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Airports as Energy Nodes Activity Summary

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Abstract

Advanced aircraft concepts that use non-traditional aviation energy storage methods such as batteries or cryogenic hydrogen are in development and are expected to enter regular service at airports worldwide within the next decade. The energy needs for these aircraft may quickly overwhelm the existing energy infrastructure at airports, particularly at smaller and more remote facilities. Without energy upgrades, these airports will not be able to host these advanced vehicles, but without the advanced vehicle traffic, these airports will not have the rationale or funding to build up their energy infrastructure. The Airports as Energy Nodes (ÆNodes) activity, a collaboration between the National Aeronautics and Space Administration (NASA) and the National Renewable Energy Laboratory (NREL), was executed to understand and model the energy needs that advanced aircraft concepts may levy on these smaller airports, determine cost-effective approaches to enhance the airport energy infrastructure, and demonstrate the enhanced resilience of these energy infrastructure upgrades to the airport and surrounding community via "digital twin" simulation at relevant energy and dynamic time scales. The ÆNodes team also investigated future reference aircraft designs and materials to enable cryogenic hydrogen storage for aircraft. The ÆNodes team conducted analysis at two U.S. airport partner sites — Winchester Regional Airport in Winchester, Virginia, and Tweed/New Haven Airport in New Haven, Connecticut. The goal of this partnership was to develop data and reference infrastructure designs that could accommodate advanced aircraft in the future at these airports while also enhancing the resiliency of the energy supply to the surrounding airport community, which could be used to capture funding to enable the infrastructure upgrades. Over the course of the study, a method was developed to estimate air traffic requiring advanced energy services over the course of a year using a mix of historical data and companion studies on advanced aircraft transportation networks. The study has concluded at NASA but continues at NREL, who will develop a final report discussing the energy infrastructure upgrades and digital twin results. Preliminary results indicate that unrestricted adoption of advanced battery-electric aircraft may double traffic at these airports and increase peak daily power usage by an order of magnitude, while increasing electricity energy needs by a factor of two to four. The infrastructure upgrades necessary to accommodate these increased energy needs could be used to provide enhanced energy services to the airport community to offset the cost and increase the utility of the upgrades, which will be described in the NREL final report.

1. Introduction

Airports are essential components of most forms of air transportation. Their runways and required clearways enable safe takeoff and landing for aircraft. Their ramps and hangars enable parking, storage, and maintenance of air vehicles. Their terminals and warehouses hold people and cargo prior to loading onto the aircraft or just after being unloaded. Airports are rarely the initial departure point or the ultimate destination – they are a node in an intermodal transportation system that may include other air or surface transportation elements to route people or goods from intended origin to destination.

Airports serve yet another critical role in many forms of air transportation – they are often the location where an aircraft will be loaded with the appropriate amount of energy to enable the aircraft to travel to its next destination. Today, this energy is almost exclusively in the form of jet fuel or aviation gasoline. A means to safely store and distribute this fuel to aircraft is required. Airports with fuel service vary from those that only have a small number of fixed fuel pumps or fuel trucks to those with elaborate fueling systems that enable fuel to be plumbed to various hydrants and pumps around the airport from a large set of fuel tanks located on or off airport property. In either extreme, airports serve as an important energy node in the air transportation system that today is almost exclusively reserved for aircraft use.

1.1. Airports in the United States

The United States has an extensive network of airports and other landing facilities.[1] In September 2022, the U.S. was home to 13,112 airports across all states and territories.[*] Of these, 4,909 were designated as public-use facilities, and 504 had Airport Operating Certificates issued under Title 14 of the Code of Federal Regulations (14 CFR) Part 139 (hereon "§139" or "Part 139").[2,3] These certificates are issued to airports to ensure they have adequate safety facilities and other key features associated with operation of larger commercial aircraft, such as transport category passenger jets. In 2019, just 30 of these airports served over 73% of all enplanements in the conterminous United States (CONUS), while only 98 airports accounted for 95% of enplanements.[4] Similarly, 30 airports were responsible for almost 80% of all air cargo by weight, with 75 accounting for up to 95% of all air cargo. Figure 1 shows the geographic distribution of airports in the CONUS, including restricted use, public use, Part 139, and airports that serve 95% of all cargo and passenger traffic.[†]

Many public-use airports in the United States are eligible for Federal funds for maintenance and improvements. Federal Aviation Administration (FAA) Order 5090.5 governs the National Plan of Integrated Airport Systems (NPIAS) and the Airports Capital Improvement Plan (ACIP).[6] The NPIAS "identifies the amounts and types of airport development eligible for Federal funding."[7] Per Order 5090.5,

> *The NPIAS identifies existing and proposed airports that are important to national air transportation, and it provides a forward-looking estimate of the type and cost of the eligible Airport Improvement Program (AIP) development needed to meet the needs of civil aviation.*
>
> *The ACIP, a subset of the NPIAS plan for airport development, is the primary financial planning tool for systematically identifying, prioritizing, and assigning funds to help meet the capital project needs of airports within the NPIAS. The ACIP also provides the basis for grant planning and management under the AIP.*

NPIAS airports are a subset of all public-use airports in the United States. The 2025-2029 NPIAS identifies 3,247 NPIAS airports out of 4,889 public-use airports in April 2024. These airports are further classified according to use, with commercial enplanements as a main discriminator. An airport is considered a "commercial service airport" if it has more than 2,500 annual enplanements. An airport is otherwise categorized as "reliever" ("An airport … to relieve congestion at a commercial service airport and to provide more general aviation access…") or "general aviation" ("A public airport that does not have scheduled service or has scheduled service with less than 2,500 passenger boardings each year"). Airports that serve more than 10,000 enplanements per year are considered "primary" airports, with the rest of the airports considered "nonprimary." All NPIAS primary airports have an Airport Operating Certificate under Part 139, but only a small fraction of the nonprimary airports are certified to Part 139.

The distinctions in the NPIAS are used to prioritize airport improvements eligible for AIP or other Federal funding. Airports not listed in the NPIAS are not eligible for said funding. This can be a challenge for smaller airports because the criteria for non-commercial service airports to be incorporated in the NPIAS include being more than 30 miles away from another NPIAS airport. Hence, a busy general aviation airport that is located within 30 miles of a large commercial hub airport (which is always part of the NPIAS) may not be eligible to be included in the NPIAS and therefore may not be eligible for Federal funding of airport improvements.

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[*] Any facility identified as an "airport" in Ref. 1, which excludes "balloonport," "gliderport," "heliport," "vertiport," "seaplane base," and "ultralight."

[†] This paragraph, including its data and citations, was adapted from Ref. 5. Also, note that the total number of airports in Figure 1 is different than mentioned in this paragraph, since Figure 1 only shows airports in the CONUS.

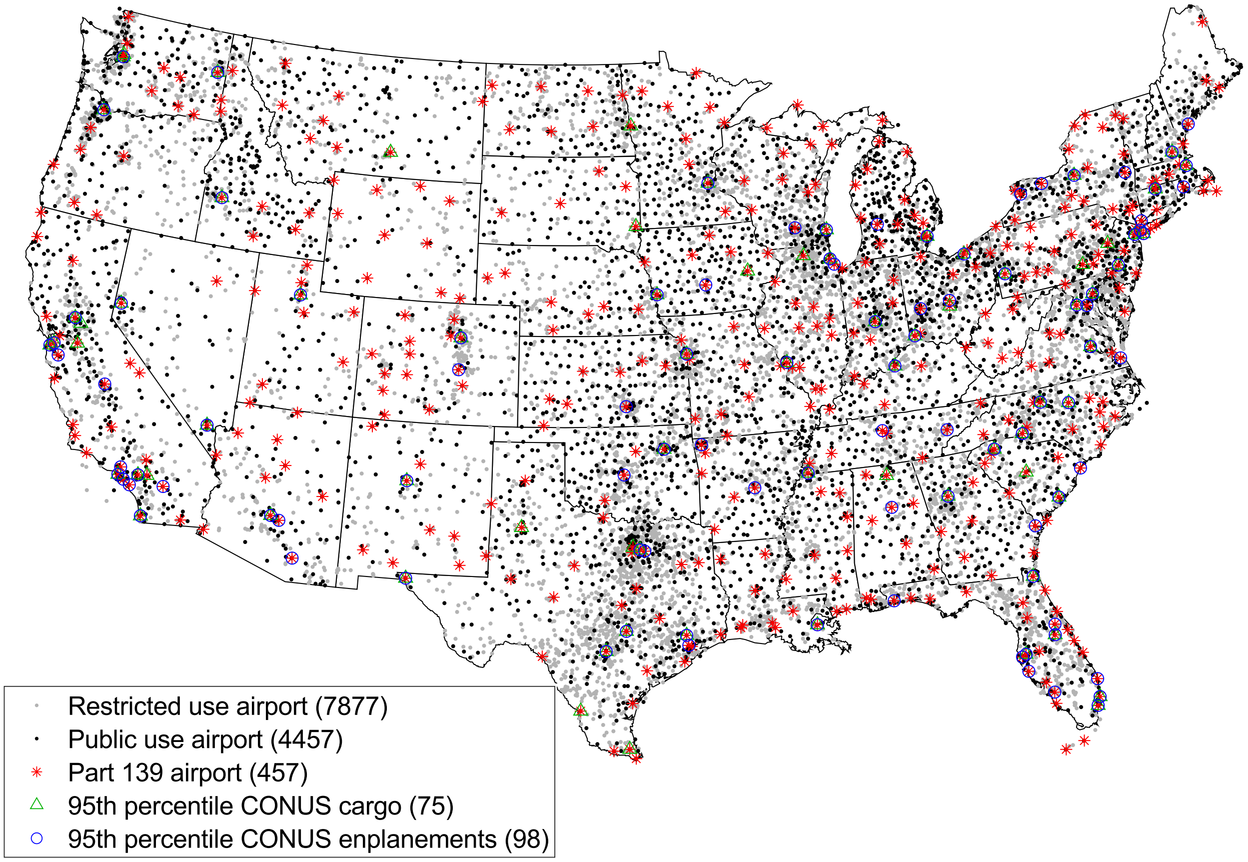

Figure 1: Airports in the CONUS as of September 2022 (credit: Ref. 5).

1.2. Energy for Aviation

Today's aircraft almost exclusively use one of two types of a liquid hydrocarbon fuel – either "jet fuel," which is similar to diesel fuel, and "aviation gasoline" or "avgas," which is similar to gasoline. There are many variations of both categories of fuels, including those that are not refined from crude oil, but nearly all civil aircraft today will consume a variant of jet fuel or avgas.

The amount and availability of fuel at airports is dependent on the types of operations at those airports. The vast majority of aviation fuel consumed is in the form of jet fuel, generally by the transport category airplanes that provide commercial air transportation of goods and services.[8] Most of these aircraft operate out of a small number of airports – as noted in the discussion associated with Figure 1, 95% of CONUS passenger enplanements occur at fewer than 100 airports. Smaller aircraft, such as those used for flight training, personal use, and some commercial purposes, use avgas.[9] These aircraft are distributed among the thousands of public- and private-use airports around the country. Hence, the need for aviation fuel storage and distribution at airports is highly dependent on the intended use – a few airports that serve a large portion of commercial air transportation needs require vast infrastructure to acquire, store, and distribute jet fuel, whereas most other airports need far less infrastructure that includes both jet fuel and avgas services.

Several emerging concepts in air transportation have moved away from these traditional aviation fuels. Although a variety of different energy carriers are proposed, the work described in this document focuses on the needs of battery-electric aircraft (including plug-in hybrids), and, to a limited extent, hydrogen-fueled vehicles. This follows trends seen in the flight training market, the emerging sector of Advanced Air Mobility (AAM), and even some future transport category aircraft concepts.

1.2.1. Advanced Flight Training Aircraft

Flight training is a use case that has seen significant development of alternative aircraft in recent years, mostly focusing on battery-electric powertrains. Most primary flight training is accomplished close to an airport, with short mission times and range requirements as compared to the capabilities of the traditional primary training fleet. This "performance oversupply"[10] (i.e., the higher-than-typically-utilized range and endurance capability of typical primary flight training aircraft) ripens the market for solutions that exceed in other metrics, such as operating cost – opening the door for battery-electric aircraft concepts. These battery-electric concepts include clean-sheet designs (e.g., Pipistrel Velis Electro,[11] Bye eFlyer 2[12]) and retrofit aircraft (e.g., Diamond eDA40,[13] CAE Electric Archer[14]). To avoid conflict with air commerce, much primary flight training does not occur at or near major commercial airports and instead is distributed among many smaller airports throughout the country.

1.2.2. Advanced Air Mobility

Advanced Air Mobility (AAM) is an emerging field that can be defined as "safe, sustainable, affordable, and accessible aviation for transformational local and intraregional missions," and includes Urban Air Mobility (UAM), Regional Air Mobility (RAM), and low-altitude uninhabited aircraft system (UAS) operations.[15] UAM is discussed as missions around metropolitan areas involving helicopter-sized aircraft that may be capable of carrying passengers. Reference 15 notes that RAM "focuses on building upon existing airport infrastructure to transport people and goods using innovative aircraft that offer a huge improvement in efficiency, affordability, and community-friendly integration over existing regional transportation options for trips of approximately 50-500 miles." Low-altitude UAS operations may occur in urban or rural environments and are generally envisioned to remain below 400 ft above ground level.

The Congressional language in the 2024 FAA reauthorization[16] defines AAM as "a transportation system that is comprised of urban air mobility and regional air mobility using manned or unmanned aircraft." The FAA reauthorization defines RAM as "the movement of passengers or property by air between 2 points using an airworthy aircraft," and UAM as "the movement of passengers or property by air between 2 points in different cities or 2 points within the same city using an airworthy aircraft." The FAA reauthorization notes that both RAM and UAM include vehicles that have a maximum takeoff weight of greater than 1,320 pounds and have "advanced technologies, such as distributed propulsion, vertical takeoff and landing, powered lift, nontraditional power systems, or autonomous technologies." Otherwise, the text does not offer other differentiators between RAM and UAM other than to note in the definition for RAM that it "is not urban air mobility."

UAM is generally meant to include electric vertical takeoff and landing (eVTOL) aircraft operating in an urban environment as discussed by Uber in 2016.[17] Typical trips include vertiports,[‡] heliports, and airports among the origin and destination options. An example network that includes all these types of facilities can be found in Ref. 18, which includes facilities suitable for UAM operations at existing airports and heliports as well as new facilities designed exclusively for UAM operations. Most aircraft currently in development for UAM operations are battery-electric eVTOL aircraft (e.g., Joby S4[19], Archer Midnight[20]), though some concepts and demonstrators have included hydrogen fuel cell vehicles (e.g., Alaka'i Technologies[21], Unither/Robinson Proticity[22]).

Per the FAA Reauthorization definition, RAM can include vertical takeoff and landing vehicles, though the mission is more likely to involve an origin and destination with a runway and therefore includes a greater emphasis on conventional airplanes, or perhaps those capable of short takeoff and landing (STOL) operations. A key discriminator for RAM is the ability to leverage the thousands of existing airports that are currently underutilized for commercial operations;[5,23] per McKinsey,[24] 90% of the U.S. population lives within a 30-minute drive from the nearest "regional airport," while only 60% are within the same drive time from the nearest "commercial airport."[§]

[‡] Defined in Ref. 16 as "an area of land, water, or a structure used or intended to be used to support the landing, takeoff, taxiing, parking, and storage of powered-lift aircraft that vertiport design and performance standards established by the Administrator can accommodate."

[§] Reference 24 does not define a "regional" vs. a "commercial" airport in the context of NPIAS, Part 139, etc. We presume they are referring to airports with scheduled commercial service as "commercial airports" and the nearest public-use airport as "regional airports."

A variety of different aircraft have been proposed for RAM that include operations at a variety of airports, from larger Part 139 airport operations ("primary" NPIAS airports) to airports that do not have Part 139 certification and may not be within the NPIAS to even new facilities designed for STOL operations. The power and propulsion architectures of these aircraft vary greatly. Companies such as Harbour Air[25] and Væridion[26] are developing battery-electric solutions, others such as Ampaire[27] and Electra[28] are developing hybrid electric aircraft that use jet fuel and batteries, and still others such as ZeroAvia[29] are investigating the use of hydrogen fuel cells for power.

Most UAS operations today operate outside of the purview of public-use airports due to current operating rules, though those rules are changing, and airports may soon see UAS operations. In this case, we are referring to UAS that are generally under a maximum takeoff weight of 1,320 pounds because aircraft over that weight limit could likely be considered under UAM or RAM. Many of the smaller UAS are battery-operated or may use a variety of fuels, but the amount of energy they consume is not likely to have a significant impact at an airport unless the number of operations grows far beyond those of the traditional aircraft. For example, the Pyka Pelican 2,[30] an all-electric UAS for agricultural and cargo operations, uses an 18 kWh battery pack in a vehicle with a maximum gross takeoff weight of 1,400 pounds. The amount of energy for typical operations would be far less than this amount and is less than the amount of electricity used by a typical U.S. home in a single day. This is in contrast to UAM and RAM aircraft, which may have battery capacities in excess of 100 kWh and require charging rates of 350 kW or more.

1.2.3. Advanced Transport Aircraft

Most air transportation in the CONUS today uses less than 100 airports, as discussed earlier and shown in Figure 1. Given the large volume of passenger or cargo traffic, it is impractical to use many smaller airplanes on these routes, so most air travel is on large transport aircraft. Though the transport category is defined for aircraft with a maximum seating configuration of more than 19 passengers, typical "narrowbody" jet transports (e.g., Boeing 737,[31] Airbus A320[32]) can carry 200 passengers and have a maximum takeoff weight of nearly 200,000 pounds, and "widebody" transports (e.g., Boeing 777,[33] Airbus A350[34]) can seat 350 passengers and have a maximum takeoff weight of 700,000 pounds or more. Narrowbody aircraft may carry enough fuel to fly 4,500 miles, and widebodies sometimes carry enough fuel to fly twice that distance, which requires an enormous amount of jet fuel per aircraft – typically 20 to 40% of the aircraft's weight, with the higher percentages typical of the larger widebody aircraft.

Transport aircraft need to store an enormous amount of energy as compared to smaller vehicles flying on shorter routes, such as AAM. As such, the advantages of battery-electric propulsion systems are generally not impactful enough to enable battery-electric transport aircraft. This is because jet fuel is an incredibly dense energy storage medium with a typical specific energy of approximately 43 MJ/kg. Modern batteries may have less than 1/50th of this specific energy at the pack level,[35] though advances are being made due to accelerated investment in batteries for AAM. Cryogenic hydrogen is a possible energy carrier as it can have a much higher specific energy of 120 MJ/kg but requires about four times more volume than jet fuel per unit energy,[36] plus additional mass and volume for the tank insulation as compared to jet fuel.

The specific energy and volumetric density of these alternative energy carriers introduces significant design challenges for transport-class aircraft powered by batteries or fueled by liquid hydrogen. Still, some companies are developing solutions to these challenges. Elysian is investigating a 90-passenger battery-electric aircraft with a range of 500 miles for handling busy shorter routes currently dominated by narrowbody jet transport aircraft.[37] NASA issued five awards as part of its Advanced Aircraft Concepts for Environmental Sustainability (AACES) 2050 solicitation and includes some research teams pursuing cryogenic hydrogen concepts.[38] Other concepts, such as the Wright Spirit, consider hybrid battery-jet fuel architectures that may include plug-in hybrid options.[39] Should these or similar concepts enter operation, they will require significant changes to the energy infrastructure at the large airports that will be their host.

1.3. Infrastructure Challenges

The network of airports in the United States provides a substantial, well-distributed, public-use infrastructure available for nationwide (and worldwide) air travel. Though only a fraction of these airports and associated capabilities are used anywhere near their capacity for commercial air commerce, the advanced aircraft concepts described above may breathe new life into these facilities, large and small. Yet, any major change in the energy carrier away from jet fuel or avgas will bring new challenges, given the large amount of energy necessary for many of these airborne operations.

The implications of RAM aircraft were studied recently by the Georgia Institute of Technology (Georgia Tech) and the National Renewable Energy Laboratory (NREL) in studies funded by NASA. Georgia Tech researchers created two notional RAM networks in portions of the CONUS, one in the eastern region and one centered on the state of Colorado. The networks were created by modeling demand for a fleet of aircraft that included a battery-electric aircraft capable of carrying nine passengers (enabling scheduled operations at both Part 139 and non-Part 139 airports) as well as two different plug-in hybrid aircraft capable of carrying 19 and 48 passengers (both of which were restricted to Part 139 airports).[40] The baseline aircraft had battery capacities ranging from 360 to 1,086 kWh, and the networks were developed across a range of different technology assumptions (e.g., battery specific energy, which would modify the capacities quoted above) and network goals (e.g., maximum profit or trade of profit versus system-level emissions). The resulting network served more than 100 airports in all cases. Figure 2 shows one of the output networks from a mid-term deliverable of this study, with the baseline set of assumptions, that included 156 airports.[**]

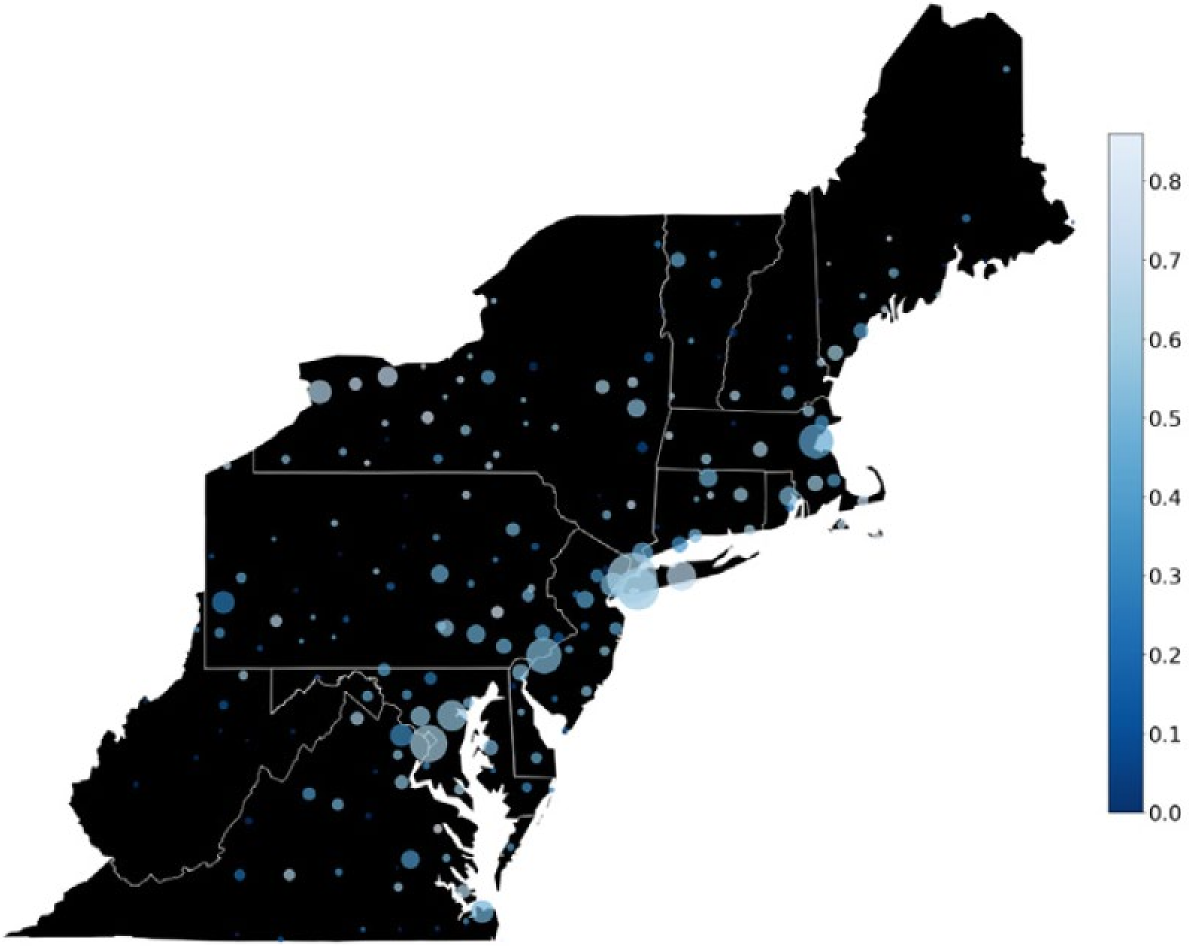

Figure 2: Airports served in Georgia Tech Regional Air Mobility Study showing relative amount of demand (size of circle) and amount of demand served by profitable network (shade of blue). Image created by Georgia Tech and provided to NASA without restriction under Contract NNL13AA08B, Task Order 80LARC20F0103.

The NREL team used the flight schedule data and energy use estimates from the Georgia Tech study to investigate the energy requirements for these aircraft within the regions studied.[41] They also used data from two specific airports—Newport News (PHF) in Virginia and Harrisonburg (ABE) in Pennsylvania—to estimate how the RAM demand at those specific airports would impact the energy requirements of those airports and develop cost estimates for required energy upgrades. NREL investigated different charging scenarios, representing the philosophy associated with charging the aircraft (e.g., fastest charge possible to keep chargers clear, slowest charge possible to meet flight

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[**] The Georgia Tech team has revisited the assumptions of this study and included hydrogen-fueled concepts, which are planned to be published in an upcoming NASA Contractor Report by C. Justin et al.

schedule to keep charge power down). The results showed that these operations increased airport electricity usage by a factor of 1.3 to 4.0 and increased peak power consumption by a factor of 2 to 14, depending on if the airport had only a few flights a day or if it was a RAM "hub" that aggregated multiple flights. This also only considered flights within a RAM network that needed battery charging and did not consider other types of AAM or advanced aircraft, nor did it consider the impact of other energy carriers. The infrastructure upgrades needed for any of these increases in energy and power consumption could be daunting, particularly for smaller airports in more remote areas.

The NREL study also considered the impact of various utility rate structures (costs associated with energy and power usage) to determine the amortized cost of these upgrades. This study varied the charge power (fast/fewer chargers, more peak power required; slow/more chargers needed, less peak power required), the utility cost for energy ($/kWh), and the utility cost for peak power use ($/kW). These costs were then broken into the utility bill itself, the cost of energy infrastructure upgrades, and the cost of the individual chargers at the airport. The energy infrastructure upgrades included a cost-optimal mix of increasing the utility supply to the airport, adding onsite battery storage (to blunt the peak power charges from the utility), and adding onsite solar harvesting (PV) at the airport. The results were then amortized over the number of RAM operations. A summary of the results is given in Figure 3.

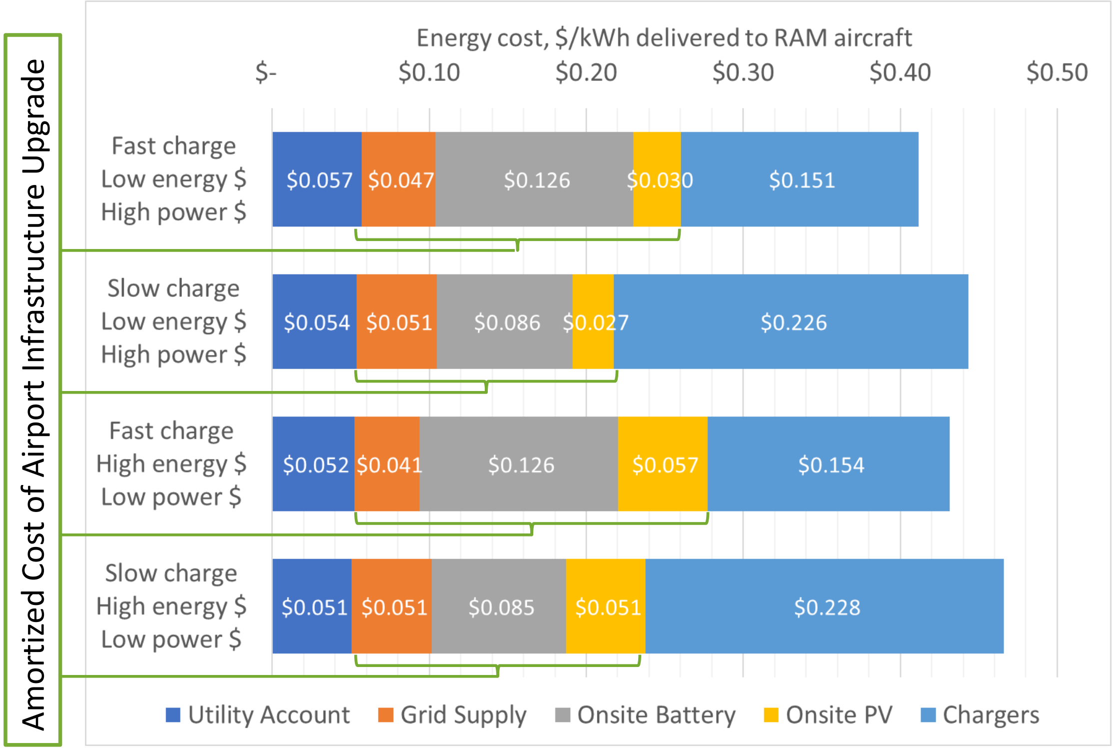


Figure 3: Cost of electricity and associated equipment upgrades if amortized exclusively over RAM operations within the NREL study. [41] *Results do not include taxes or fees. Data derived from NASA-DOE interagency agreement IAG-21-18149.*

The results of the economic analysis indicated both a challenge and an opportunity. If the RAM users were to fully amortize the costs of electricity for their aircraft needs, they would need to pay more than $0.40/kWh. This is equivalent to $14.48/gal of jet fuel[††]—far more than the typical cost of jet fuel. However, in all cases, upgrading the airport energy infrastructure with a mix of utility grid supply upgrades, onsite battery storage, and onsite solar harvesting showed a positive net present value versus just upgrading the size of the utility supply. This indicated that airports, their users, and the utility could *all* benefit by having the airport serve as part of the energy supply and storage network rather than solely act as an energy consumer.

[††] This assertion is made based on the lower heating value of jet fuel at 43 MJ/kg. This does not account for differences in efficiency possible for creating propulsive work from jet fuel versus electricity, which is a driving consideration for electrified AAM vehicles.[42]

Other efforts have looked at the impact of large-scale hydrogen generation at large airports to meet transport category aircraft fuel needs. Research conducted by the FAA indicated that many of the largest airports would need energy on the scale of the largest current nuclear power station to meet the energy needs for cryogenic hydrogen fuel production and processing if all jet fuel were to be replaced with hydrogen at that airport.[36] This reference did not investigate the smaller airports or their energy needs.

Communities in the United States are also facing energy infrastructure challenges. More ground vehicles are using battery-electric powertrains, moving loads that previously were served by gasoline and diesel products to the electrical grid.[43] New data centers, necessitated by the recent boom in "artificial intelligence" use and research, are large power consumers that challenge existing electricity infrastructure and require more electricity production.[44] Centralized utilities can provide large-scale efficiency, but extreme weather and wind events make them vulnerable to disruption, which can impact communities far from areas directly impacted by these events.[45]

1.4. Challenges for Powering Future Aviation

The arrival of advanced aircraft will challenge airport energy distribution infrastructure if these aircraft do not use traditional fuels. These challenges have been studied in part; for example, the FAA investigated the energy needs of vertiports serving largely UAM-type operations in the vicinity of the FAA's William J. Hughes Technical Center in Atlantic City, New Jersey.[46] The Department of Energy is sponsoring development of tools to cover ground vehicle and AAM energy needs along with the associated onsite energy generation and storage systems under the NREL-led Athena effort.[47] This effort includes partnerships with 16 U.S. airports. The Colorado Department of Transportation recently sponsored a study conducted by NREL that included the impact of electric training and RAM operations at six airports.[48] These are a few examples of many recent and ongoing efforts to tackle this energy infrastructure challenge.

Citing some of these studies, Ref. 49 notes that, with respect to their existing electrical energy infrastructure, "airports may be able to accommodate initial operations of a single operator with a few flights a day." Reference 49 further cautions that "as operation tempos increase and multiple operators start using an airport or other public-use venue, the existing utility network won't be able to handle the proposed electrical demand unless upgrades are performed" and further notes that "airports are already expressing concerns about meeting the electric demands of rental car companies electrifying their fleets." The Athena and Colorado efforts are good steps to help those airports plan for such loads, but the 16 airports in the Athena study are some of the busiest airports in the CONUS. All the airports evaluated in the Colorado study are in the NPIAS and certificated under Part 139. Yet, advanced aircraft operations may include large and small airports, including those not certificated under Part 139, and perhaps not even in the NPIAS (and therefore not eligible to receive funding from certain Federal grant programs). Some of these small airports may be at the forefront of advanced training and AAM operations but will not have the electrical infrastructure to support more than a few operations, nor access to traditional funding mechanisms to expand their infrastructure. These challenges act as a further headwind to adoption of advanced air transportation solutions such as AAM.

The remoteness of some airports can have benefits. Airports are already community lifelines in times of disaster. They have been used to bring much-needed supplies into areas that are otherwise inaccessible due to washed-out roads[50] or used as a base of operations for emergency responders and aerial firefighters.[51] If the most cost-effective way to upgrade the energy infrastructure for an airport includes onsite energy storage, harvesting, and/or generation, those same assets may be useful to the local community in nominal times for "peak" loads or off-nominal scenarios, such as power outages to support critical infrastructure. Expanding the airport energy infrastructure for the benefit of the local community may be able to help offset initial costs and provide an early customer of the upgraded facilities prior to the arrival of advanced aircraft. This is reflected in the recent FAA commentary cited above,[49] which further notes that "airport planners are encouraged to work with city planners to better understand the electrical needs of communities surrounding airports and identify potential collaboration for grid upgrades."

These considerations showcase not just a challenge, but an opportunity. Do the needs of advanced air mobility users and the community around local airports represent an opportunity to enable airport-based energy solutions? This was the driving question for what became the Airports as Energy Nodes (ÆNodes) activity within NASA.

2. Airports as Energy Nodes

ÆNodes grew out of two areas within NASA: the NASA Aeronautics Research Mission Directorate (ARMD) Intercenter Systems Analysis Team (ISAT) and the Convergent Aeronautics Solutions (CAS) project within ARMD's Transformational Aeronautics Concepts Program (TACP). ISAT's contribution to ÆNodes was born from the "What's next in Regional (Air) Mobility" effort that focused on the RAM market.[52] This effort funded the Georgia Tech[40] and NREL[41] studies referenced above. The formulation of ÆNodes in CAS paralleled some of the ISAT efforts but was broadened to include other forms of AAM.

2.1. Convergent Aeronautics Solutions

The Transformational Aeronautics Concepts Program was created in 2014 as part of a major reorganization of ARMD. TACP was considered a "seedling program" within ARMD versus the other three "mission programs" within the mission directorate.[53] TACP was charged with "high-risk, leap-frog ideas" that supported all thrusts of the newly formed ARMD Strategic Implementation Plan (SIP), which was introduced in 2015, and updated in 2017, 2019, and 2023.[54] CAS is one of three projects within TACP, with the goal to "rapidly assess the feasibility of novel concepts to determine whether additional investment is warranted."[55] Activities within CAS were expected to be:

- **Convergent** – exploit the benefits of combining multiple disciplines and multiple partners, both within and external to NASA.
- **Transformative** – exhibit the potential for substantially greater impact than current approaches.
- **Targeted** – address challenges and opportunities relevant to NASA's strategic objectives and outcomes reflected in NASA Aeronautics Research Mission Directorate's Strategic Implementation Plan.
- **Feasibility Focused** – determine whether and the degree to which the concept is feasible with minimal further development of the technologies involved.
- **Rapidly Executed** – complete feasibility assessments in less than 2.5 years.

As with other NASA ARMD activities, the CAS process evolved over time. The iteration that resulted in ÆNodes began with a "mapping" and "synthesis" process, gathering subject matter experts and "intrapreneurs" to scour the space for selected problem areas relevant to the NASA ARMD SIP.[56] The selected area was dubbed "Energy for AAM at Scale" and included five opportunities for discussion in the "roundtable" process. One of these opportunities was dubbed "Airports and Aircraft as Energy Nodes." Referencing the NASA Urban Air Mobility Maturity Level (UML) scale,[57] the resulting Opportunity Concept Report for Airports and Aircraft as Energy Nodes[58] noted:

> *Growth in the AAM market provides an opportunity to fill gaps in electrical grid infrastructure, implementing energy-saving, renewable energy-based methods to address significant shortcomings the grid is predicted to experience as ground electric vehicles (EVs) and electric aircraft become commonplace. Demand on the electrical grid is already expected to grow with the further adoption of ground EVs, but the addition of thousands of AAM aircraft in the UML-4 to 6 timeframe will introduce unmanageable grid demand to recharge the electric AAM vehicles. While investment into AAM vehicle development is significant and growing, investment into energy infrastructure in support of AAM is lacking. By using aircraft and airports/vertiports as "energy nodes," power is generated at the point of use by on-site renewable energy sources, introducing "multifunctionality" to transition traditional single-use objects to dual-use, and power sharing through vehicle-to-grid connections with other EVs. By doing so, a symbiotic relationship is created between the infrastructure and the ridership, allowing opportunities for cost-share and power buyback. With similar options on the cusp of being investigated for ground EVs and the push for renewable energy, a strong case exists for desirability and necessity to accommodate growth of the AAM vehicle market. NASA is uniquely positioned to encourage development across converging, multidisciplinary areas for this transformational "system of systems" concept to address energy infrastructure growth and successfully implement AAM at UML-4 to 6.*

Following the roundtable discussion for Energy for AAM at Scale, some of the Opportunity Concept Reports were selected for "pre-execution," including Airports and Aircraft as Energy Nodes in January 2022. In this phase, the core team was responsible for developing and refining what CAS refers to as the desirability, viability, and feasibility barriers. This is further compounded by "wickedness," which generally refers to a dynamic, interdisciplinary, complex problem space. Specifically, CAS defines these barriers as follows:

- **Desirability** – Who are the key people (stakeholders) or personas who need this? How will you obtain their feedback and use it?
- **Viability** – Typically viewed as business or economic value. What new business/market does it unlock and make possible?
- **Feasibility** – How will this activity overcome key technical barriers; how will it be done? Feasibility primarily addresses whether something is technically possible.
- **Wickedness** – How is this activity going to prioritize and make progress in the problem space which has multiple, interdependent, dynamic, and uncertain aspects?

The Airports and Aircraft as Energy Nodes pre-execution activity lasted longer than typical of other CAS pre-execution efforts, partially because of availability of key personnel who were working on other efforts that were concluding, and partially to enable the completion of the ISAT work noted earlier to inform remaining barriers to success. In September 2023, what became known as the Airports as Energy Nodes (ÆNodes) activity was formulated and presented to CAS management for an investment decision review. This review was successful, resulting in a baseline "execution" activity starting in October 2023. As is typical systems engineering practice, the team defined statements of need, project goals, and project objectives to the overarching question of: *Do the needs of advanced air mobility users and the community around local airports represent an opportunity to enable airport-based energy solutions?* These needs, goals, and objectives are listed below for ÆNodes.

- ***Need*** is to enable local airports to accommodate advanced air transportation that may require alternative forms of energy while establishing the airport as a desirable component of the community energy solution.
- ***Goal*** is to develop solutions that are robust to an uncertain future mix of vehicles/energy needs and types, provide lasting community value, and enable investment pathways that accelerate adoption.
- ***Objective*** is to generate data, reports, and/or designs of future airport energy architectures for at least one airport suitable to achieve buy-in from key stakeholders (FAA, utility, airport, community) for full-scale development and demonstration.

The high-level barriers identified for ÆNodes were as follows:

- **Desirability** – Energy system must be able to provide energy to future aviation users (of which the energy mix is unknown) and local community (whose energy needs and types are evolving).
- **Viability** – Energy must be provided to users at an affordable cost to enable adoption with low emissions to reduce environmental impact locally and globally.
- **Viability** – Airport energy system upgrade path must be in place at critical locations prior to aviation users arriving, resulting in long payback periods with little/no return.
- **Feasibility** – Airport energy harvesting and distribution must comply with uncertain future regulatory framework.
- **Wickedness** – Airport upgrade path must remain viable with uncertainty in number of aircraft served, preferred energy product, and timing, while also navigating regulatory uncertainty and maintaining positive community impact.

2.2. ÆNodes Structure and Schedule

ÆNodes was structured into five intersecting tasks:

- **Stakeholder Engagement** – Engage aviation and community stakeholders to define future airport, aircraft, and non-aviation scenarios and events of interest, and ensure the ÆNodes data products appropriately address stakeholder concerns. Select and engage with airport partners for detailed analysis in Airport Modeling and Energy Virtual Twin tasks.

- **Airport Modeling** – Develop parametric models of airport energy systems to determine the most robust mix of onsite distributed energy resources (DERs) and utility connections to meet a variety of possible future airport energy scenarios.
- **Energy Virtual Twin** – Emulate one or more selected airport sites with high-value alternatives identified from the Airport Modeling task efforts in a mixed physical/virtual environment at relevant energy and time scales to assess resiliency, de-risk design choices, and build confidence in the selected architectures.
- **Aircraft Modeling** – Identify possible aircraft archetypes that could be relevant for the selected airports in the future, including relevant features associated with the energy system of these aircraft. Develop air traffic scenarios for airport sites to be used for Airport Modeling and Energy Virtual Twin efforts.
- **System Testing & Integration** – Explore relevant vehicle and related infrastructure technologies, including battery and hydrogen storage and transfer mechanisms, that could add value for the airport, aircraft, and/or operator.

These tasks were performed by a multi-center team at NASA with contributors from the Armstrong Flight Research Center, Glenn Research Center, and Langley Research Center. In addition, the NASA team formed an interagency agreement with the Department of Energy[‡‡] to work with NREL on the Stakeholder Engagement, Airport Modeling, and Energy Virtual Twin tasks.

ÆNodes was formally started in October 2023 and was scheduled to complete technical work at the end of December 2025, with closeout (reporting, etc.) from January through March 2026. However, changes within NASA ARMD associated with the President's Fiscal Year 2026 Budget Request[59] eliminated the CAS project and required an early closeout for all activities within CAS, including ÆNodes. Hence, most technical activities for ÆNodes among the NASA team ceased in the summer of 2025, and the NASA team's closeout obligations were completed at the end of September 2025. The NREL activities are still planned to continue through the scheduled end of the closeout period in March 2026. Figure 4 shows the detailed activity timeline and milestones as executed through mid-September 2025.

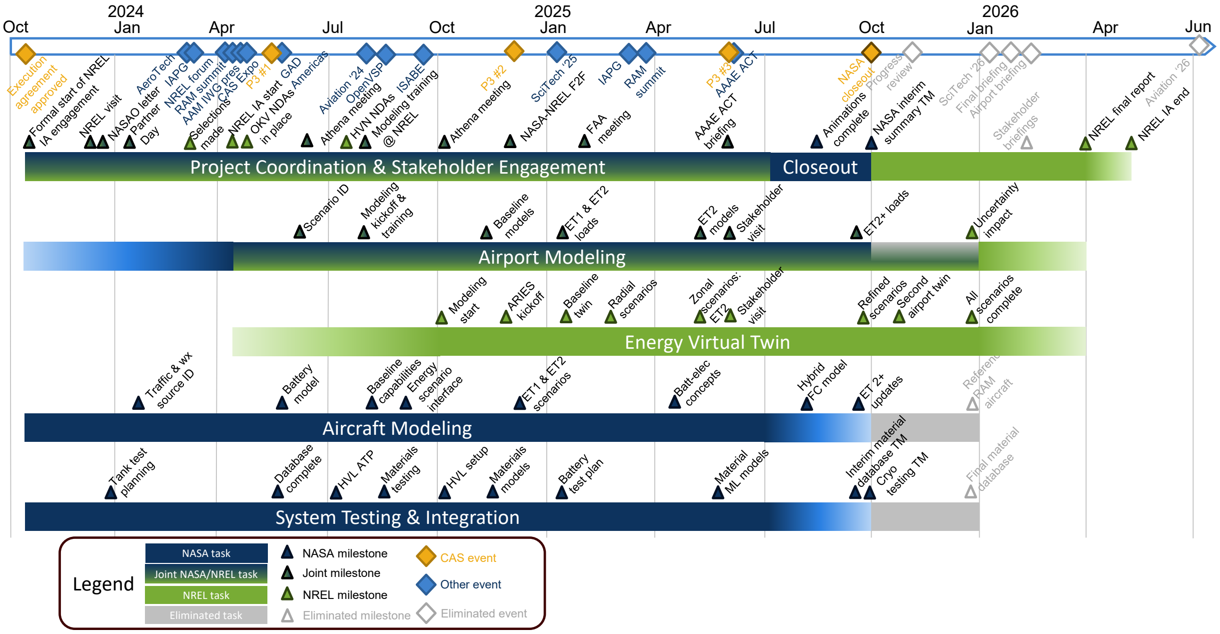


Figure 4: ÆNodes schedule, milestones, and key events as executed through September 2025.

[‡‡] IAG-24-24860, "Airports as Energy Nodes," April 2024-May 2026.

3. Progress Highlights

This document was originally intended to be a summary of results at the end of both the NASA and NREL portions of the ÆNodes effort; however, due to the accelerated closeout schedule for NASA, some deliverables were eliminated and others associated with NREL efforts have yet to be completed. That said, several stakeholder meetings took place and a handful of publications were generated throughout the ÆNodes execution period, and more are planned to be released. These data products, past and anticipated for the future, are highlighted below in reference to their parent task, though many of the efforts were interrelated and therefore may have involved efforts spanning multiple tasks.

3.1. Stakeholder Engagement

A crucial component of ÆNodes was to capture the interactions between airports, utilities, aircraft operators, regulators, and the local community. This required proactive engagement with these entities. The Stakeholder Engagement task included several different elements – working with airport/utility/community partners, interaction with aviation regulators, and overall engagement with other interested or impacted members of the public.

The NREL team contacted the National Association of State Aviation Officials (NASAO)[60] in December 2023 to invite interested parties to a "Partner Day" on 17 January 2024. A total of 19 entities, including airports, utilities, and manufacturers, attend the virtual event. During the event, ÆNodes team members from NASA and NREL outlined the history and goals of the ÆNodes activity and invited teams to propose to NREL to be site partners. Airport site partner proposals were required to include, at a minimum, an airport that could provide in-kind support for airport-related data and a utility partner willing to participate in providing information on utility-owned assets. The teams partnered directly with NREL, who worked with NASA through the interagency agreement between NASA and the Department of Energy referenced above. The goal was to select two sites: one as a smaller Part 139 airport and one that did not have an operating certificate under Part 139.

The NREL team created a group of non-supervisory ÆNodes team members from NREL and NASA to evaluate the partner proposals. Six teams responded to the call for partners, from which two teams were selected. These were the Winchester Regional Airport (airport identifier: OKV) in Winchester, Virginia with the Rappahannock Electric Cooperative and the Tweed/New Haven Airport (airport identifier: HVN) in New Haven, Connecticut with United Illuminating. Both sites are shown in Figure 5. These teams were typically just referred to by the corresponding airport identifier (i.e., OKV or HVN). These site partners represented both a non-Part 139 and a Part 139 airport, respectively, and had local catchment areas that were amenable to UAM and RAM networks. Both sites also had geographic and/or major traffic barriers on ground transportation routes that could be served by AAM.

The ÆNodes team held multiple discussions with regulatory stakeholders in the Department of Transportation and the FAA, including individuals in the FAA's Office of Airports. These meetings identified potential areas for collaboration, including the Department of Energy's Athena effort[47] mentioned in the Introduction. The discussions with these regulators indicated an interest in the ÆNodes' Aircraft Modeling task, specifically the development of vehicle archetypes and AAM vehicle schedules that could be extended to other airports under Athena or other initiatives associated with AAM traffic estimation and energy consumption. Ultimately, these efforts were terminated with the early closeout of the NASA portion of the ÆNodes tasks, though the NASA team still intends to publish details of the traffic modeling approach used for the ÆNodes airports as a future NASA Technical Memorandum. A summary of the air traffic modeling approach and vehicle archetypes is provided in a later section on the Aircraft Modeling task.

Although opportunities for AAM have been studied broadly, the ÆNodes team found little literature associated with the impact of AAM on the Airport and Airway Trust Fund (AATF), which is one of the mechanisms used to fund the AIP (highlighted in the Introduction). The AATF is traditionally funded from excise taxes, including taxes on passenger tickets, aviation gasoline, and jet fuel. With a move towards non-traditional energy carriers such as batteries, AAM operations would not provide the AATF with the same revenue as an equivalent fuel-burning aircraft. ÆNodes team member Richard Walsh used FAA estimates associated with the number of future UAM operations to identify the potential impact in the amount of funding the AATF could miss due to these operations without a different excise tax mechanism in place.[61] Walsh also investigated RAM operations, largely using the state of Connecticut as an example, to identify potential RAM air cargo markets and associated AATF impact.[62]

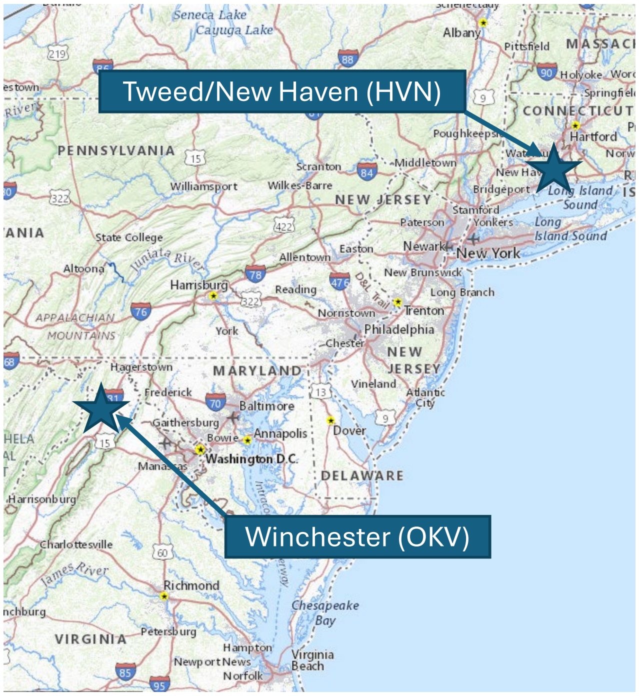


Figure 5: ÆNodes site partner locations.

Other outreach efforts included participation in events such as the Regional Air Mobility Summit,[63] a small but focused series of meetings that included researchers, technology developers, manufacturers, and operators interested in the opportunities of the associated RAM market. The ÆNodes representatives used this summit as an opportunity to highlight progress with ÆNodes and gather feedback on community impact associated with the activity. Team members presented at the NREL-led Sustainable Aviation Conference, discussing the goals and progress of the effort to airports, industry professionals, and consultants. The team also presented at other events including the American Association of Airport Executives (AAAE) Airport Consortium on Transformation,[64] a gathering of airport leaders interested in preparing for future aviation challenges, including the impact of advanced vehicles on airport infrastructure needs.

3.2. Aircraft Modeling

The Aircraft Modeling task's ultimate data product was estimates of aircraft energy needs at the partner airports. Both the Airport Modeling and Energy Virtual Twin tasks required an estimate of both the quantity of energy needed for aircraft operations as well as the time constraints associated with loading the energy on board the aircraft. To estimate these parameters, the Aircraft Modeling task was broken into three different efforts: identifying air traffic schedule source data for the partner airports, identifying the types of aircraft that need energy servicing (and associated constraints on energy type, quantity, and intake rate), and fusing this information into scenarios that could be used by the Airport Modeling and Energy Virtual Twin teams.

The air traffic schedule estimates were derived from several different data sources and considered legacy traffic, UAM operations, and RAM operations. Some advanced vehicles, such as electrified training aircraft, were considered as a replacement for legacy traffic, while UAM and RAM operations were considered additive to legacy traffic. The schedule estimates also captured weather impacts on traffic.

The ÆNodes Aircraft Modeling team members intend to release more detailed technical publications associated with the generation of these scenarios and reference aircraft in the future, but these efforts have not been formally documented as of the time of the release of this Activity Summary. As such, a summary of the approach used to generate the energy scenarios for each of the partner airports follows.

3.2.1. Legacy Air Traffic Schedule Generation and Weather Estimation

The legacy traffic and weather data for the airports were derived from NASA's Sherlock Data Warehouse.[65] This site includes an Open Data Portal for non-approved external users, as well as a more detailed data interface for NASA or other approved users. Numerous data products exist within Sherlock, but the specific products used were available in the Open Data Portal. The specific Sherlock data types used were the Integrated Flight Format (IFF) flight data files, the Reduced Data (RD) flight data files, and the weather observation text data (METAR[§§]) weather files. The IFF files capture detailed track point data (including time, position, altitude, and ground speed) for each flight observed within a controlling facility's boundaries, whereas the RD data files provide a summary of information about the flight as observed, including flight plan data (including the type of aircraft, origin airport, and destination airport) if available. The METAR files contain the specific METAR reports for all U.S. airports that provide such data, which provides information such as visibility, cloud cover, cloud ceiling, wind speed, and wind direction.

The IFF and RD files were downloaded from Sherlock from datasets aligned with the appropriate TRACON[***] facility. All files, including the IFF files, were downloaded for all of calendar years 2022, 2023, and 2024. The data were filtered and processed to isolate air traffic that arrived or departed from the two partner airports. The data were also filtered to identify so-called "touch and go" landings that are typical of flight training since these aircraft are not landing to refuel between each touchdown and takeoff. The traffic data captured arrivals and departures for each airport; however, due to many aircraft operating without a flight plan, it was not possible to pair individual aircraft arrivals and departures (e.g., aircraft that may need to refuel). A stochastic approach was used to pair arrivals with departures to estimate aircraft turnaround time, with the minimum turnaround time limited at 30 minutes.

To gain an understanding of required energy reserves for departing and arriving traffic, the surface weather data for both airport sites were categorized in accordance with the Aeronautical Information Manual.[66]. Generally, the required energy reserves apply to the flight category along the route of flight to the destination airport. However, since the destination airport was generally not known for departing flights, only the departure weather was used to understand required energy reserves, which was an optimistic estimate. The weather categories used were:

- **Low Instrument Flight Rules (LIFR)** – Cloud ceiling less than 500 feet above ground level (AGL) and/or visibility less than 1 statute mile.
- **Instrument Flight Rules (IFR)** – Cloud ceiling greater than 500 feet but less than 1,000 feet AGL and/or visibility greater than 1 but less than 3 statute miles.
- **Marginal Visual Flight Rules (MVFR)** – Cloud ceiling greater than 1,000 feet but less than 3,000 feet AGL and/or visibility greater than 3 but less than 5 statute miles.
- **Visual Flight Rules (VFR)** – Cloud ceiling greater than 3,000 feet AGL and visibility greater than 5 statute miles.

The categorization of a flight as day or night was tracked by comparing the departure or arrival time from the Sherlock data to the local sunrise and sunset on the day of the operation. For simplicity, "night" was defined as the time from 30 minutes after local sunset to 30 minutes before local sunrise, which approximates the time from the end of evening civil twilight to the beginning of morning civil twilight as specified by the FAA.[67] As with weather, the "day" or "night" categorization was used to understand the required energy reserves for the flight.

The only advanced aircraft that were converted from the legacy traffic were electric general aviation aircraft. These were one-for-one conversions of the single-engine reciprocating aircraft that operated on missions that could be satisfied with the reduced energy capacity of electrified versions of these single-engine reciprocating aircraft. Since neither airport had a based flight school, only individual flights were swapped. The Aircraft Modeling team also considered the introduction of hydrogen-fueled vehicles to replace some aircraft, but this effort was eliminated due to resource and time limitations.

[§§] METAR refers to the Meteorological Aerodrome Report, a standardized text-based weather report available at many different airports worldwide.

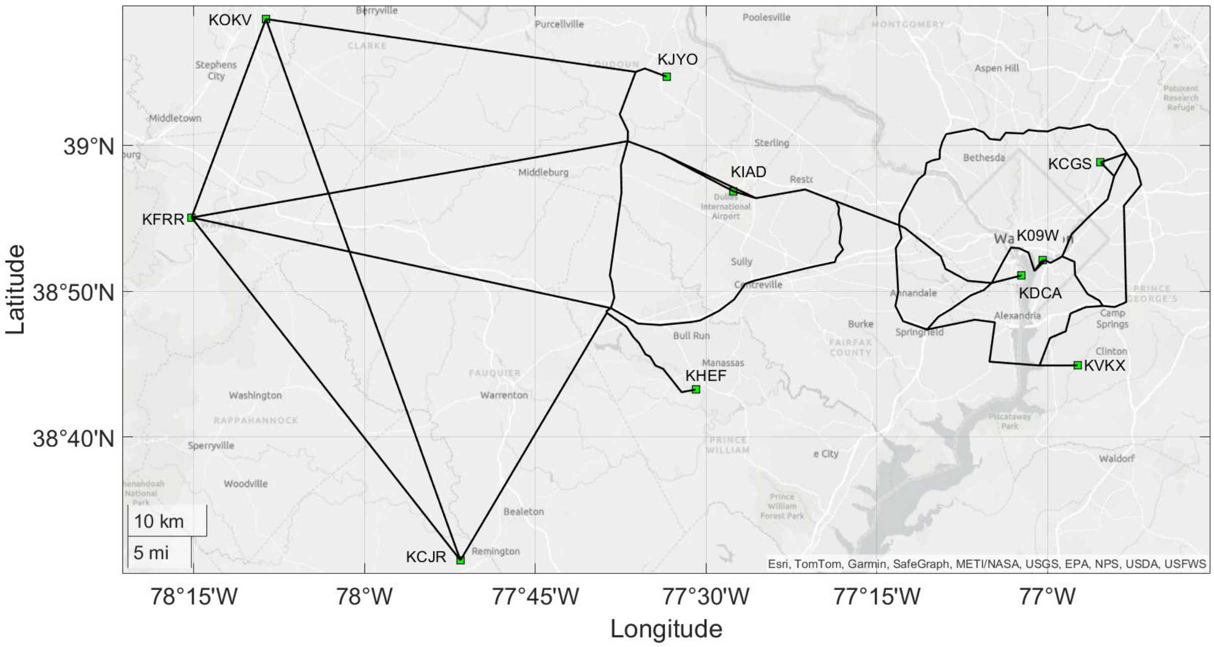
[***] TRACON refers to Terminal Radar Approach Control, which is an FAA facility responsible for managing airspace around busier airports. Both partner airports were within the geographic region of a TRACON facility – the Potomac TRACON (PCT) for OKV and the New York TRACON (Y90) for HVN.

3.2.2. Urban Air Mobility Schedule Generation

The UAM operations were generated from a mix of reference sources, assumptions, and analyses conducted by the ÆNodes Aircraft Modeling Team. The UAM network was assumed to be a fully on-demand network using 14 CFR Part 135 operating rules[68] in eVTOL aircraft capable of arriving or departing at airports or vertiports. The network used a predefined set of origin/destination pairs and routes with a stochastic passenger demand model.

Both partner airports needed an estimated network model. These were anchored on the Washington, D.C.-Northern Virginia region for OKV and the New York City-Long Island-Connecticut region for HVN. The cities and vertiports were selected by estimating eVTOL aircraft performance (described in section 3.2.4 Aircraft Archetypes) to see what airports and vertiports could be served and may have reasonable demand. The New York area network was able to leverage prior UAM modeling in the New York City metro area, which included some new proposed vertiport infrastructure.[18] Otherwise, the networks were developed from existing facilities (airports and heliports). Both the OKV and HVN networks considered airspace and geographic constraints in their route structures instead of point-to-point operations to add realism for energy consumption. The networks also included waypoints from the FAA-defined helicopter routes for the Washington, D.C. and New York Metropolitan areas.[69] The UAM route networks are shown in Figure 6 for OKV and Figure 7 for HVN.

The demand on the routes was stochastically varied by time of day and day of year. The network operated at a peak of 36 to 48 operations per hour in both cases,[†††] depending on the scenario (discussed in section 3.2.5 Scenario Development). The peak number was scaled by a daily demand model taken from a prior NASA-funded study[70] for UAM demand in nominal weather on the busiest day. The routes were selected from a predefined table of probabilities, with some origin/destination pairs more probable than others. Hence, even at the peak number of operations per hour, one of the nodes in the network (e.g., OKV or HVN) would only see a fraction of the traffic in the network. The route demand was further scaled by the departure airport weather from METAR data in 15-minute increments. The network was derived for eVTOL aircraft with enough energy onboard to fly in VFR weather minimums, so UAM flights in weather that was worse than MVFR were cancelled.



Esri, TomTom, Garmin, SafeGraph, METI/NASA, USGS, EPA, NPS, USDA, USFWS

Figure 6: OKV UAM route network, showing connections between vertiport locations, which are represented with green squares. Route network is based on existing helicopter routes, with direct routing available where no routes exist.

[†††] Note that this peak applies to the entire network across all airports and vertiports, not a single location.

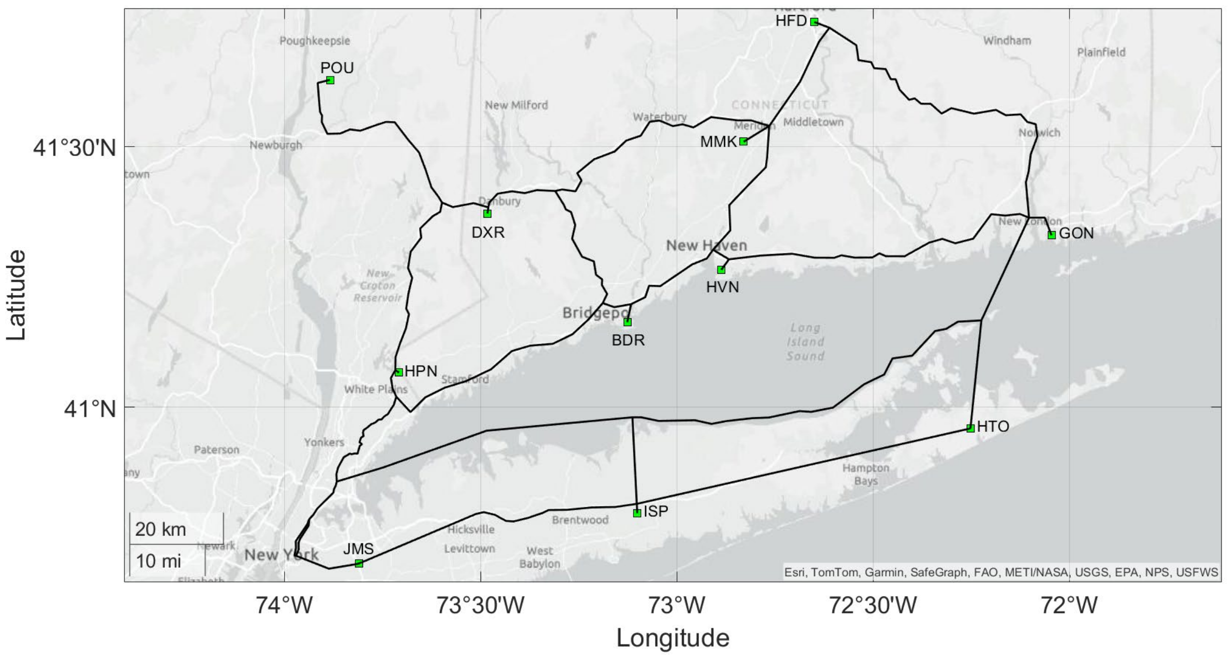


Figure 7: HVN UAM route network, showing connections between vertiport locations, which are represented with green squares. Route network is based on existing helicopter routes and additional routes following major highways.

3.2.3. Regional Air Mobility Schedule Generation

The RAM operations were generated with a different set of assumptions from the UAM schedule because the RAM network was assumed to operate as a scheduled operation under Part 135. The overarching RAM schedule was adapted from a route network developed by Georgia Tech under the prior NASA-funded study referenced in the Introduction.[40] Both partner airports (OKV and HVN) were host to RAM traffic in the prior study, and schedule data were adapted from a network that included all-electric nine-passenger aircraft (eRAM9) and plug-in hybrid electric 19-passenger aircraft (hRAM19). As discussed in section 3.2.4 Aircraft Archetypes, the aircraft energy assumptions were modified from the source study, but the route network, which included origin/destination pairs and daily schedules for each partner airport, remained the same. The nominal daily schedule from the Georgia Tech study is provided in Table 1 for OKV and Table 2 for HVN. These tables include the FAA airport identifiers for the departure point and the subsequent destination. The prior study grouped the departure times in 15-minute intervals, which led to the appearance of simultaneous departures in the schedule. In practice, these departure times would be staggered by a few minutes to ensure appropriate traffic separation, though this was not modeled as part of the study.

Table 1: Nominal daily RAM aircraft schedule for OKV in local time.

Type	Arriving From	Departing To	Arrival Time	Departure Time
hRAM19	BWI	BWI	18:44	06:45
eRAM9	LNS	PHL	19:06	07:15
hRAM19	ABE	ABE	20:38	07:15
eRAM9	PIT	PIT	20:43	07:15
eRAM9	PHL	PHL	07:48	17:45
hRAM19	LGA	LGA	08:23	13:15
eRAM9	PIT	PIT	08:43	17:45
hRAM19	ABE	BWI	09:08	17:45
eRAM9	PIT	LNS	09:43	17:45
hRAM19	BWI	ABE	13:14	17:45
eRAM9	PIT	MDT	13:43	18:15
eRAM9	PHL	PIT	18:48	19:45

Table 2: Nominal daily RAM aircraft schedule for HVN in local time.

Type	Arriving From	Departing To	Arrival Time	Departure Time
eRAM9	ISP	ABE	18:06	06:45
eRAM9	EWR	ISP	18:23	06:45
hRAM19	BOS	EWR	18:25	06:45
eRAM9	ISP	ISP	18:36	06:45
eRAM9	PHL	PHL	18:47	06:45
eRAM9	EWR	1B1	18:53	07:15
eRAM9	MMU	47N	18:56	07:15
eRAM9	47N	ALB	19:01	07:15
eRAM9	ALB	ABE	19:04	07:15
eRAM9	NY0	PHL	19:12	07:15
hRAM19	ABE	BWI	20:29	07:15
eRAM9	ISP	ISP	07:36	12:45
eRAM9	ISP	ABE	07:36	13:15
eRAM9	NY0	ISP	07:42	13:15
eRAM9	PHL	PHL	07:47	17:45
eRAM9	EWR	ISP	07:53	17:45
eRAM9	47N	ALB	08:01	17:45
eRAM9	ALB	ABE	08:04	17:45
eRAM9	PHL	NY0	08:17	17:45
hRAM19	ABE	EWR	09:29	18:15
eRAM9	ISP	ABE	13:06	18:15
eRAM9	ISP	47N	13:36	18:15
eRAM9	ABE	1B1	15:42	18:15
eRAM9	ABE	ISP	16:12	18:15

The original study considered this schedule to be a repeating network; that is, each flight operated at these exact times every day. The demand estimates for that study were estimated during a weekday. To account for changes in demand on weekends, the ÆNodes Aircraft Modeling team culled all departures after 14:00 local time on Saturdays and prior to 12:00 local time on Sundays. In addition, departures were cancelled if a flight could not meet the required energy reserves for the route due to time of day or weather. In both cases (weekends or energy reserve cancellations), no attempt was made to reschedule flights; the flight simply disappeared from the yearly schedule, and no energy need was recorded. This was a limiting assumption largely meant to reduce the effort to incorporate the daily schedule from the prior study into a yearly list of temporal aircraft energy needs with day-of-week and weather variations.

3.2.4. Aircraft Archetypes

Each arrival-departure pairing in the schedule represented a time at which an aircraft may need to have its energy system replenished. For legacy traffic, this was jet fuel or avgas, and for UAM and RAM traffic, this could include electricity. Information on the type of aircraft, coupled with information on the route to and from the airport, was needed to estimate the type and amount of energy to load onto the aircraft.

The legacy traffic data for each airport included the type of aircraft, if specified. However, many of the operations included unspecified aircraft types since many aircraft (particularly smaller general aviation and trainer aircraft) operate in VFR conditions without a flight plan. When provided, the Sherlock data include an aircraft type that is generally cataloged in the FAA Aircraft Type Designator database.[71] This database includes specific information on the aircraft type, engine type, number of engines, and weight class. Though extensive, this information was generally too granular for the purposes of the ÆNodes study. As such, the legacy aircraft were broken into nine archetypes:

- **SR**: single engine reciprocating (e.g., Cessna 182, Cirrus SR22)
- **MR**: multiengine reciprocating (e.g., Cessna 402, Piper Aztec)
- **ST**: single engine turboprop (e.g., Cessna 208, Piper Malibu)
- **MT**: multiengine turboprop (e.g., Cessna 408, Beechcraft King Air)

- **SJ**: single engine jet (e.g., Cirrus SF50)
- **MJ**: multi engine jet (e.g., Cessna Citation, Gulfstream V)
- **HE**: helicopter (e.g., Bell 206, Airbus H160)
- **TJ**: transport jet (e.g., Boeing 737, Airbus A320)
- **U**: unknown

All aircraft identified as Unknown in the Sherlock data (U) were classified as SR for energy consumption calculations. When aircraft types were not provided in the dataset, the type was assumed based on the approach speed for arrivals and the initial climb speed for departures. The speed was taken as the average ground speed reported within the Sherlock IFF within 300 feet of the airport's altitude at the airport location, adjusted for wind direction and wind speed to arrive at an estimated airspeed. Aircraft with final approach or takeoff airspeeds of less than 20 knots were disregarded as bad data points; values greater than or equal to 20 knots but less than 85 knots were classified as SR; values greater than or equal to 85 knots but less than or equal to 100 knots were classified as MT, and values greater than 100 knots were classified as MJ. Though crude, this allowed the team to estimate fuel requirements for all legacy aircraft in the schedule. As discussed in Section 3.2.5, this also led to a large under-representation in the number of helicopter operations.

The aircraft data were used to estimate the fuel consumption of each identified legacy operation, as well as the required fuel reserves (based only on the local airport weather and time of day of the operation). If the origin/destination pair was known from the traffic data, this information was included (along with additional assumptions on time in the traffic pattern, indirect routing, etc.) in the estimation of fuel requirements. Table 3 contains the information that was used to derive performance for each of the legacy archetypes. Here, L/D_{cr} refers to the lift-to-drag ratio at cruise (also known as aerodynamic efficiency), W is the maximum takeoff weight, V_{cr} is the cruise speed, η_p is the propulsive efficiency in cruise, and η_t is the thermal efficiency of the engine at cruise. The energy use and needs were calculated based on the cruise energy consumption between the origin and destination at maximum takeoff weight plus non-travel time denoted as $t_{pattern}$. If the aircraft was traveling in LIFR conditions, the dispatch energy requirements included energy for cruise to an alternate airport at a distance of r_{alt}, plus the required time-based reserves (30 to 45 minutes, depending on time of day and weather category). For simplicity, a specific energy of 12 kWh/kg was assumed for all aviation fuel types. If origin and destination data were not available, the distance was set to the average of the aircraft archetype. Though admittedly coarse, this technique provided credible estimates for aircraft fuel consumption upon arrival and fuel needs upon departure, which could be helpful when determining if an aircraft could be replaced with a different aircraft with a different energy system.

Table 3: Data used to calculate energy use upon arrival and energy needed for departure for legacy aircraft archetypes.

Archetype	**SR**	**MR**	**ST**	**MT**	**SJ**	**MJ**	**HE**	**TJ**
L/D_{cr}	10	12	10	13	16	17	4	17
W, lbf	3,000	7,500	8,000	15,000	6,000	25,000	4,000	150,000
V_{cr}, KTAS	100	150	175	200	350	400	75	400
η_p	80%	80%	80%	80%	80%	80%	80%	80%
η_t	30%	30%	20%	20%	30%	30%	20%	45%
$t_{pattern}$, min	20	10	10	10	10	5	20	5
r_{alt}, nmi	50	50	100	100	100	200	25	500

Electric general aviation aircraft (archetype identifier: eGA) was another archetype introduced in the scenario modeling. As noted above, these aircraft were one-for-one replacements for a portion of the SR traffic in the dataset. These aircraft were assumed to use 25% of the power[‡‡‡] required by the SR and have a battery capacity of 87.5 to 140 kWh, depending on the scenario. Not all SR traffic was swapped for eGA; the only SR flights considered eligible for swapping with an eGA operation were those operations that could be completed with the limited amount of battery energy available to the eGA aircraft, inclusive of sufficient reserves based on departure or arrival weather.

[‡‡‡] This corresponds to an improvement in powerplant efficiency (i.e., thermal efficiency for combustion, drivetrain efficiency for electric) from 30% to 90% and an increase in aerodynamic efficiency (i.e., lift-to-drag ratio) of 33%.

The UAM network was flown with a single vehicle type with eVTOL as the ÆNodes archetype identifier. Though many different eVTOL vehicles are in development, the data on these vehicles are preliminary and/or proprietary. Instead, the ÆNodes team used performance and energy consumption data derived from the "Lift+Cruise" concept from the NASA-developed UAM Reference Vehicles.[72] The energy capacity for UAM aircraft was based on a battery size of 256 to 341 kWh according to the scenario.

The RAM network was flown with two vehicle types, a nine-passenger battery-electric fixed-wing aircraft and a 19-passenger plug-in hybrid fixed-wing aircraft, denoted as eRAM9 and hRAM19 as described in the schedule discussion of section 3.2.3. The original source data was the prior Regional Air Mobility study cited earlier,[40] though some changes were made to the energy consumption metrics to better align the technology assumptions between the legacy aircraft, eGA aircraft, and UAM aircraft. Namely, the energy consumption was increased to 1.5x the amount as specified in the original study for the baseline aircraft and the battery capacity was defined as 746 kWh for the eRAM9 aircraft and of 440 kWh for the hRAM19 aircraft.

The Aircraft Modeling team originally planned to model several hydrogen-fueled aircraft concepts. This included 9- and 19-seat RAM aircraft powered by hydrogen fuel cells and two hydrogen combustion concepts at the business jet and transport aircraft scales. These designs were eliminated from consideration due to lack of accessible source data, and resource limitations associated with modeling the impact of hydrogen infrastructure at the airport.

Work was originally planned to develop NASA RAM reference vehicles, in an effort similar to the one that generated the UAM reference vehicles, as part of the Aircraft Modeling task. In addition, the NASA team began developing the Rapid Conceptual Development Environment (RapCDE) to quickly generate credible reference designs for fixed-wing aircraft suitable for ÆNodes or other applications. However, these efforts were terminated before they were completed due to the early closeout of the NASA-only activities. The release of publication(s) related to the design and performance estimates for NASA RAM vehicles, hydrogen vehicles, and of RapCDE still remains an aspiration for the team members and may be incorporated into future NASA efforts. Some elements of RapCDE have been published, including a battery system model,[73] a rapid flight dynamics model,[74] and takeoff/landing analysis for conceptual design.[75]

3.2.5. Scenario Development

The traffic, weather, and aircraft data above were integrated into different traffic scenarios meant to be representative of different technology assumptions roughly comparable with an optimistic timeframe for widespread adoption of these networks. The technology assumptions tracked the specific type of aircraft operations. Four epochs were initially considered: baseline (ET0), electrification technology 1 (ET1), electrification technology 2 (ET2), and electrification technology 3 (ET3). ET3 included hydrogen fuel cell and hydrogen combustion options ("H2"). Table 4 shows the initial technology assumptions associated with these epochs. As noted in section 3.2.4, the hydrogen concepts were eliminated partway through the study, so ET3 was never developed.

The baseline traffic and weather year was initially selected to be 2023 since the source data for 2024 were not yet available at the start of the activity. Unfortunately, some of the legacy traffic data for 2023 were missing for the airports due to data corruption. The baseline year was switched to 2024 late in the activity as this year contained complete legacy traffic information for the full calendar year. The battery-electric aircraft were dispatched with no more than 90% of the stated battery capacity to account for cell aging and charge time considerations. The SR aircraft were converted to eGA aircraft only if the eGA aircraft had sufficient range with appropriate reserves to complete the mission of the original SR aircraft in the dataset. The resulting distribution of yearly arrival and departure pairs and associated weather category for departure is shown in Figure 8 for ET0 and Figure 9 for ET2. In these figures, "prop" refers to legacy SR, ST, MR, and MT traffic, "jet" refers to SJ, MJ, and TJ, and "RAM" refers to both eRAM9 and hRAM19. In all cases, "departures" refers to matched departures, meaning legacy traffic that had a tracked arrival and departure time and needed energy.[§§§] ET1 is not shown because the scenario was deemed less important to the airport modeling team that was instead focusing efforts on ET2 infrastructure buildout, and the results in general for ET1 were unremarkable. The approach used to filter the legacy traffic data for helicopter operation yielded very few helicopter arrivals and departures, so these were dropped from the legacy dataset.

[§§§] Note that this may differ from the number of operations reported at an airport in the legacy traffic year since those operations may include training operations that do not require fuel in between flights (e.g., "touch and goes").

Table 4: Assumptions for initial air traffic scenarios. All epochs use weather observations from 2024.

Traffic	**ET0**	**ET1**	**ET2**	**ET3**
Legacy	2024 traffic	2024 minus eGA	2024 minus eGA	2024 minus eGA, H2 business jet, H2 transport
eGA	N/A	100% of SR traffic accessible with 87.5 kWh battery	50% of SR traffic accessible with 140 kWh battery	Same as ET2
eVTOL	N/A	Network accessible with 256 kWh battery	Network accessible with 341 kWh battery	Same as ET2
eRAM9	N/A	N/A	Network accessible with 746 kWh battery	ET2 minus demand served by H2 RAM
hRAM19	N/A	N/A	Network accessible with 440 kWh battery	ET2 minus demand served by H2 RAM
H2 RAM fuel cell	N/A	N/A	N/A	9- and 19-pax, enhanced network from upcoming NASA contractor report by C. Justin et al.
H2 bus. jet	N/A	N/A	N/A	25% of MJ traffic accessible within range
H2 transport	N/A	N/A	N/A	25% of TJ traffic accessible within range

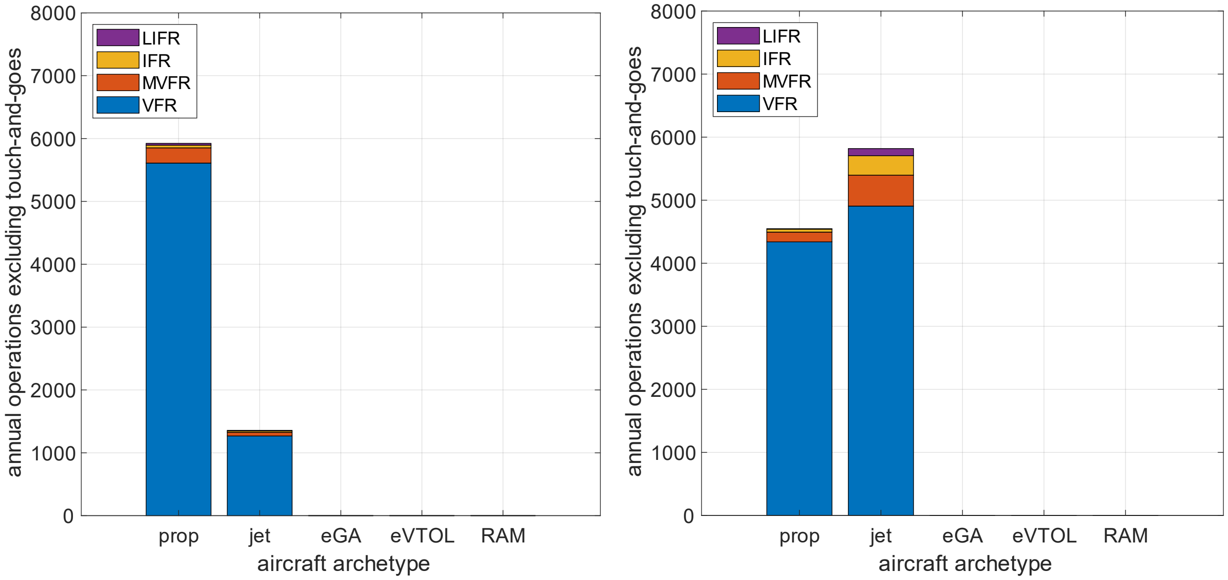


Figure 8: Annual departures for ET0 at OKV (left) and HVN (right) indexed to weather category at time of departure.

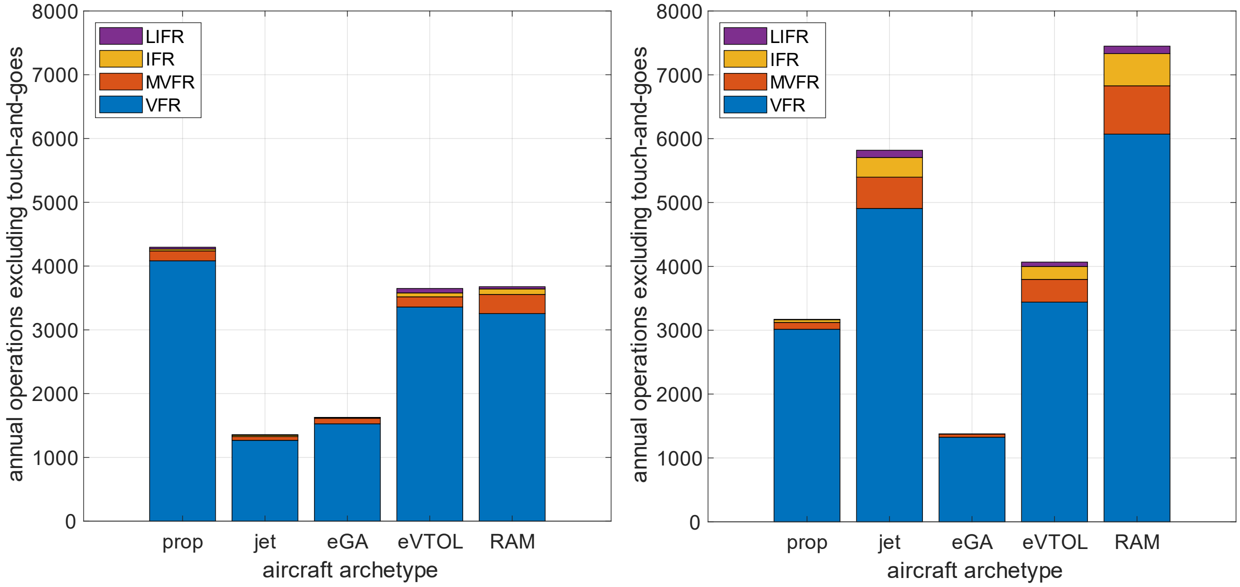


Figure 9: Annual departures for ET2 at OKV (left) and HVN (right) indexed to weather category at time of departure.

These figures show how the eGA traffic came at the expense of legacy traffic (since the SR traffic is "converting" to eGA) but otherwise how eVTOL and RAM traffic was additive to the traffic estimates. This also shows the scale of eGA, eVTOL, and RAM operations that may occur at these airports over time – leading to the energy use seen in the Airport Modeling section (section 3.4).

The amount of time the aircraft spend on the ground was critically important to understanding the impact of delivering energy to the aircraft since this represents the maximum amount of time to service the aircraft, minus any time where recharging/refueling is not possible (e.g., taxi in/out). A histogram of the annual amount of time between arrival and departure for the different types of aircraft in ET2 is shown in Figure 10 for OKV and Figure 11 for HVN. Here, the scheduled nature of the RAM service is apparent, showing up as high peaks for certain timeframes, whereas the on-demand UAM service is spread out over a far more variable ground dwell time. Depending on the time of day of the departure, the RAM and UAM energy loads could stack up and result in high demand charges from the utility without careful scheduling of charging actions or use of equipment to reduce the peak power demand on the grid.

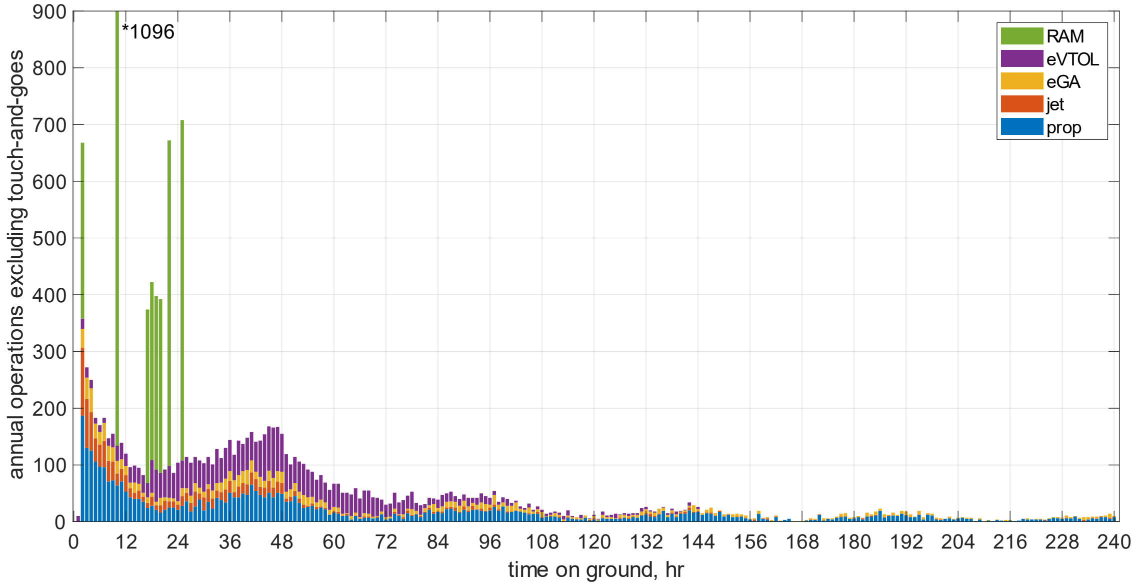


*Figure 10: Histogram of annual dwell time for ET2 at OKV. Note that some operations are off scale (denoted by *).*

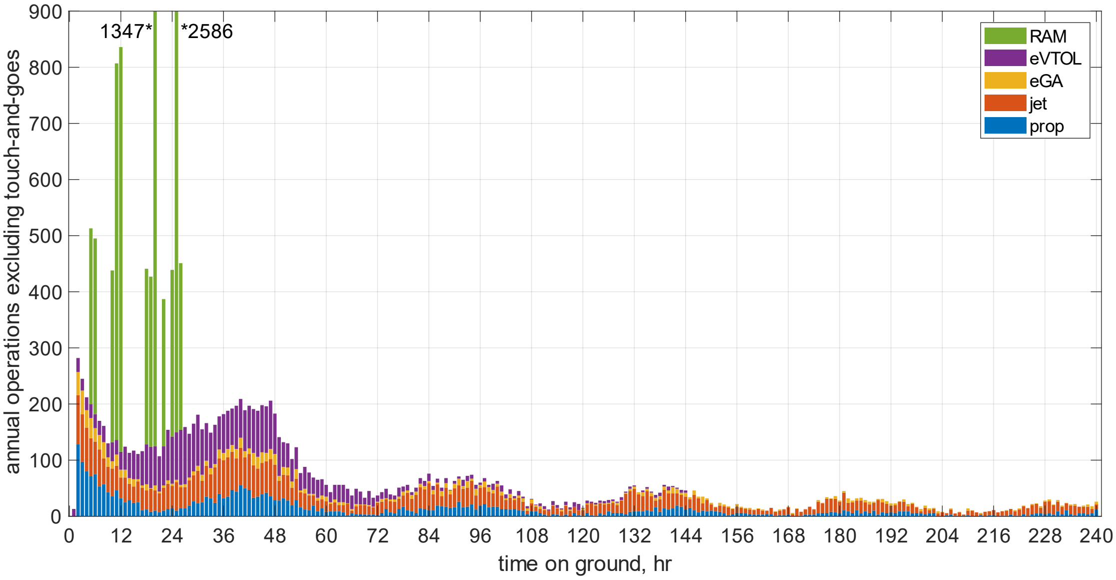


*Figure 11: Histogram of annual dwell time for ET2 at HVN. Note that some operations are off scale (denoted by *).*

3.3. Airport Modeling

The airport modeling task proceeded much in the same fashion as the NREL studies referenced in the Introduction.[41,48] This analysis was performed by both the NASA and NREL teams, with the NREL team leading and conducting the initial OKV analysis and the NASA team following with the HVN analysis. NASA transitioned the HVN models to the NREL team for final analysis due to the early closeout of the NASA efforts. Given that the NREL team is continuing this work and capturing it in a final report that is due in the first half of 2026, the tools, methods, and data sources are not discussed in this Activity Summary. Some data are provided in this section associated with the results of the airport modeling, though these are preliminary data that will be updated in the NREL final report.

A key element of the Airport Modeling approach was the estimation of vehicle charge loads associated with the eGA, eVTOL, eRAM9, and hRAM19 aircraft. Additionally, the non-electric flights could trigger ground support equipment operation, which could also invoke charging loads for electrified equipment. A summary of the annual and average operations and charging loads for ET2 is shown in Table 5 for OKV and Table 6 for HVN.

Table 5: Annual aircraft operations and charging loads in ET2 for OKV. Preliminary data; will be updated in NREL final report.

Aircraft Type	Annual Flights	Avg. Daily Flights	Max Daily Flights	Ann. Charging Energy (MWh)	Avg. Load per Flight (kWh)	Min. Turnaround Time (min)
Non-electric	6576	18.2	96	0	0	30
eGA	1827	5.6	31	87	48	30
UAM	2964	8.9	24	288	97	15
eRAM9	2000	6.4	7	186	93	56
hRAM19	1234	3.4	5	43	35	270

Table 6: Annual aircraft operations and charging loads in ET2 for HVN. Preliminary data; will be updated in NREL final report.

Aircraft Type	Annual Flights	Avg. Daily Flights	Max Daily Flights	Ann. Charging Energy (MWh)	Avg. Load per Flight (kWh)	Min. Turnaround Time (min)
Non-electric	7387	21.6	51	0	0	30
eGA	1440	4.8	14	60	42	30
UAM	2844	8.7	21	214	75	15
eRAM9	6338	17.3	21	339	53	123
hRAM19	627	2.0	3	0	0	525

In general, the charge loads were calculated based on meeting the minimum battery state of charge for the aircraft to make its next destination with the required energy reserves, so these preliminary results should be considered a lower bound. In some cases, such as hRAM19 at HVN, there were zero charge loads since the aircraft always had enough battery energy upon landing to make the next trip (though these vehicles did require fuel); the battery state of charge was assumed to be 90% at the prior departure. In the final version, the NREL team will modify the assumptions for charging scenarios, including taking the vehicles to a 90% state of charge as the default if the time and number of chargers required exist.

Even at this lower bound of energy required for the aircraft, the required electrical energy is far larger than used by the airports for current-day operations. The preliminary estimates for non-aircraft charging loads based on existing electricity data at the airports indicated that OKV would consume 218 MWh annually and HVN would consume 847 MWH annually. The larger airport load at HVN was due to the increased facilities, including a commercial passenger terminal. Considering that electric aircraft would need 604 MWh of annual energy at OKV and 613 MWh of annual energy at HVN, the addition of these loads would result in a significant increase in the energy consumption at these airports.[****]

A major consideration for installing new equipment at an airport is not just the amount of energy required, but the power required to meet the energy needs in the appropriate amount of time. Utilities typically charge large entities such as airports based on the peak amount of power used over a specified period in addition to the amount of energy used. The estimated average daily maximum power level, mean power level, and maximum power level over a year of operations determined for ET2 are shown in Table 7 for OKV and Table 8 for HVN. These loads assume that not all time between arrival and departure are available for charging; some time is necessary for taxiing time and other non-charging operations that will be detailed in the NREL final report.

Table 7: ET2 power usage at OKV. Preliminary data; will be updated in NREL final report.

Load	Mean Ann. Power (kW)	Avg. Daily Peak (kW)	Max Ann. Peak (kW)
Base Airport Facilities	25	48	149
eGA Charging	11	205	288
UAM Charging	36	309	347
RAM Charging	29	452	522
All ET2 Charging	76	619	1,058

Table 8: ET2 power usage at HVN. Preliminary data; will be updated in NREL final report.

Load	Mean Ann. Power (kW)	Avg. Daily Peak (kW)	Max Ann. Peak (kW)
Base Airport Facilities	97	141	240
eGA Charging	8	171	288
UAM Charging	35	295	347
RAM Charging	43	712	795
All ET2 Charging	78	813	1,346

These preliminary power estimates show that the addition of aircraft charging loads in ET2 add daily peak loads that are many factors higher than the base airport facilities for both OKV and HVN, which can lead to excessive demand charges without equipment to reduce the peak loads (such as airport storage batteries) installed. The updated loads and proposed infrastructure solutions, as well as their associated payback periods and overall changes in airport energy resilience, will be detailed in NREL's final report, which is planned to be released in 2026.

[****] The charging loads borne by the airport would be higher since this represents the energy going into the aircraft battery not inclusive of charging or line losses at the airport. The data in the NREL final report will reflect these losses.

3.4. Energy Virtual Twin

The Energy Virtual Twin task sought to develop a modular digital twin framework for an airport microgrid that could dynamically adapt to load changes and support future electrification initiatives. This digital twin was part of a symbiotic feedback loop between the two tasks: the Airport Modeling task would identify high-value airport microgrid alternatives, and the Energy Virtual Twin task would evaluate the dynamics of a selected alternative in dozens of different scenarios and configurations at relevant energy and time scales using a mix of actual and virtual hardware.

To accomplish this task, the ÆNodes team leveraged the NREL Advanced Research on Integrated Energy Systems (ARIES) environment, a highly capable and scalable asset developed by the Department of Energy at the NREL campuses.[76] ARIES is capable of operating microgrids at a physical scale of 20 MW and virtually at the GW scale using supercomputing-based simulation. The Energy Virtual Twin task within ÆNodes was originally scoped to model a single airport from the two airport partners, though efficiencies discovered by the team during the initial modeling phase have enabled the NREL team to expand their scope to consider modeling both partner airport sites. At the completion of the work, the NREL team hopes to have a scalable, modular set of assets capable of emulating multiple airport environments. The NREL final report in 2026 is planned to include more details for both sites.

3.5. System Testing and Integration

The System Testing and Integration task focused on NASA-internal testing to advance understanding of representative electrified and hydrogen-fueled vehicles that could yield additional insight for the Airport Modeling and Energy Virtual Twin tasks. The task was broken into two main areas: (1) aircraft electrified propulsion architectures and (2) testing of materials and systems for aircraft fueled by cryogenic hydrogen.

The electrified propulsion architecture testing efforts focused on developing charge acceptance curves for representative battery-electric AAM vehicles. The NASA team intended to use batteries and hardware from the NASA X-57 subproject[77] to generate publicly available charge characterization curves using X-57 batteries at different charge rates and temperatures. After plans for a high-voltage test laboratory at the NASA test site were delayed, the team developed a plan to develop the characterization curves at the NREL ARIES facility. Challenges associated with loss of critical personnel within NASA ultimately led to the termination of this effort.

The work on cryogenic hydrogen systems research proceeded along with other parallel efforts within NASA under the umbrella of the Commercially-viable Hydrogen Aircraft for Reduction of Greenhouse Emissions activity.[78] Specific work conducted under ÆNodes included characterization of lightweight, high-strength materials for cryogenic hydrogen tanks.[79] Additionally, ÆNodes personnel released a public request for information associated with industry needs for cryogenic hydrogen test facilities.[80,81] The results of this request for information are being used by NASA to develop plans to enhance U.S. cryogenic hydrogen test capabilities.

4. Work Products and Next Steps

The ÆNodes activity was initiated by the question, “do the needs of advanced air mobility users and the community around local airports represent an opportunity to enable airport-based energy solutions?” The progress to date has not yielded a definitive answer, but the data developed thus far indicate that future electrified aircraft energy and power needs are significantly higher than the current projected airport energy and power needs. Preliminary results from the Airport Modeling task have indicated that the infrastructure upgrades needed to provide this quantity of energy and power can favor the use of distributed energy resources (DERs), including large storage batteries and photovoltaic energy harvesting, and preliminary results from the Energy Virtual Twin task indicate that these resources can help the airport not just deal with aviation energy loads but also increase airport energy resiliency in the event of an airport power outage. This work will continue with members of the NREL team, who plan to publish their final results at the conclusion of their portion of the work in mid-2026. These results are planned to include DER system sizes and sensitivities to key input assumptions (such as DER unit costs) for both partner sites, as well as validation results from the ARIES Energy Virtual Twin environment. These results can serve as a blueprint for these site partners and can also serve as guidance to other airports regarding the types of systems and infrastructure upgrades that may be needed to prepare for these advanced aircraft.

Some of the NASA activities for ÆNodes were eliminated or terminated early due to changes in NASA mission priorities that led to an earlier closeout that initially planned. However, several data products were in work that will be made available as time and funding permit. This includes providing more details on the development of demand models for advanced aircraft at the partner sites. The approach used by the ÆNodes team leveraged historical data on weather and aircraft operations for a particular airport site, converted a portion of this traffic into electrified general aviation aircraft, established UAM traffic networks based on stochastic demand assumptions, and established RAM scheduled demand. Though this activity summary document provides some details on this demand modeling, the Aircraft Modeling task team members still intend to release a NASA Technical Memorandum detailing this modeling approach so that it can be adapted for use at other airport sites. The NASA team is also investigating future collaboration mechanisms with NREL so that this modeling capability can be implemented with other interested partner sites.

Another element of the NASA portion of the ÆNodes activity was the development of aircraft archetypes suitable for integration into the site demand estimates for establishing aircraft energy needs and energy storage system characteristics. The development of a rapid conceptual development capability suitable for generating aircraft concepts (RapCDE) was augmented by ÆNodes funding, and some of the individual elements were developed and published over the ÆNodes execution period. The NASA team hopes to publish both the RapCDE approach and improved RAM aircraft concepts as they are able.

The aircraft and demand modeling associated with hydrogen-fueled aircraft was eliminated from ÆNodes due to challenges with modeling and source data within the resources available to the ÆNodes team, though work on these items may grow from the scheduled demand model and RapCDE publications. The NASA team was able to continue work on material properties suitable for lightweight cryogenic hydrogen tanks for aircraft and was able to canvass industry and academia regarding gaps and needs in cryogenic hydrogen system testing. This information will be used to inform NASA investments in such testing and development capability.

The ÆNodes team developed a test plan and identified public test articles for characterization of the charging behavior for a battery representative of those used in AAM vehicles. This included testing in different thermal environments and at different charge rates. Though this effort was terminated early due to loss of critical personnel, public data on AAM battery charge characterization is a necessary but missing piece of information for future airport infrastructure planning. As time, funding, and personnel skillsets align, the team hopes to be able to revive charge curve characterization efforts within NASA.

References

1. "Airport Data and Information Portal," U.S. Department of Transportation, Federal Aviation Administration, https://adip.faa.gov/agis/public/#/public, accessed Sept. 2022.
2. "Part 139 – Certification of Airports," 14 CFR §139, https://www.ecfr.gov/current/title-14/chapter-I/subchapter-G/part-139, accessed April 2023.
3. "Part 139 Airports," U.S. Department of Transportation, Bureau of Transportation Statistics, https://www.bts.gov/part-139-airports, accessed Sept. 2022.
4. "Passenger Boarding (Enplanement) and All-Cargo Data for U.S. Airports – Previous Years, U. S. Department of Transportation, https://www.faa.gov/airports/planning_capacity/passenger_allcargo_stats/passenger/, accessed Oct. 2022.
5. Borer, N., Blaesser, N., Patterson, M., "Regulatory Considerations for Future Regional Air Mobility Aircraft," AIAA-2023-3294, AIAA AVIATION 2023 Forum, San Diego, CA, June 2023. Publicly available at https://ntrs.nasa.gov/citations/20230006666.
6. "Formulation of the NPIAS and ACIP," Order Number 5090.5, U.S. Department of Transportation, Federal Aviation Administration, Sept. 2019.
7. "National Plan of Integrated Airport Systems (NPIAS) 2025-2029," U.S Department of Transportation, Federal Aviation Administration, 2024.
8. "Jet fuel consumption, price, and expenditure estimates, 2023," U.S. Energy Information Administration, https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=C400000001&f=A, accessed Sept. 2025.
9. "U.S. Aviation Gasoline All Sales/Deliveries by Prime Supplier," U.S. Energy Information Administration, https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=C400000001&f=A, accessed Sept. 2025.
10. Christensen, Clayton M., *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*, Harvard Business Review Press, Boston, MA, 1997.
11. "Electric Pioneer," Pipistrel, https://www.pipistrel-aircraft.com/products/velis-electro/, accessed Sept. 2025.
12. "eFlyer Aircraft," Bye Aerospace, https://byeaerospace.com/eflyer-aircraft/, accessed Sept. 2025.
13. "eDA40 All-Electric Aircraft," Diamond Aircraft, https://www.diamondaircraft.com/en/flight-school-solution/aircraft/eda40/overview/, accessed Sept. 2025.
14. "CAE launches Electric Aircraft Modification Program with Piper Aircraft Inc.," CAE, https://www.cae.com/media-centre/press-releases/cae-launches-electric-aircraft-modification-program-with-piper-aircraft-inc/, accessed Sept. 2023.
15. Garrow, L., German, B., Schwab, N., Patterson, M., Mendonca, N., Gawdiak, Y., Murphy, J. "A Proposed Taxonomy for Advanced Air Mobility," AIAA-2022-3321, AIAA AVIATION 2022 Forum, Chicago, IL, June 2022. Publicly available at https://ntrs.nasa.gov/citations/20220006225.
16. "FAA Reauthorization Act of 2024," H.R. 3935, 118th Congress, 2024, https://www.congress.gov/bill/118th-congress/house-bill/3935, accessed Sept. 2025.
17. Holden, J., Goel, N., "Uber Elevate: Fast-Forwarding to a Future of On-Demand Urban Air Transportation," Uber Technologies, October 2016.
18. Denham, Casey L., Cummings, William G., "Air Traffic Management Response to Vertiport Closure," International Air Transportation Research & Development Symposium 11th International Conference, Singapore, July 2024. Publicly available at https://ntrs.nasa.gov/citations/20240005452.
19. "Electric Aerial Ridesharing," Joby Aviation, https://www.jobyaviation.com/, accessed Sept. 2025.
20. "Air Travel Reimagined," Archer, https://archer.com/aircraft, accessed Sept. 2025.
21. "Alaka'i Technologies: Hydrogen Powered Aircraft," Alaka'i Technologies, https://www.alakai.com/, accessed Sept. 2025.
22. Blekhman, David, "Hydrogen Robinson Helicopter On The Bleeding Edge Of Organ Delivery," Forbes, https://www.forbes.com/sites/davidblekhman/2025/05/06/hydrogen--robinson-helicopter-on-the-bleeding-edge-of-organ-delivery/, accessed Sept. 2025.
23. Antcliff, K. et al., "Regional Air Mobility: Leverage Our National Investments to Energize the American Travel Experience," NASA Langley Research Center, April 2021, https://ntrs.nasa.gov/citations/20210014033.
24. Ridel, R., Kloss, B., "Right in your Backyard: Regional airports are an accessible and underused resource for future air mobility," McKinsey & Company, Future of Mobility blog, May 2021, https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/future-air-mobility-blog/right-in-

your-backyard-regional-airports-are-an-accessible-and-underused-resource-for-future-air-mobility, accessed Oct. 2022.

25. "Going Electric," Harbour Air, https://harbourair.com/going-electric/?tab=Specification, accessed Sept. 2025.
26. "Commercial Flight. 100% Electric." Væridion, https://vaeridion.com/, accessed Sept. 2025.
27. "Hybrid-Electric Aircraft," Ampaire, https://www.ampaire.com/, accessed Sept. 2025.
28. "Pioneering Direct Aviation," Electra, https://www.electra.aero/, accessed Sept. 2025.
29. "The Clean Future of Flight," ZeroAvia, https://zeroavia.com/, accessed Sept. 2025.
30. "Introducing Pelican 2," Pkya, https://www.flypyka.com/pelican-2, accessed Sept. 2025.
31. "Boeing Next-Generation 737," Boeing, https://www.boeing.com/commercial/737ng, accessed Sept. 2025.
32. "Airbus A320," Airbus, https://www.airbus.com/en/products-services/commercial-aircraft/passenger-aircraft/a320-family, accessed Sept. 2025.
33. "Boeing 777," Boeing, https://www.boeing.com/commercial/777, accessed Sept. 2025.
34. "Airbus A350," Airbus, https://www.airbus.com/en/products-services/commercial-aircraft/passenger-aircraft/a350-family, accessed Sept. 2025.
35. Borer, N. et al., "Overcoming the Adoption Barrier to Electric Flight," AIAA-2016-1022, AIAA SciTech 2016, San Diego, CA, January 2016. Publicly available at https://ntrs.nasa.gov/citations/20160010795.
36. Hileman, J., "Environment & Energy Research & Development Portfolio Overview," Research, Engineering, and Development Advisory Committee Meeting, Federal Aviation Administration, October 2022.
37. "Leading the charge in emission-free air travel," Elysian, https://www.elysianaircraft.com/, accessed Sept. 2025.
38. Quinlan, J., Hendricks, E., Madavan, N., "Advanced Aircraft Concepts for Environmental Sustainability (AACES) 2050: Overview," National Aeronautics and Space Administration, Washington, D.C., Nov. 2025. Publicly available at https://ntrs.nasa.gov/citations/20240014374.
39. "The Wright Spirit," Wright Electric, https://www.weflywright.com/aircraft, accessed Sept. 2025.
40. Justin, C., Payan, A., Mavris, D., "Integrated fleet assignment and scheduling for environmentally friendly electrified regional air mobility," *Transportation Research Part C: Emerging Technologies*, vol. 138, May 2022.
41. Cox, J., Harris, T., Krah, K., Morris, J., Li, X., Cary, S., "Impacts of Regional Air Mobility and Electrified Aircraft on Airport Electricity Infrastructure and Demand," NREL/TP-5R00-84176, National Renewable Energy Laboratory, Golden, CO, Feb. 2023.
42. Borer, N., "Catalyzing Disruptive Mobility Opportunities through Transformational Aviation Power," AIAA-3356, AIAA AVIATION 2018 Forum, Atlanta, GA, June 2018. Publicly available at https://ntrs.nasa.gov/citations/20190033417.
43. "Impact of Electric Vehicles on the Grid," U.S. Department of Energy, June 2024. Publicly available at https://www.energy.gov/sites/default/files/2024-10/Congressional%20Report%20EV%20Grid%20Impacts.pdf, accessed Sept. 2025.
44. Ennes, J., "Big Tech, power grids take action to reign in surging demand," Reuters, https://www.reuters.com/business/energy/big-tech-power-grids-take-action-reign-surging-demand-2025-08-18/, accessed Sept. 2025.
45. "Public Safety Power Shutoff Program," City of Riverside Public Utilities, https://riversideca.gov/utilities/residents/our-energy/public-safety-power-shutoff-program, accessed Sept. 2025.
46. Solanki, B. et al., "Federal Aviation Administration Vertiport Electrical Infrastructure Study," NREL/TP-5R00-86245, National Renewable Energy Laboratory, Golden, CO, December 2023.
47. "Wisdom to guide mobility transformations at U.S. Ports," U.S. Department of Energy, https://www.athena-mobility.org/, accessed Sept. 2025.
48. Morris, J., Rathod, B., Kim, A., Robby, K., Harris, T., Grue, N., Cary, S., "Colorado Alternatively Powered Aircraft Airport Infrastructure Study," NREL/TP-5R00-9144, National Renewable Energy Laboratory, Golden, CO, July 2025.
49. Torres, J. "Electrical and Hydrogen Infrastructure Considerations," Airport Safety & Standards National Consultant Workshop, Federal Aviation Administration, August 2024.
50. Siemaszko, C., "Volunteer pilots are flying supplies to trapped Hurricane Helene victims," NBC News, Oct. 2024, https://www.nbcnews.com/news/us-news/volunteer-pilots-are-flying-supplies-trapped-hurricane-helene-victims-rcna173885, accessed Sept. 2025.

51. Walsh, A., “GA Airports: Cal Fire’s Greatest Arsenal,” Aircraft Owner’s and Pilot’s Association, August 2020, https://www.aopa.org/news-and-media/all-news/2020/august/27/ga-airports-cal-fires-greatest-arsenal, accessed Sept. 2025.
52. Borer, N., “What’s Next in Regional (Air) Mobility? Finding the next possible big ideas in selected problems,” ARMD Systems Analysis Symposium, National Aeronautics and Space Administration, Hampton, VA, October 2022. Publicly available at https://ntrs.nasa.gov/citations/20220016262.
53. Dryer, J., “NASA Aeronautics – Strategy and Portfolio Planning,” Research, Engineering, and Development Advisory Committee Meeting, Federal Aviation Administration, August 2014.
54. “NASA Aeronautics Strategic Implementation Plan 2023,” National Aeronautics and Space Administration, https://www.nasa.gov/directorates/armd/armd-strategic-implementation-plan/, accessed Sept. 2025.
55. “NASA Convergent Aeronautics Solutions (CAS) Overview,” National Aeronautics and Space Administration, https://www.nasa.gov/directorates/armd/tacp/nasa-convergent-aeronautics-solutions-cas-overview/, accessed Sept. 2025.
56. Papathakis, K., “CAS Wicked Works,” AIAA AVIATION 2021 Forum, virtual, August 2021. Publicly available at https://ntrs.nasa.gov/citations/20210019246.
57. Goodrich, K. H., Theodore, C. R., “Description of the NASA Urban Air Mobility Maturity Level (UML) Scale,” AIAA-2021-1627, AIAA SciTech 2021 Forum, virtual, January 2021. Publicly available at https://ntrs.nasa.gov/citations/20205010189.
58. Clarke, S., DeMattia, B., Patterson, M., Bomarito, G., “Opportunity Concept Report: Airports and Aircraft as Energy Nodes,” CAS Roundtable Discussion for Energy for AAM at Scale, National Aeronautics and Space Administration, Oct. 2021. *Internal NASA paper that is not in the public domain at the time of this publication.*
59. “Fiscal Year 2026 Budget Request,” National Aeronautics and Space Administration, May 2025, https://www.nasa.gov/fy-2026-budget-request/, accessed Sept. 2025.
60. “National Association of State Aviation Officials,” https://nasao.org/, accessed Sept. 2025.
61. Walsh, R., “Assessing the Electrification of Aviation’s Impact on the Airport and Airway Trust Fund,” NASA-CR-20250001574, METIS Technology Solutions, February 2025. Publicly available at https://ntrs.nasa.gov/citations/20250001574.
62. Walsh, R., “Regional Air Mobility: Infrastructure Challenges, Passenger and Cargo Market Potential, and Sustainability Strategies for Underserved Airports,” NASA-CR-20250002542, METIS Technology Solutions, March 2025. Publicly available at https://ntrs.nasa.gov/citations/20250002542.
63. Thurber, M, “Regional Air Mobility Summit Addresses Rebooting Local Air Transportation,” Aviation International News, https://www.ainonline.com/aviation-news/futureflight/2025-04-02/regional-air-mobility-summit-rebooting-local-air, accessed Sept. 2025.
64. “Innovation in Action: Empowering Airports and Partners Together,” https://aaae.org/act, accessed Sept. 2025.
65. “Sherlock Data Warehouse,” National Aeronautics and Space Administration, https://www.nasa.gov/ames/aviationsystems/sherlock-data-warehouse/, accessed Sept. 2025.
66. “Aeronautical Information Manual,” U.S. Department of Transportation, Federal Aviation Administration, Feb. 2025.
67. “General definitions,” 14 CFR §1.1, https://www.ecfr.gov/current/title-14/chapter-I/subchapter-A/part-1/section-1.1, accessed Sept. 2025.
68. “Part 135 – Operating Requirements: Commuter and On Demand Operations and Rules Governing Persons On Board Such Aircraft,” 14 CFR §135, https://www.ecfr.gov/current/title-14/part-135, accessed Sept. 2025.
69. “Helicopter Route Charts,” U.S. Department of Transportation, Federal Aviation Administration, https://www.faa.gov/air_traffic/flight_info/aeronav/productcatalog/vfrcharts/helicopter/, accessed Sept. 2025.
70. Rimjha, M., Li, M., Hinze, N., Tarafdar, S., Hotle, S., Swingle, H., Trani, A., Smith, J. “Demand Forecast Model Development and Scenarios Generation for Urban Air Mobility Concepts,” NASA CR-20205005881, Virginia Tech Air Transportation System Laboratory, April 2020. Publicly available at https://ntrs.nasa.gov/citations/20205005881.
71. “Aircraft Type Designators,” Air Traffic Organization Policy Order JO 7360.1J, U.S. Department of Transportation, Federal Aviation Administration, April 2024.
72. Silva, C., Johnson, W., Solis, E., Patterson, M., Antcliff, K., “VTOL Urban Air Mobility Concept Vehicles for Technology Development,” AIAA-2018-3847, 2018 Aviation Technology, Integration, and Operations Conference, Atlanta, GA, June 2018. Publicly available at https://ntrs.nasa.gov/citations/20180006683.

73. Hallock, T., Michal, B, “A Parametric Battery Model for the Conceptual Design of Electric Aircraft,” AIAA-2024-3902, AIAA AVIATION Forum 2024, Las Vegas, NV. Publicly available at https://ntrs.nasa.gov/citations/20240007599.
74. Abraham, T., Denham, C., “Flight Dynamics Modeling for a Rapid Conceptual Development Environment,” AIAA-2024-4051, AIAA AVIATION Forum 2024, Las Vegas, NV. Publicly available at https://ntrs.nasa.gov/citations/20240007153.
75. Martinez Rodriguez, G., Blaesser, N., Borer, N., “Sensitivity Analysis for Takeoff and Landing Distance Parameters for Regional Air Mobility (RAM) Aircraft,” AIAA-2024-3916, AIAA AVIATION Forum 2024, Las Vegas, NV. Publicly available at https://ntrs.nasa.gov/citations/20240007499.
76. “Advanced Research on Integrated Energy Systems,” National Renewable Energy Laboratory, https://www.nrel.gov/aries, accessed Sept. 2025.
77. Clarke, S., Terry, J., Harris, K., Avanesian, D., “X-57 Traction Power and Command Systems Development,” 34th Congress of the International Council of the Aeronautical Sciences, Florence, Italy, September 2024. Publicly available at https://ntrs.nasa.gov/citations/20240009560.
78. Lvovich, V. F. et al., “Commercially-viable Hydrogen Aircraft for Reduction of Greenhouse Emissions,” 26th International Society for Air Breathing Engines Conference, Toulouse, France, September 2024. Publicly available at https://ntrs.nasa.gov/citations/20240007956.
79. Bednarcyk, B. A., Hearley, B. L., Pineda, E. J., “Multiscale Modeling of Thermoplastic Matrix Composites for Cryogenic Hydrogen Storage Applications,” submitted to MDPI Modelling, Sept. 2025.
80. “Development for Test Facility in Advancing Hydrogen Technology Development for Aeronautic Applications,” Notice 80GRC025RFI0001, National Aeronautics and Space Administration, Jan. 2025.
81. Lvovich, V. F., Johnson, W. L., Vivod, S. L., “Cryogenic Hydrogen Studies and Testing for Advanced Aircraft at NASA,” VFS 4th Annual H2-Aero Symposium, Long Beach, CA, April 2025. Publicly available at https://ntrs.nasa.gov/citations/20250002550.