 2023. Target True Zero: Delivering the Infrastructure for Battery and Hydrogen-Powered Flight. Geneva: World Economic Forum.

logistically not simple." As a second option, using electricity to liquefy hydrogen that is piped as a gas to the airport would, in the previous scenario, require the energy from a solar field the size of the city of Paris. As a third option, producing hydrogen through electrolysis and then liquefying it at the airport would create substantial space problems.

When these three options are analyzed, the last turns out to be the cheapest for almost all global airports. However, due to transportation costs and local resource availability, the cost of liquid hydrogen will vary across global airports. This causes problems in parts of the world where those costs are high.

The third challenge is the distribution of hydrogen within airports. Building tanker trucks and cryogenic pipelines to transport hydrogen would require an estimated \$250 billion in infrastructure investments, which is also a very large amount of money in the aviation industry. The fueling of planes needs to be done safely while ensuring separation between jet fuel and hydrogen. And fueling needs to be done quickly to avoid having planes sitting on the ground and not earning money, which is a technical challenge that will need to be solved.

"Please don't misunderstand this," said Allroggen. "I'm not trying to tell you that this is impossible. I'm just trying to tell you that we need to carefully think through these challenges and how we are going to address them." A well-trained and capable workforce (the subject of the next chapter) will be essential to make progress on these issues, he concluded.

THE INFRASTRUCTURE FOR ELECTRICITY

Subramanian Vadari, founder and president of Modern Grid Solutions, pointed out that he lives in Redmond, Washington, outside Seattle. Three miles from his house are a Microsoft depot, a United Parcel Service depot, a U.S. Postal Service depot, and a FedEx depot. Given plans for transportation in those depots to be completely electrified over the next ten years, supplies of electricity to each will need to go from around 0.5 to 1.5 megawatts to between 25 and 150 megawatts. "How do I bring 150 megawatts of supply into downtown Redmond?" he asked.

The same issue applies to airports. Nuclear power plants cannot be built next to them to provide power for sustainable fuels. If electric power is brought from elsewhere, new transmission lines will need to be built through neighborhoods, which is likely to generate opposition. "How many of you would like to see a transmission line in your backyard?"

The answer to the problem of making aviation sustainable, said Vadari, will be "all of the above." Small planes, including general aviation planes, and large aircraft have different needs. So do airports of different sizes, ranging from major international airports like Sea-Tac to small regional and local airports. Sustainable aviation fuels, hydrogen, and electricity will all play roles, and different solutions will be appropriate for different airports. For large hubs, transporting electricity is cheaper at scale than transporting hydrogen, and especially cryogenic hydrogen. Large hubs may opt for making hydrogen on site, while small airports may choose to bring hydrogen canisters from elsewhere or transfer hydrogen by pipeline. Some fuels will be transitional, such as SAFs, while others will be long term. "It depends on the context in which you want to do this."

Saying that the state government, the federal government, and companies will pay for electrification means, ultimately, that consumers will pay for it, Vadari observed. "From the perspective of a utility, we always think about it does to the rates of the consumer." SAFs and hydrogen both pose similar problems of costs, even if those costs are distributed and paid for differently.

"It is a difficult problem but not insurmountable," said Vadari. "It needs a lot of smart people working together." In particular, engineers and scientists need to find innovative solutions that policymakers then can advocate. "I don't have an answer, but I believe in my heart that, one, we can solve it and, two, that the answer will have all of the above built into it." Some of the solutions may be transitional and others may prevail—"only time will tell."

In response to a question, Vadari observed that, for the most part, the electricity grid in the United States has fairly good capacity, but "there are always bottlenecks." Just as highway traffic can flow at speed most of the time but not during rush hour, electricity delivery can face obstacles at particular times and in particular circumstances. "We always

3. Infrastructure Challenges

talk about supply and think that delivery is just available," said Vadari. But delivery requires transmission and distribution

> a luxury good through decarbonization by making it incredibly expensive. We have to keep this in mind or we'll lose acceptance."

> Vadari said that policymakers need to focus on what is important, how much does it cost, and how quickly can it get done.

A POLICY WISH LIST

At the end of the panel, moderator Pagliorello asked each of the three presenters to list a single item on which policymakers should focus.

"Infrastructure siting and construction reform" was Wolcott's reply.

Allroggen pointed to the equity consequences of decarbonizing aviation. "We can't afford to make aviation

Key Infrastructure Takeaways

- Airports face many constraints in accommodating the infrastructure needed for sustainable aviation.
- SAFs can make use of many components of the current infrastructure, but their production at scale will require the construction and operation of many new facilities and new sources of sustainable carbon (biogenic or power-to-liquid).
- Airports face many constraints in accommodating the infrastructure needed for sustainable aviation.
- SAFs can make use of many components of the current infrastructure, but their production at scale will require the construction and operation of many new facilities and new sources of sustainable carbon (biogenic or power-to-liquid). SAF production must be dramatically expanded while its cost must be reduced by 4x to be competitive.
- The production of hydrogen and its transport to airports, or the production of hydrogen at airports in either gaseous or liquid form, poses major facilities, operations, and logistics challenges, emphasizing that its introduction will be a phased process focused initially on regional aircraft.
- The production and distribution of renewable electric power must be expanded regardless of the propulsion technology selected all three options will require significant renewable power.
- The accelerated electrification of airports will enable expanded use of electric aircraft, but different sized airports must be evaluated for transmission and storage capacity constraints.
- A sustainable aviation future is likely to involve a mix of fuels that are phased in at different rates over time.

lines, which are also difficult to build and "make delivery constraints non-trivial."

4. Workforce Development

Creating the Workforce for a Sustainable Aviation Future

"Whatever the technology development is, without the people to build the vehicles, operate the vehicles, build the infrastructure, operate the infrastructure, and maintain all these systems, this transition to sustainable aviation will fail—and we cannot fail," said Roger Myers, past president of the Washington State Academy of Sciences and chair of the symposium. "We must ensure that workforce development efforts meet this challenge. We must have the people with the required skills as we think about these new technologies and new operating paradigms. We don't have enough people to do all the new jobs that are going to be created to sustain any of these technologies. Where are these people going to come from?"

The session on workforce development at the symposium had two parts. First, Howard McKenzie, chief engineer of the Boeing Company and executive vice president of Engineering Test and Technology, gave a second keynote address that focused on the steps Boeing has taken to create the workforce for a sustainable aviation future. Second, a panel of experts considered specific issues and things that need to be done to create a sustainable aviation workforce.

CREATING PATHWAYS TO SUSTAINABLE AVIATION JOBS

In his keynote address, McKenzie began by describing the four routes being taken by Boeing to achieve the aerospace industry's goal of net-zero emissions by 2050. Through fleet renewal, new airplanes provide significant efficiency gains as each generation reduces fuels and emissions by anywhere from 15 to 25 percent. "Fully deploying the latest generation of airplanes is one of the most significant contributions to carbon dioxide emissions reduction available over the next decade," McKenzie said. Through greater operational *efficiency*, the aviation industry can reduce emissions by about 10 percent by flying more efficiently. With today's airplanes, sustainable aviation fuel offers the largest potential of *renewable energy* to reduce carbon emissions over the next 30 years in all aviation segments, though McKenzie advocated not for a "SAF or" approach but for a "SAF and" approach, including a role for electricity and hydrogen. And from an advanced technology perspective, Boeing has partnered with NASA and other major airlines to develop the X66-A sustainable flight demonstrator, with a truss wing design that aims to reduce fuel consumption by up

to 30 percent compared with current domestic aircraft, while investing in research and development to enhance the efficiency and scalability of electric and hybrid electric propulsion systems.

"At the heart of all this is the top talent that we need," said McKenzie. "All this paradigm-shifting work requires a multifaceted approach when it comes to preparing the future workforce."

Collaborating with educational institutions, Boeing is striving to promote education in science, technology, engineering, and medicine (STEM) from an early age and to inspire young people to pursue careers in aerospace. It is providing access to resources, workshops, and educational programs to foster creative problem solving, collaboration, and curiosity. It is supporting hands-on experiences, internships, and apprenticeships that allow students and young professionals to apply their knowledge in real-world settings. It is particularly focused on reaching underserved communities and inspiring more young people to think about a future in aerospace. In these ways, it is seeking to impart not only practical skills but a sense of purpose and responsibility. "We need to encourage employees to think creatively, explore new ideas, take calculated risks, and work and think across disciplines. Encouraging risk taking and creating cross-functional teams and platforms for sharing ideas will stimulate a culture of innovation that drives sustainability forward."

One of Boeing's most significant initiatives is Core Plus Aerospace, a two-year high school advanced manufacturing curriculum that was launched in 2015 and is now offered in more than 50 high schools and skill centers in Washington. During the 2022-23 school year, more than 2,200 students were enrolled in Core Plus aerospace, and Boeing hired more than 1,000 graduates into full-time jobs. In addition, Boeing has been a founding partner in the Washington State Opportunity Scholarship since its inception in 2011, contributing over \$30 million to support low- and middle-income students who are pursuing certificate, apprenticeship, and degree programs in the state. The program, which has supported more than 1,000 students to date, is a unique public-private partnership that invests private dollars matched by the state to provide financial aid and scholarships for students in high-demand fields.

At the collegiate level, Boeing's longstanding relationship with the University of Washington dates back over a century, when the company's founder, Bill Boeing, made a charitable contribution in 1917 to create a research wind tunnel. In 2022, Boeing committed \$10 million to construct a new interdisciplinary engineering building at the University of Washington aimed at fueling economic growth and fostering a pipeline of local engineering talent. Also in 2022, Boeing pledged \$5 million to establish a new student success center in the Voiland College of Engineering and Architecture on the Pullman campus of Washington State University, which will provide students with access to networking, mentoring, advising, and career services.

When considering the entire value stream of the aviation industry, the skills required are very wide ranging, from those who develop the architecture of aircraft to those working on future fuels to those who set the standards required of fuels to those who are responsible for the end life of aircraft. The aviation infrastructure includes engineers, technicians, mechanics, accountants, program managers, and many others. "It is a vast value stream of skills because it requires global activity across the whole value stream to make all this work."

In addition, lifelong learning opportunities in the rapidly evolving landscape of sustainability technology require continuous learning, McKenzie said. Boeing offers its workforce access to ongoing training and development opportunities, ensuring that employees stay updated on the latest advancements, technologies, and practices. "We have to be in this together—industry, policymakers, and academia. We all must commit to preparing the future workforce to design, build, and maintain the infrastructure and products required to meet our goals."

A COMMITMENT TO DIVERSITY

McKenzie, who was born in Jamaica and has wanted to work on airplanes since he was a child, has watched the industry undergo a profound technological transformation. Now, he said, "I have the opportunity to see the great transition to sustainability to preserve our planet." Throughout his education and career, he was provided with focused support and with opportunities to take leadership positions and make a difference. "I now have an obligation to do the same for new entrants into our business to continue the legacy of growth, opportunity, and innovation to continue to change the world."

The only way to meet the workforce requirements needed to achieve net zero in aviation is "to open the aperture to those who might not see themselves as engineers," said McKenzie. "We have to provide more opportunities to underserved communities, continue to encourage diversity and inclusion, and create pathways for all students to apprenticeships and internships."

McKenzie has worked with the University of Washington, with his alma mater the University of California, Berkeley, and with other universities to influence the content of curricula, interact with faculty, and improve K-12 STEM education. He also has advocated for students to have the agency to shape their own education. On recruiting trips, representatives of Boeing listen to students' preferences on how they want to develop a career. "Students share and tell us what they want to focus on and learn." Boeing then tries to reflect these preferences back to an institution's curriculum to affect what is taught and how it is taught. For example, the students at Berkeley had an interest in aerospace, and it was from this interest that an aerospace major was instituted at Berkeley. "We have to be thoroughly tuned in to listen to what these highly talented students are telling us," he said. "We have to be in a space where we can be open and transparent and have a receiving body at the institution to collaborate and build out what that looks like." Furthermore, "to their credit, all of the academics, boards, advisors, and faculty at all of

THE CHALLENGE OF NUMBERS

In her introduction to the panel presentations on workforce development at the symposium, moderator Kristi Morgansen, chair of the Department of Aeronautics and Astronautics at the University of Washington, highlighted the size of the problem. Across the United States, the aviation and space industries have hundreds of thousands of jobs that they cannot fill. The situation is similarly dire in the semiconductor industry, computer science, and other STEM areas. Given the numbers of workers that will soon be retiring from these sectors, millions of workers will be needed for these jobs by 2030, Morgansen said.

In 2022, 3.3 million high school students graduated from public high schools in the United States. That same year, college students received on the order of 500,000 STEM

the universities I've engaged with have received those kinds of messages with open arms."

Boeing has seen results from its investments, and "that's why we continue to drive those investments forward," McKenzie concluded. "It's a partnership between industry, academia, and governments to ensure that we're continuing to develop that interest and the access to resources that students need to further their interests."

degrees from two-year and four-year colleges, representing about 15 percent of the high school students who graduated that year. Given these numbers, "we need to at least double the number of people going into STEM. That's frightening."

Providing a STEM education is much more expensive than providing an education in other fields, Morgansen pointed out in response to a later question. At the same time, the amount of tax dollars coming from Washington State to the university system is proportionately lower than in the past. "We need the public to say that, as a group, we will pay for the education of our students, and not just at the college level [but at] the K-12 level, because the public school systems are not properly funded."

CHANGES IN THE WORKFORCE

Carolyn Busch, director of workforce innovation and industry sector program coordinator at the Washington State Department of Commerce, extended Morgansen's observations in describing workforce shortages in aviation and in manufacturing more generally in Washington State.

First, a profound income gap has developed in Washington State. Among Washington households that reported adjusted gross incomes on their federal tax forms in 2020, 46 percent made less than \$50,000 per year, "probably living paycheck to paycheck," Busch said. Collectively, these households represent 12 percent of the adjusted gross income reported in the state. On the other side of the income distribution, households with adjusted gross incomes greater than \$100,000 per year represent 25 percent of the households and hold 71 percent of the adjusted gross income. That leaves middle-class households at just 25 percent of households and 19 percent of all adjusted gross income. "We do not have a middle class," Busch said, which is an issue that "must be addressed if you expect people to go to work." People are not going to enter the workforce for "low wages that will not feed them, will not allow them to buy a home or rent an apartment or pay for child care—they are making horrible choices between owning a home and having children."

Compounding these broad economic trends, generational change has had a major effect on the workforce. Baby Boomers (born between 1946 and 1964) now make up just

6 percent of the workforce, so their generally work-centric, ambitious, and risk-taking characteristics are becoming less common in the workplace. The members of Gen X (born between 1965 and 1980) and Gen Y (born between 1981 and 1996 and commonly known as millennials), now each make up 35 percent of the workforce. Gen Xers tend to be flexible, informal, and independent, said Busch, while Gen Yers are more civic and open-minded, achievement-oriented, and digitally savvy. Finally, Gen Zers (born between 1997 and 2012) are more progressive, entrepreneurial, and reliant on technology. They expect maximum flexibility and social justice and are wary about low-paying jobs, knowing that they can rely on the gig economy to get by.

In Washington State, Gen Xers, Millennials, and Gen Zers make up about equal percentages of the population, with Boomers at about two-thirds those levels. Many Gen Zers are still in high school, but among those who are adults, fewer are in the workforce in Washington State than among Gen Xers and Millennials (Figure 4-1). If Gen Zers participated in the workforce at the same level that other generations do, their numbers would already be greater than those of the Baby Boom generation, but "they're not showing up," said Busch. "That has a lot to do with insufficient wages."





Women are underrepresented in the aviation workforce and in manufacturing in general. Though women represent 48 percent of the workforce in Washington State, they are only 28 percent of the manufacturing workforce. "If you want to get into a new market of employees, women are a very good place to go," said Busch. "But that's going to mean real changes in the way that you do HR. It's going to demand childcare, among other changes."

Members of minority groups make up only 22 percent of the workforce in manufacturing, and these numbers are far worse in the leadership ranks. Among business owners in Washington State, 93 percent are white men, and just three percent are people of color.

Despite the large demand for workers, enrollments in community and technical colleges have been plummeting,

down nearly 30 percent in the past decade, and many fouryear colleges have also seen enrollment declines. "Gen Zers are not showing up in college," Busch said. "Again, it comes down to an income issue. Why would they when they can't earn a living wage and could instead do the gig economy, get pretty good wages, and have a very flexible schedule." But the lack of college attendance by young people is contributing to intergenerational wealth disparities, "because our young people are not able to move up within the system to get good-paying jobs."

As a result of its insufficient production of college graduates, Washington State is a net importer of talent from other states and other countries. To stay on the cutting edge of the modern economy, Washington needs "to serious address its supply of higher education." College needs to be more relevant and more applicable, and it needs to recognize the communication needs of young people, "which are different than the communication needs of you and me."

Busch urged the creation or adaptation of state systems that foster the skills of business owners, including women and members of minority groups. Employers need to listen to the values and needs of new workers, provide accessible training and educating for living wage jobs, incorporate women and minority group members into those jobs, and support local workforce development boards and their coordination with local economic development councils. On this last topic, workforce development boards are the backbone of workforce development throughout Washington State, Busch noted. Busch also observed, in response to a question, that multiple levels of skills are required within the aviation industry and in any advanced manufacturing, and not all of them require a bachelor's or higher degree. Technical colleges and apprenticeship programs can teach these skills while responding to Gen Z's need for maximum flexibility. "The University of Washington and Washington State University are stellar organizations doing high-quality work, but other kinds of education also need to occur in other areas of our education system."

"I'm the eternal optimist," she concluded. "While these are barriers and hurdles to be overcome, through solid public policy and good public engagement with all of you and others outside of this room, there is a path forward."

WORKFORCE DEVELOPMENT AT NASA

The objectives of NASA's STEM engagement efforts are to immerse students in NASA's work, enhance STEM literacy, and inspire the next generation to explore. "We use NASA's unique mission to educate and provide learning experiences for students," said David Berger, STEM engagement embed for aeronautics at NASA. In this way, NASA creates unique opportunities for a diverse set of students to contribute to the agency's work in exploration and discovery, attracts diverse groups of students to STEM through learning opportunities that spark interest, and provides connections to NASA's mission and work.

Building a sustainable aviation workforce ties into NASA's focus areas of broadening student participation and building strategic partnerships, said Berger. Though NASA may seem like a large agency, "we have way more ideas than we have the capacity to explore those ideas." NASA reaches out to students at all levels, from K-12 to graduate education. In NASA's aeronautics program, for example, the agency engages with external communities to build relationships that can support STEM opportunities linked to NASA's aeronautics research milestones. It creates timely and engaging activities connected with aerospace milestones that help youth discover and experience real-life applications of STEM skills. It also offers young people options to stay connected to NASA's aeronautics family. "It's very important

 \ldots that we inspire and educate at the K-12 level to bring people into this group."

As a specific example, Berger mentioned the University Leadership Initiative, in which universities take the lead, build their own teams, and set their own research paths to address strategic thrusts and special topics relevant to NASA's mission.¹² Awards have included teams working on net-zero emissions topics, such as work conducted by the University of Illinois, Urbana-Champaign, and a network of industry and university partners on an electric plane employing hydrogen fuel cells and superconducting electric drivetrains. Berger also described the workforce development efforts being carried out under the Sustainable Flight National Partnership to identify and retain top talent for pursuit of aviation sustainability through undergraduate internships, graduate student scholarships, and mid-career fellowships.

Finally, he described the Space Workforce 2030 program, which is a partnership that demonstrates the power of collaborative efforts.¹³ The program includes a long-term commitment to improving diversity in the workforce and holding the agency accountable for measurable results.

A particular need, mentioned several times earlier in the session, is for new entrants into the skilled technical workforce, said Berger. "It is a good career to go into the

¹² More information is available at https://www.nasa.gov/aeroresearch/programs/tacp/uli/description.

¹³ More information is available at https://swf2030.org.

skilled trades. Engineering is great. Science is great. But skilled technical jobs are not a consolation prize. There is no stigma in wanting to go into those good high-paying jobs." Industry and government need to work together to inspire more students in these areas "so we can build the base rather than simply competing to steal that welder or that technician that we need." Supporting students to enter these careers meets both NASA's near-term workforce needs and national demand as well.

THE ROLE OF COLLEGES AND UNIVERSITIES

Industry leaders often say that they want well-rounded students who can tackle big societal problems, observed Nancy Allbritton, Frank and Julie Jungers Dean of Engineering at the University of Washington. Instead of a "T-shaped education"-deep in a particular engineering discipline with some exposure to the full range of engineering-they want students with a "pie-shaped education," so that they have deep technical expertise in their core engineering discipline plus experience with artificial intelligence and machine learning. They want students who understand that there are no rigid boundaries between disciplines, students who can reach across boundaries to communicate and collaborate with colleagues around the globe. They especially want students who are well versed in artificial intelligence and machine learning "because those are going to be fundamental tools and technologies that students are going to have to use as they move forward to solve some of the big problems."

Being involved in high-impact research and entrepreneurship can help university students develop those skills, said Allbritton. At the Boeing Advanced Research Center, for example, Boeing-affiliated instructors work side by side with faculty and students on real problems.¹⁴ There are "no black and white solutions here but a whole host of different solutions." At the Advanced Composite Center, students are involved "from top to bottom" in using data science and machine learning tools to develop high-rate cost-efficient manufacturing methods.¹⁵ "Students have to do more than just one flavor of engineering, so they begin to get the idea of how they're going to work in the future."

As dean, Allbritton has been committed to enhancing linkages between the university's engineering program and industry. "Let's be honest, industry is where the rubber meets the road. It's where the solutions enter the marketplace and where we begin to change people's lives. So one of our big goals is to change how we interface with industry." Faculty members who spend time in industry can bring cutting-edge technology and industry problems back to academia. Students can work with real-world engineers, which is when "they really start to get excited about their coming profession." Interactions with industry improve course content and update it to reflect the state of the art and the needs of industry, which is where most students will end up working.

The University of Washington is also developing postgraduate programs to help upskill the workforce. Continued development of the workforce can create nimble and productive employees as they progress through their career. For example, the College of Engineering is rolling out a machine learning and artificial intelligence certificate for workers.

Engineering is facing an "all hands on deck" moment, said Allbritton. Engineering needs to be open to anyone, no matter what their background. "You shouldn't be an engineer just because of an accident of birth." The University of Washington has a structured outreach and engagement program designed to reach students in low-income underserved public high schools. "I was in Chehalis a week and a half ago, and we had high school students building Rube Goldberg machines out of recyclable materials like cardboard. Their machines were awesome. You could see the budding engineers."

If students have hands-on real-world experiences from the beginning of their engineering education, they can understand, for example, why they are taking calculus. "This is how I'm going to change the world if I stick with it." The university also knows that it needs to help students if they are to succeed, so it provides them with a wide range of wraparound services. "Our goal is for every student that comes to engineering to graduate and have a good career." For example, the Pathways for Inclusive Excellence program provides talented and

¹⁴ More information is available at https://depts.washington.edu/barc.

¹⁵ More information is available at https://depts.washington.edu/uwacc.

motivated students, including those with little exposure to universities, with the support and advice they need to navigate university systems and succeed.¹⁶

The fact that Washington State has been importing talent is distressing, said Allbritton. Students from the state should be the ones who are taking the available jobs and earning the good salaries the industry pays. "We want to build the state and the economy of the state," she concluded. "We want to partner with you to make it happen."

In response to a question about how to add material to an engineering curriculum that is already crowded, Albritton agreed that "engineering is maxed out, we cannot add a single more credit. We have to get our students out in four years." But there are other ways to teach students what they need to know. One is embedding additional skills in their existing coursework, such as learning about artificial intelligence and machine learning in the context of one of their required classes. Students also love clubs, which are numerous at the University of Washington. "That's where they learn a lot of these extra skills, like team building." Another way to build skills is to have industry engineers teach courses, such as in the capstone projects at the university, where Boeing is a major participant. "You start learning leadership skills. That's part of the curriculum. They're learning foundations and engineering also."

Allbritton also pointed out that the College of Engineering at the University of Washington is "absolutely maxed out on the number of students; every single lab is filled to the gills. We have a Mars rover team that's been working out of a janitor's closet." The university would like to take more engineering students, but it needs faculty and space to accommodate them. Engineering education is complex, she said. Students are working on large and complicated machinery and need to be kept safe. Industrial support helps, including through the provision of scholarships. "It's a group effort of everyone coming in to support the students. . . . We want to have great students and help build the State of Washington. Work with us. We're happy to make it happen."

CREATING PROSPEROUS COMMUNITIES IN WASHINGTON STATE

In the effort to prepare Washington State students for the technologically cutting-edge jobs of the future, Washington State experiences both a skills gap (labor's and industry's need for employees) and an opportunity gap (guiding K-12 students to fulfilling careers), said Dana Riley Black, vice president of education at The Museum of Flight. For example, the week before the symposium, she and her colleagues were talking with an industry partner, Alaska Airlines, about the current pilot shortage and how the museum might partner with the airline to inspire interest in that career. That same week, she had lunch with a colleague from the Kent School District who said students in the community need to understand how to navigate access to more opportunities in aviation. Addressing the skills and opportunity gaps together could create "prosperous communities in which our local students stay local with local careers."

Though environmental sustainability is a priority topic in Washington State's K-12 educational system, sustainability education has not been a focus, said Black. A recent poll reported that 77 percent of young people are somewhat or very concerned about climate change, but 65 percent are unsure what they can do about it. "Focusing on sustainability when introducing aviation is one of our 'ins," said Black. "It's an in for attracting more students to consider career pathways into aviation if we talk about contemporary sustainability efforts in aviation. We can shift the narrative from flight shaming to aviation as a solution to environmental sustainability."

In Washington State, pathways to high school graduation and graduation requirements have been updated in recent years to reflect students' interest and abilities as well as communitybased opportunities. To graduate, students must have not just enough credits but also a High School and Beyond Plan, which begins development in middle school as students start to explore educational and career pathways. "When students begin developing their High School and Beyond Plans is a great time to start partnering with our school systems," said Black. Students also engage in Graduation Pathways that can include traditional assessments, college preparatory courses, dual credit courses, or Career and Technical Education (CTE). The Graduation Pathways afford opportunities for communities to

¹⁶ More information is available at https://www.engr.washington.edu/admission/pathways-inclusive-excellence.

collaborate with schools and to create real-world experiences for students, but many educators do not know how to access these partnerships. "We need to figure out how to come together with our educators, many of whom are not familiar with the conversations that we're having here today," said Black. Fostering community connections with K-12 school systems requires different thinking and different actions. "How do we show up at teacher conferences? How do we show up at school board meetings?"

Black also advocated starting these pathways before middle school. Citing Morgansen's observation that only 15 percent of high school graduates go on to get STEM degrees in college, Black said, "I could have predicted that by looking at 10-year-olds in our state." Students need to have an interest in something to pursue it, but they also need an aspiration, and these aspirations take shape very early. "By the time a student is in fourth or fifth grade, their aspiration is pretty settled. How do we start to work with youth at the younger grades to help them?... How do we create out-of-school-time opportunities and introduce them to real-world science roles? How do we support our teachers to have positive attitudes and understanding about the topics that we're discussing here?" The Museum of Flight has a strategic plan that is focused on its audiences, including school-age learners and their educators as well as people who have been historically underrepresented in aerospace. It has developed a careerconnected learning model for its educational work with stages of programming designed to inspire students, to allow them to more deeply explore, and to prepare them for careers in aerospace through pre-professional experiences that award high school and college credits. The same day as the symposium, programs ongoing at the museum included the week-long Aerospace Camp Experience designed to inspire elementary-age students, the Amelia's Aero Club designed for middle school girls to explore aerospace over several months, and the Washington Aerospace Scholars program for rising high school seniors. The students in this last program, for instance, receive industry- and college-recognized credentials.

The museum would like to be seen as a partner for introducing space and aviation into education and career pathways. "Industry, education, and government need to come together to solve" the problem of guiding more students' involvement in aerospace, Black concluded. "The leadership of the Washington State Academy of Sciences can help drive that."

Key Workforce Development Takeaways

- Workforce development institutions of all types need to partner with sustainable aviation leaders to identify and implement changes to technical training programs driven by the transition to a sustainable aviation ecosystem.
- To meet the needs of cutting-edge industries, the number of people going into STEM careers needs to at least double.
- Washington State is forced to import talent from other states and from other countries because it does not produce enough students with STEM degrees.

- Boeing is partnering with educational institutions to promote STEM education from an early age and to inspire young people to pursue careers in aerospace, including young people who might not have seen themselves as engineers.
- Federal agencies like NASA can use their unique missions and work to inspire and educate diverse groups of students in STEM fields.
- Engineering needs to be open to anyone, no matter what their background, which requires structured programs of outreach and support at the K-12 and college levels.

- Many jobs in sustainable aviation will not require a four-year college degree, and skilled technical jobs have many openings and pay high wages.
- Because today's youth care deeply about the environment, introducing K-12 learners to aerospace through the perspective of environmental sustainability is a strategy for attracting youth to aerospace education and career pathways.
- Outreach to students needs to start in elementary school, since many of their aspirations are in place by the time they reach middle school.

5. Realizing the Promise in Washington State

Leading the Way Into the Future of Sutainable Aviation

During a reception following the symposium, and earlier in the day, several members of Washington State's legislature and leaders of the aviation ecosystem in Washington State remarked on the unique role and opportunity for Washington State in achieving a sustainable aviation future.

"What's the thing that we can do that will change the world?" asked Joe Fitzgibbon, representative from Washington's 34th Legislative District and House Majority Leader. The answer, he said, is sustainable aviation. "We need to show other parts of the world that it can be done. We have the farms and the forests for the feedstock. We have an advanced refining sector here in the state. We have a large aerospace sector, amazing research institutions, an international airport. And more than anything, we have a commitment to fighting climate change."

To achieve a sustainable aviation future, the Washington legislature has established a grant program for sustainable aviation and the Aviation Sustainability Center co-led by Washington State University and the Massachusetts Institute of Technology, Fitzgibbon observed. It has enacted a generous tax credit for sustainable aviation fuel, and a proposed bill would ease the permitting process for clean energy projects. It has prioritized workforce development through the Washington College Grant financial aid program, low-interest student loans for graduate degrees in areas with workforce shortages, and a proposed Washington Climate Corps to create good-paying jobs in clean energy. "I'm very appreciative of all the bright minds working in rooms like this one on how to make Washington the leader in ensuring that we have a transportation system that moves people and goods all over the world without coming at the expense of a safe planet for current and future generations."

Emphasizing the urgency of the situation, Vandana Slatter, representative of the 48th Legislative District in Washington State, observed that "we have all felt the physical effects of climate change and seen its fingerprints on the tragic impacts in Maui, on fragile ecosystems, and across our warming planet. Alternative energies and innovative technologies are no longer an ideal for the future but a necessity for the present." "We didn't think we were going to see demonstration projects and first flights for years out," said Emily Wittman, president and chief executive officer of Aerospace Futures Alliance. "Now we see the headlines every day. . . . Washington State has brought that reality closer to home." Many of the aircraft on display at the Museum of Flight were born out of a sense of urgency, Wittman observed. "You're going to see the aircraft that we're developing now, whether it's sustainable fuels or electric or hydrogen aircraft, hanging in this gallery within the next 10 to 20 years, and that is because of a common sense of urgency around climate change."

Mehran Mesbahi, executive director of the Joint Center for Aerospace Technology Innovation (JCATI), emphasized the importance of collaboration among industry, research institutions, and Washington State to realize the vision of sustainable aviation. Since 2013, JCATI has supported 166 projects aimed at innovative aerospace technologies so that new ideas will have an impact on industry. In the process, JCATI has been helping to develop "the next generation of leaders, managers, engineers, and employees who will be on the floor doing all this exciting work."

Finally, Matt Hayes, president and chief executive officer of the Museum of Flight, reiterated the themes of innovation and progress. "One of my favorite things about working here is seeing researchers come here and say, 'Can I look back at some great ideas? Because back then the materials science of today or the propulsion ideas didn't exist, but the idea was sound." Museums also engage young people who "see themselves in this work," said Hayes. The museum's new mission statement talks about not just collecting and preserving but participating in the stories of aerospace. "We can inspire. We can make a difference with the past, present, and future of aerospace."

Appendix A: Event Sponsors and Planning Committee

The Washington State Academy of Sciences is grateful to the sponsors and co-organizers who made this event possible.







Planning Committee

Roger M. Myers, PhD, Chair Kayla Coffey, Aerospace Futures Alliance Donna Gerardi Riordan, Washington State Academy Sciences Beth Hacker, Joint Center for Aerospace Technology Innovation Mehran Mesbahi, PhD, University of Washington Cindy Messey, Museum of Flight Kristi Morgansen, PhD, University of Washington Robin Toth, Washington State Department of Commerce Emily Wittman, Aerospace Futures Alliance

Appendix B: Symposium Agenda

12:30pm	WELCOME
	Dr. Roger Myers, Chair, WSAS Past President and Aerospace Consultant
	• Dr. Vandana Slatter, WA Representative of the 48th District
12:45pm	KEYNOTE PRESENTATION: A Vision for Sustainable Aviation The Need, Technology Options, and Implications
	Dr. Richard Wahls, Mission Integration Manager, Sustainable Flight National Partnership, NASA Aeronautics Research Mission Directorate
1:25pm	PANEL 1: Sustainable Aircraft Propulsion Vehicle Technologies and Fuels
	Moderator:
	• Dr. Anna Oldani, Sustainable Aviation Fuel Program Manager, Federal Aviation Administration
	Panelists:
	 Dr. Josh Heyne, Co-Director, WSU-PNNL Bioproducts Institute, Washington State University. Sustainable Aviation Fuels
	P. Scott Cary PE, Ports and Airports Program Lead, Energy Systems Integration Directorate, NREL. <i>Electric Aircraft</i>
	Dr. Jonathan Gladin, Senior Research Engineer, Chief, Propulsion and Energy Division, Georgia Tech, Hydrogen
2:20pm	BREAK
2:35pm	PANEL 2: Infrastructure Changes for Sustainable Aviation
	Moderator:
	Melinda Pagliarello, Managing Director, Environmental Affairs Airports Council International – North America
	Panelists:
	 Dr. Michael Wolcott, Regents Professor and LP Distinguished Professor, Department of Civil and Environmental Engineering, WSU: Sustainable Aviation Fuel – scaling production and engine certification
	• Dr. Florian Allroggen , Research Scientist, Department of Aeronautics and Astronautics at MIT, and Executive Officer, Laboratory for Aviation and the Environment, MIT: Hydrogen production and transportation challenges
	Dr. Subramanian Vadari: Founder and President of Modern Grid Solutions: Electric Aviation – challenges to the power grid

3:35pm	 2ND KEYNOTE: Workforce Development for the Sustainable Aviation Ecosystem In light of the technology and infrastructure challenges, what new educational and training initiatives will we need in this new sustainable ecosystem? Howard E. McKenzie, Chief Engineer and Executive Vice President, Engineering, Test & Technology, The Boeing Company
4:10pm	BREAK
4:25pm	 PANEL 3: Workforce Development Needs to Support the Sustainable Aviation Ecosystem Moderator: Dr. Kristi Morgansen, Chair, Dept. of Aeronautics and Astronautics, University of Washington Panelists: Dr. Nancy Allbritton, Dean, College of Engineering, UW: Academic Pipeline Dave Berger, STEM Engagement Embed for Aeronautics, NASA: STEM Engagement Opportunities for Sustainable Aviation Dr. Dana Riley Black, VP of Education, The Museum of Flight: K-12 and Training Pipeline Carolyn Busch, Director of Workforce Innovation and Industry Sector Program Coordinator, Washington Department of Commerce Office of Economic Development and Competitiveness: Access and Opportunities to Build the Sustainable Aviation Workforce
5:20pm	CLOSING REMARKS
5:30pm	 RECEPTION AND NETWORKING Remarks from: Representative Joe Fitzgibbon, Majority Leader and Chair, WA House Environment and Energy Committee, Mehran Mesbahi, PhD, Executive Director, JCATI, Matt Hayes, President and CEO, the Museum of Flight, and Emily Wittman, CEO of Aerospace Futures Alliance

Appendix C: Symposium Speakers



Dr. Roger Myers

Aerospace consultant with over 30 years of experience

Dr. Myers served as President of the Washington State Academy of Sciences (WSAS) from 2020-2022. From 1996 to 2016 he held executive positions at Aerojet Rocketdyne's Redmond Operations, the world's leading supplier of spacecraft propulsion systems, focusing on technology development and strategic planning for next-generation in-space missions and architectures, propulsion, power and integrated systems. Prior to joining Aerojet Rocketdyne in 1996, he worked at NASA's Glenn Research leading research and development of advanced propulsion technologies. He has led dozens of development and space flight programs and published over 100 papers on electric, chemical and nuclear propulsion technology and in-space transportation architectures. Additionally, Dr. Myers served as Chair of the Washington State Joint Center for Aerospace Technology Innovation and President of the Electric Rocket Propulsion Society (ERPS) until 2020. He is a Fellow of the American Institute of Aeronautics and Astronautics (AIAA), was elected to the WSAS in 2012, won the AIAA Wyld Propulsion Award in 2014, was elected to the Board of Trustees for the Seattle Museum of Flight in 2015 and won the ERPS Stuhlinger Medal in 2017. He has served on several committees for the National Academy of Sciences, Engineering and Medicine and was elected to the National Academy of Engineering in 2022, He was named the PNW AIAA Industry Engineer of the Year in 2023. Dr. Myers holds a Bachelor of Science degree in Aerospace Engineering, summa cum laude, from the University of Michigan. He received his Ph.D. in Mechanical and Aerospace Engineering from Princeton University.



Dr. Richard Wahls

NASA's Sustainable Flight National Partnership (SFNP) Mission Integration Manager for the Aeronautics Research Mission Directorate.

Dr Wahls is responsible for long-range strategic technical planning and coordination of projects supporting the mission across NASA programs and with industry, academia, and national/international government agencies. Dr. Wahls has been with NASA for 32 years serving in increasingly broad and influential leadership positions in national aeronautics programs, most recently as the senior technical and strategy advisor to the Director of NASA's Advanced Air Vehicles and Fundamental Aeronautics Programs at NASA Headquarters. Previously, Dr. Wahls served as Assistant Head of the Configuration Aerodynamics Branch at NASA Langley Research Center where his career began as a researcher. His personal research emphasized high Reynolds number aerodynamics/ scale effects utilizing the unique capabilities of the U.S. National Transonic Facility, and the study of innovative aerodynamic technologies and aircraft configurations. He is the author or co-author of 80 technical publications and has given invited presentations around the world. Dr. Wahls is a Fellow of the American Institute of Aeronautics and Astronautics and the Royal Aeronautical Society, and earned his B.S., M.S., and Ph.D. in aerospace engineering from North Carolina State University.



Dr. Anna Oldani

Aviation Energy Program Manager at the U.S. Federal Aviation Administration, Office of Environment and Energy

Dr. Oldani leads numerous Sustainable Aviation programs, both with academia through the Aviation Sustainability Center (ASCENT) Center of Excellence and with industry under the Continuous Lower Energy, Emissions and Noise (CLEEN) Program. Her work focuses on Sustainable Aviation Fuel development and deployment, along with alternative aviation energy technologies, to make near-term progress while ensuring long-term aviation sustainability. She supports interagency coordination with USDA and DOE through the SAF Grand Challenge. Alongside her colleagues, she is advancing the new Fueling Aviation's Sustainable Transition through Sustainable Aviation Fuels (FAST-SAF) and Low Emission Aviation Technologies (FAST-Tech) Grant Program. She is passionate about working across government, academia and industry to achieve significant environmental goals for aviation. Dr. Oldani received her PhD in Mechanical Engineering from the University of Illinois where she focused on fuel characterization and alternative jet fuel integration.

Dr. Joshua Heyne

Co-Director, WSU-PNNL Bioproducts Institute, Washington State University.

Dr. Heyne facilitates the development of sustainable aviation fuels by aligning novel technologies for commercialization, utilizing new low-volume experimental methods, and researching compositional needs for 100% SAF. Previously, Heyne was the integrator and coordinator of the National Jet Fuels Combustion Program (NJFCP) from 2014 to 2020, aiming to streamline the evaluation and qualification process of sustainable aviation fuel (SAF). In addition, he contributes to national and international media and has published 1 book, 4 chapters, >40 archival peer-reviewed, and over 40 conference publications. He holds four degrees from three institutions, including a Ph.D. from Princeton University in Mechanical and Aerospace Engineering in 2014. In April 2022, he joined WSU Tri-Cities.



Scott Cary, PE, LEED

Ports and Airports Program Lead, Energy Systems Integration Directorate, NREL.

Mr. Cary has more than 25 years of experience leading planning, finance, design, acquisition and construction teams for Port, Airport and Department of Defense infrastructure and facilities efforts, worldwide. For the National Renewable Energy Laboratory, Mr Cary aligns port and airport programs lab-wide, integrating the unique expertise of a Department of Energy National Laboratory with aviation and maritime needs. He has a specific focus currently championing the Sustainable Aviation initiative which is assisting industry in accelerating adoption of new technologies worldwide across an array of energy carriers including Sustainable aviation fuel, hydrogen, and electricity. Clients currently include multiple large hub airports, the FAA, NASA, USAF, USSF, and industry collaboration across the Advance Air Mobility spectrum. Mr. Cary is the principal investigator for FAA analysis exploring infrastructure deployment needs for both electric and hydrogen based propulsion systems. He is a former USAF officer, a licensed professional engineer and LEED accredited professional.



Dr. Jonathan Gladin

Senior Research Engineer at the Aerospace Systems Design Lab at the Georgia Institute of Technology.

Dr. Gladin received a B.S., M.S., and Ph.D degree in Aerospace Engineering from Georgia Tech. He has worked as a research engineer at ASDL since 2015 and is the division chief for the propulsion and energy group. His work is heavily focused in the area of advanced propulsion systems design and analysis, with a focus on advanced cycles, electrified aircraft, propulsion airframe integration, zero emissions/hydrogen aircraft, and sustainable aviation. He has been involved with many NASA funded projects related to the conceptual design of various advanced concepts including two recently funded university initiatives to research zero emission aircraft concepts with alternative fuels.



Melinda Pagliarello

Managing Director, Environmental Affairs at ACI-NA.

In this role, Ms.Pagliarello has primary responsibility for ACI-NA's activities in aviation environmental matters and sustainability. She monitors and reports on international and federal agency actions, programs, requirements, research and regulations affecting environmental matters for airports and aviation at North American airports. Specific areas of focus within Melinda's portfolio include airport noise; air and water quality, including PFAS issues at airports; airport sustainability initiatives; and the range of environmental regulations, policies, and procedures that affect airports in the U.S. and Canada.



Dr. Michael Wolcott

Regents Professor and LP Distinguished Professor, Department of Civil and Environmental Engineering, WSU

Dr. Wolcott has been a member of the WSU faculty since 1996 conducting research in the field of biobased materials, chemicals, and fuels. Wolcott currently serves as the Director of ASCENT, the FAA Center of Excellence for Alternative Jet Fuel and the Environment. He was formerly Project Co-Director for NARA – Northwest Advanced Renewables Alliance, a USDA AFRI Sustainable Biofuels CAP project, which most notably flew the first cellulosic biofuel flight cross-country with partners Gevo and Alaska Airlines. Until recently, Wolcott served as the WSU's Associate Vice President for Research where he managed the strategic relationship between WSU and the Department of Energy's Pacific Northwest National Laboratory (PNNL) building research alliances and graduate student education opportunities.



Dr. Florian Allroggen

Research Scientist, Department of Aeronautics and Astronautics at MIT, and Executive Officer, Laboratory for Aviation and the Environment, MIT

Dr. Allroggen is the Executive Director Aerospace Climate & Sustainability in MIT's Department of Aeronautics and Astronautics and a member of the MIT Climate & Sustainability Consortium (MCSC). He co-leads the MIT Laboratory for Aviation and the Environment and the Transportation pathway within MCSC. His research brings together Transport Economics, Environmental Economics, and related research questions in Energy Economics. In his recent work, he focuses on understanding the transition of transportation towards sustainable solutions. He develops and applies methods for techno-economic and lifecycle assessments, policy analyses, cost-benefit analysis, energy potential assessments, and market response modeling.



Dr. Mani Vadari

Founder and President of Modern Grid Solutions

IEEE Fellow, electricity industry visionary, and leader, Dr. Vadari delivers strategic services to a global set of utilities, vendors, and service providers seeking deep subject matter expertise in setting the business and technical direction to develop the next-generation electric/energy system. As a Business Architect, Dr. Vadari has been delivering solutions focusing on Transmission/Distribution/ generation operations, Energy markets, and Smart Grid for over 35 years. In addition, he is an Adjunct Professor at Washington State University and an Affiliate Professor at the University of Washington. He has published two popular books, **"Smart Grid Redefined: Transformation of the Electric Utility"** and **"Electric System Operations – Evolving to the Modern Grid, 2ndEdition**", in addition to over a hundred industry papers, articles, and blogs. His books are serving as textbooks at several universities in the US and around the world.



Howard McKenzie

Chief Engineer and Executive Vice President, Engineering, Test & Technology, The Boeing Company

Mr McKenzie leads the Boeing Engineering function of more than 57,000 engineers worldwide and oversees the company's technology vision, strategy and investment. His responsibilities also include oversight of all aspects of safety and technical integrity of Boeing products and services. His organization is an incubator for businesses that will define the future of urban, regional and global mobility, as well as those aimed at near-term opportunities. McKenzie is a member of the company's Executive Council. McKenzie is a 2019 recipient of the Black Engineer of the Year Award (BEYA) Science Spectrum Trailblazer Award and an active member of the BEYA STEM community. He also serves as the Boeing executive focal for the University of California, Berkeley. McKenzie has a Bachelor of Science in mechanical engineering from the University of California, Berkeley.



Dr. Kristi A. Morgansen

Professor and Chair of the UW William E. Boeing Department of Aeronautics & Astronautics.

Dr. Morgansen's research focuses on nonlinear systems where sensing and actuation are integrated. Her work includes over 100 peer-reviewed publications and field testing in systems such as the Boeing ecoDemonstrator. She is Director of the Washington NASA Space Grant Consortium, co-Director of the UW Space Policy and Research Center, Fellow of AIAA, Chair of the AIAA Aerospace Department Chairs Association, and member of the Washington State Academy of Sciences.



Dr. Nancy L. Allbritton

Frank & Julie Jungers Dean of Engineering at the University of Washington.

As Dean, Dr. Allbritton is committed to engineering excellence for the public good by fostering high-impact, interdisciplinary research and technology translation and building an inclusive community of faculty, staff and students. Allbritton is an international expert on multiplexed single-cell assays, microfabricated platforms for high-content cytometry combined with cell sorting, and microengineered stem-cell-based systems for recapitulating human organ-level function. Five companies have been formed based on her research discoveries: Protein Simple (acquired by Bio-Techne in 2014), Intellego, Cell Microsystems, Altis Biosystems and Piccolo Biosystems. Allbritton holds an appointment in the UW's Department of Bioengineering. She has been nationally recognized for her research and is a Fellow of the American Association for the Advancement of Science, the American Institute for Medical & Biological Engineering and the National Academy of Inventors. She has received numerous awards for her leadership, including BMES Robert A. Pritzker Award and the Edward Kidder Graham Award for Leadership and Service. Prior to joining the UW, Allbritton led the Joint Department of Biomedical Engineering at the University of North Carolina at Chapel Hill and North Carolina State University which spans two universities and three colleges.



David Berger

STEM Engagement Embed for Aeronautics, NASA

Mr. Berger is the NASA STEM Engagement Embed for Aeronautics. He works on collaborations for research opportunities and learning experiences between NASA's Aeronautics Research Mission Directorate, NASA's Office of STEM Engagement, and academia. Prior to his current role, David was the NASA MUREP Institutional Research Opportunity (MIRO) activity manager where he oversaw grants to build institutional capacity in NASA research areas at Minority Serving Institutions. David has worked as a test lead, test conductor, flight test engineer, and principal investigator on aerodynamics and air breathing propulsion research projects at NASA Armstrong since first working at Armstrong 22 years ago. David has aerospace engineering degrees from Purdue and University of Michigan. He is a senior AIAA member and previously taught as an adjunct lecturer for Cal State University Long Beach-Lancaster.



Dr. Dana Riley Black

Vice President of Education at The Museum of Flight

Dr. Riley Black began her role of Vice President of Education at The Museum of Flight in the summer of 2020. Prior to joining the Museum she served as an Assistant Superintendent for Everett Public Schools with prior work experience at the Harvard-Smithsonian Center for Astrophysics, University of Washington Office of the Provost and the Institute for Systems Biology. She is currently serves on Washington's State Board of Education and serves on the Governor's STEM Education Innovation Alliance. Dr. Black grew up in Washington State. She received her Bachelor of Science in Psychology from the University of Washington, Masters in Science Education and Doctorate of Philosophy in Educational Leadership and Curriculum Studies from Miami University.



Carolyn Busch

Director of Workforce Innovation and Industry Sector Program Coordinator, Washington Department of Commerce Office of Economic Development and Competitiveness

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Appendix D:

White Paper – *Sustainable Aviation in Washington State*

Connecting Policy, Technology, Infrastructure and Workforce Development Needs

August 2023

Sustainable Aviation in Washington State

Connecting Policy, Technology, Infrastructure and Workforce Development Needs

August 2023

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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 wellpositioned 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 billion¹ 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 revenue². 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 Ecology³, 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 higher⁴.

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-impactstudy-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://doi.org/10.00016/j.

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 2050⁶. In 2021, the White House⁷ 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 limits⁸ – 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

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/statementsreleases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-targetaimed-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,

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 pathways¹⁰ 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%, SAF¹¹, 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 flight¹² 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 tons¹³ 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 Seattle¹⁴ found that the Pacific Northwest region could produce up to 220-290 million gallons of biomass-based sustainable aviation fuel per year, which is about

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.

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 costs¹⁵ 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 reductions¹⁶ 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 CO₂ generated by fermentation is very pure (99.7%) making sequestration possible, although there is some debate about whether it is truly a climate friendly fuel¹⁷. 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 addition¹⁸ 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 SAFs¹⁹ are synthetically produced liquid hydrocarbon fuels that involve hydrogen production via electrolysis of water using renewable electricity and a source of climate-neutral CO₂. 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 aircraft²⁰. Washington State is well-positioned to generate PtL fuels 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

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.

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, biomassderived 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.

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 operation²¹; however, emissions can be generated by non-renewable sources powering the electric grid.

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?

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 Alice²².

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.

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

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.

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 zeroemission option for aviation. Whether the power grid can be sufficiently

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?

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.

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 pollutants²⁴. In 2023, both ZeroAvia²⁵ and Universal Hydrogen²⁶ 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 stored²⁷ 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.

Besides the technological hurdles, producing clean hydrogen power is expensive. Similar to PtL SAFs,

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?

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 reforming²⁸ – which is not sustainable. To address this challenge, the Department of Energy is funding regional clean hydrogen hubs²⁹ across the nation. These hubs will accelerate the use of hydrogen as a source of clean energy by creating networks of hydrogen producers, consumers, and local connective infrastructure. The Pacific Northwest

 $^{^{24}}$ Alastair C. Lewis, "Optimising Air Quality Co-Benefits in a Hydrogen Economy: A Case for Hydrogen-Specific Standards for NO $_{\rm X}$ Emissions," *Environmental Science: Atmospheres* 1, no. 5 (2021): 201–7, https://doi.org/10.1039/D1EA00037C.

²⁵ ŻeroAvia, "ŻeroAvia Makes Aviation History, Flying World's Largest Aircraft Powered with a Hydrogen-Electric Engine," PR Newswire, Cision, January 19, 2023, https://www.prnewswire.com/newsreleases/zeroavia-makes-aviation-history-flying-worlds-largest-aircraft-powered-with-a-hydrogen-electricengine-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 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 initiative³¹, 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 netzero 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 Roadmap³³, 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.

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

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.

those land-use changes. Converting grassland or forests to cropland can generate significant amounts of GHG emissions³⁴ 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 SAFs³⁵ requires renewable electricity to generate hydrogen using water electrolysis and a source of non-fossil CO₂. 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 generation³⁶. 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 pipeline³⁸, 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 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.

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.

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 study³⁹ 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 infrastructure⁴⁰ 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 transportation in Washington State will depend on the development of a network of charging and operations infrastructure⁴¹. Ensuring the economic viability of electric aircraft production and

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."

⁴¹ Coenen, Malarkey, and MacKenzie, "Washington Electric Airport Feasibility Study."

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 gas⁴².

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 Hydrogen⁴³ 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 ZeroAvia⁴⁴ 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 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

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/.

to sustainability. Washington State's workforce development infrastructure includes a network of skills training programs⁴⁵ managed by technical colleges⁴⁶, a Center of Excellence for Aerospace and Advanced Manufacturing⁴⁷, certificate and university degree programs⁴⁸, apprentice programs in industry, and public-private partnerships⁴⁹.

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 required⁵⁰. 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 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.

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.

Electric Aviation

The workforce for the electric aircraft industry⁵¹ 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 today⁵². 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 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

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).

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. 	
Maintenance	 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 1170⁵³, 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 5447⁵⁴ 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 1216⁵⁵ 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 ground⁵⁶ on a new facility in Moses Lake in July where they will produce fuel using renewable electricity, water and waste biomass CO₂. Roughly 100 construction workers will be needed to build the plant and 20 full-time "green jobs" to operate it. SkyNRG's project⁵⁷, which has not yet announced a location, is expected to produce about 30 million gallons of SAF per year, requiring an investment of between \$600

⁵⁴ "SB 5447 - 2023-24," Washington State Legislature, accessed August 1, 2023,

⁵⁵ "HB 1216 - 2023-24," Washington State Legislature, accessed August 1, 2023,

https://app.leg.wa.gov/billsummary?BillNumber=5447&Year=2023&Initiative=False.

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-fuelstartup-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/.

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 2028⁵⁸.

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 announced⁶¹ 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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