DEPARTMENT OF TRANSPORTATION
AERONAUTICS

# MINNESOTA ELECTRIC AVIATION NETWORK

# M.E.A.N.

# STUDY

TECHNICAL REPORT

AUGUST 2025

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Project leadership contact information:

**Joseph Block**
Advanced Air Mobility Program Manager
MnDOT Aeronautics
651.392.3920
joseph.block@state.mn.us

**Rylan Juran**
Aviation Planning Director
MnDOT Aeronautics
651.234.7190
rylan.juran@state.mn.us

Prepared with support from:

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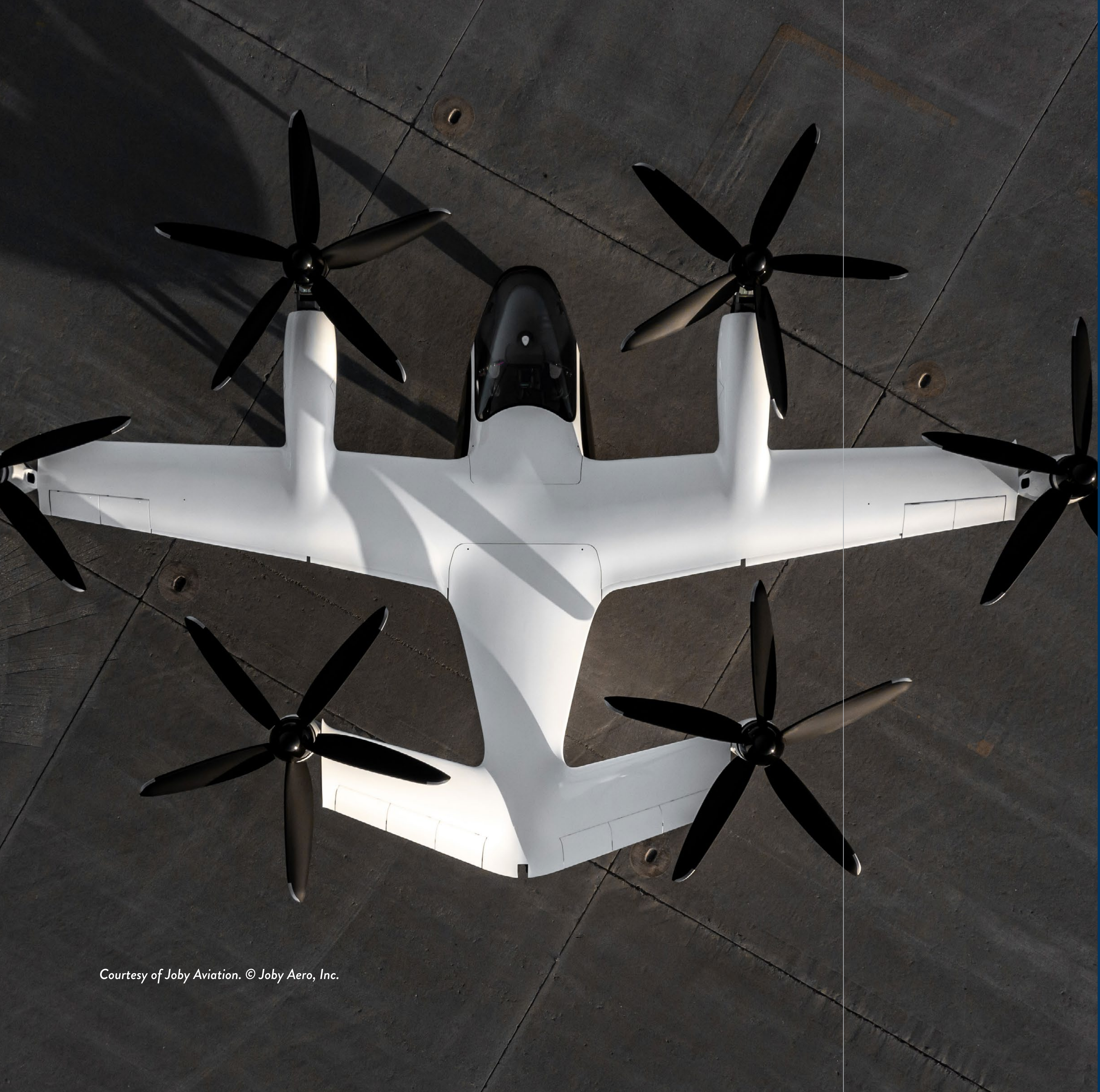

Courtesy of Joby Aviation. © Joby Aero, Inc.

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*Minneapolis Flying Cloud Airport*

*Section 1*

# CONTEXT AND FRAMEWORK

## TOPICS

- INTRODUCTION
- ELECTRIC AVIATION OVERVIEW
- MEAN STUDY APPROACH
- STAKEHOLDER ENGAGEMENT

## 1.1 INTRODUCTION

Minnesota's aviation system is a pillar of the state's transportation infrastructure and economic vitality. With 132 public-use airports—including nine commercial service and 123 general aviation (GA) facilities—aviation in Minnesota connects communities, supports industries, and enables critical services to operate swiftly and efficiently. As the aviation industry undergoes a transformative shift toward sustainability and innovation, MnDOT Aeronautics is taking proactive steps to ensure Minnesota remains at the forefront of this evolution.

## WHY THE MEAN STUDY?

**The study aims to initiate stakeholder dialog, identify viable opportunities, and lay the groundwork for a more sustainable aviation future.**

The rise of electric aviation technologies presents exciting opportunities and complex challenges. Manufacturers around the world are developing electric fixed-wing and electric vertical takeoff and landing (eVTOL) aircraft in an effort to reduce emissions, lower operating costs, and expand access to air transportation. Collectively, these technologies are often referred to as advanced air mobility (AAM). While the potential of these technologies is promising, their successful integration into existing aviation systems requires deliberate planning, infrastructure readiness, and broad stakeholder collaboration.

In alignment with its vision for a multimodal transportation system that promotes the health of people, the environment, and the economy, MnDOT launched the Minnesota Electric Aviation Network (MEAN) Study. This strategic initiative explores how electric aviation can be integrated into Minnesota's existing airport network.

The MEAN Study represents a foundational step in preparing Minnesota for a sustainable aviation future. **It seeks to identify a network of airports across the state (the MEAN) that are well positioned to support electric aircraft operations within the next decade, helping MnDOT and its partners determine where electric aviation can be most effectively deployed and what resources are required to support its growth.** Conducted in close collaboration with stakeholders from across the aviation ecosystem, the MEAN Study emphasizes an approach that is informed, inclusive, and forward looking. Ultimately, it will provide a practical framework to guide future decisions related to infrastructure development, policy, and investment.

## WHY MINNESOTA?

Minnesota is uniquely positioned to lead the nation in sustainable aviation, thanks to its forward-thinking policies, robust transportation infrastructure, and commitment to innovation. MnDOT is actively advancing sustainable aviation through strategic planning, investment, and collaboration with industry leaders, academic institutions, and local communities.

With one of the most comprehensive and well-connected intermodal transportation systems in the country, Minnesota offers a powerful platform to integrate electric aviation technologies to urban and rural settings.

By leveraging Minnesota's strengths in advanced manufacturing, renewable energy, healthcare, and logistics, the MEAN Study aims to identify innovative opportunities that will drive economic growth over the next decade. This includes exploring new business models and infrastructure. Ultimately, this study will establish a solid foundation for future policy decisions, ensuring that Minnesota remains at the forefront of aviation innovation while delivering long-term environmental and economic benefits for all Minnesotans.

This initiative supports MnDOT's broader mission to foster a cleaner, more efficient, and resilient transportation network



*Courtesy of BETA Technologies*

## LEADING WITH PRAGMATISM

MnDOT recognizes the inherent complexities and uncertainties surrounding the emerging electric aviation industry. In response, the MEAN Study adopts a pragmatic approach to planning—one that balances visionary thinking with practical application. While innovation is essential to drive progress, the study does not advocate for specific technologies or call for immediate infrastructure investments.

Rather, the MEAN Study prioritizes feasibility over futurism. Its goal is to develop a roadmap that is both forward looking and actionable—guiding near-term planning decisions while remaining adaptable to future technological and regulatory developments. By focusing on genuine opportunities, practical limitations, real-world constraints, and stakeholder needs, the study aims to support the thoughtful advancement of sustainable aviation in Minnesota and the broader Upper Midwest.

## 1.2 ELECTRIC AVIATION OVERVIEW

Electric aviation refers to the use of electric propulsion systems—powered by batteries, fuel cells, or hybrid configurations—to replace or supplement traditional petroleum-based aircraft propulsion systems. This emerging field spans a wide range of aircraft types, from small eVTOL vehicles to larger fixed-wing aircraft. These technologies offer the potential for quieter, cleaner, and more efficient alternatives to conventional flight, with applications across both urban and regional transportation networks. As advancements in energy storage, electronics, and lightweight materials continue to accelerate, electric aviation may reshape the future of air travel.

### ELECTRIC AVIATION WITHIN THE CONTEXT OF THE MEAN STUDY

While AAM encompasses a broad range of technologies and use cases, the MEAN Study is specifically focused on aircraft with the following four characteristics:

1. **Transport people or goods**
2. **Electric or hybrid-electric propulsion**
3. **Maximum takeoff weight of over 300 lbs. (excludes sUAS of < 55 pounds)**
4. **Conventional (CTOL), short (STOL), and vertical (VTOL) takeoff and landing capabilities**

### ELECTRIC AVIATION USE CASES

Electric aircraft have the potential to supplement a wide range of aviation applications, each offering unique benefits in terms of cost savings, environmental impact, and operational efficiency. The following are examples of the most promising emerging use cases and how electric aviation might enhance each one.

#### PILOT TRAINING

Pilot training is a foundational element of the aviation industry, requiring both theoretical and practical instruction. Flight schools—typically based at GA airports—often contribute significantly to airport revenue through facility rentals, fuel purchases, and other operational expenses. Training requirements vary by certification, ranging from 40 hours of practical instruction for a Private Pilot Certificate, to 1,500 hours for an unrestricted Airline Transport Pilot certificate.

Electric aircraft offer a cost-effective alternative for flight training. With lower energy costs (compared to fuel) and reduced maintenance needs, electric propulsion may significantly lower the overall cost of training. This makes learning how to fly more accessible to more people, while also introducing students to emerging technologies that are shaping the future of aviation.



#### SHORT-HAUL CARGO TRANSPORTATION

The rise of e-commerce and demand for rapid delivery have fueled growth in short-haul cargo transportation, typically covering distances under 300 miles. These operations are characterized by frequent, time-sensitive deliveries that are essential to logistics networks. Electric aircraft are particularly well suited for this role. With lower operating costs and reduced environmental impact, they offer a sustainable alternative to conventional cargo aircraft. Electric aircraft can efficiently move goods between major airport hubs and smaller regional distribution centers, helping logistics providers reduce emissions and lower overall costs.

#### MEDICAL TRANSPORTATION

Medical transportation involves the rapid movement of medical personnel, supplies, and patients. Services traditionally rely on ground vehicles, helicopters, and fixed wing aircraft to respond to medical emergencies. Electric aircraft can enhance medical transport, enabling swift response and deployment with minimal delay. Unlike traditional propulsion systems, electric models eliminate the need for a run-up. Advanced battery technology allows pilots to initiate startup, complete preflight checks, and launch promptly.

#### PASSENGER TRANSPORTATION

Electric aviation holds promise for both urban and regional passenger travel. Electric aircraft may serve as alternatives to cars, trains, and short-haul flights. By reducing travel time and emissions, electric passenger aircraft can improve regional connectivity and offer more sustainable travel options. This use case is especially relevant for areas with limited public transit or for routes that are underserved by current transportation options.

#### AGRICULTURE

Aerial agricultural services—such as crop spraying and field inspection—are typically performed using traditional fixed-wing aircraft, helicopters, and drones. While effective, these methods contribute to high operational costs and carbon emissions. Electric aircraft reduce operational dependence on refueling infrastructure and offer responsive power management, which can improve maneuverability in tight crop zones or sudden weather shifts near the ground. As electric aviation technology matures, its role in agriculture is expected to grow.

#### RECREATIONAL FLYING

Recreational aviation includes flying for leisure using small aircraft, gliders, and ultralights. While popular, this activity can be expensive due to fuel and aircraft maintenance costs. Electric aircraft are likely to make recreational flying more affordable and environmentally friendly. Lower operating costs and quieter engines may also attract new hobbyists, particularly those interested in sustainable technologies and innovation.

## BENEFITS OF ELECTRIC AVIATION

### ENVIRONMENTAL AND SUSTAINABILITY BENEFITS

Traditional aircraft engines burn petroleum, releasing carbon dioxide ($CO_2$) and other pollutants directly into the atmosphere. For example, aircraft that use 100LL fuel produce lead emissions. Lead is a neurotoxin that is harmful to humans and can pose risks when emitted over communities on the ground. Electric and hybrid-electric aircraft offer a cleaner alternative, producing zero or substantially fewer greenhouse gas emissions. By reducing aviation's environmental footprint, these technologies play a critical role in advancing Minnesota's global sustainability goals and supporting healthier communities.

### NOISE REDUCTION

Aircraft noise is a major concern for people and communities located near airports and under flight paths. Conventional engines generate high levels of noise, which can negatively impact quality of life and limit aircraft operational flexibility. In contrast, electric motors operate much more quietly. This reduction in noise not only improves the experience for nearby residents but also enables more flexible flight operations—particularly in urban areas where noise restrictions have historically constrained aviation activity.

### ECONOMIC OPPORTUNITY

Electric aviation presents an opportunity to revitalize and better utilize regional and local airports, many of which are underused despite their potential as local economic drivers. Electric and hybrid-electric aircraft, with their ability to takeoff and land vertically or from shorter runways, are well suited for these airports. By positioning regional airports as hubs for sustainable air mobility, communities can benefit from increased connectivity, reduced congestion at major airports, and enhanced access to short-distance travel options. This shift has the potential to stimulate local economies and support broader regional development.

### REDUCED OPERATIONAL EXPENSES

Operating conventional aircraft involves high costs related to fuel and maintenance requirements. Electric propulsion systems offer a more efficient alternative, with lower energy costs and reduced maintenance needs due to fewer moving parts within the engine. These efficiencies have the potential to lower the total cost of aircraft ownership and operation.

*Image Courtesy of BETA Technologies*



## AIRCRAFT TECHNOLOGY AND INFRASTRUCTURE

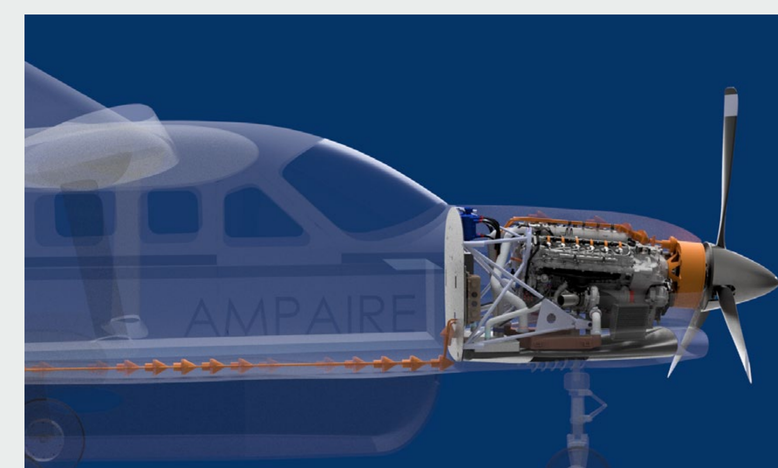
Original Equipment Manufacturers (OEMs) are companies that design and manufacturer the original components or products used in electric aviation, including aircraft, charging systems, and other supporting infrastructure. OEMs play a leading role in the advancement of electric aviation, driving innovation through the development of next-generation aircraft, electric propulsion systems, and the supporting infrastructure necessary for widespread adoption. As the aviation industry transitions toward more sustainable and energy-efficient technologies, OEMs are not only reimagining aircraft design but also addressing the complex ecosystem required to support electric flight. This section provides a brief, high-level overview of the core components and operational requirements of electric aviation, including electric propulsion technologies, aircraft battery systems, charging infrastructure, and the integration of these systems with existing electrical grids. Additional details on electric aviation technologies—including electric aircraft propulsion systems, charging standards, and emerging innovations—can be found in **Appendix B**.

### ELECTRIC AIRCRAFT PROPULSION

Electric aviation includes a diverse range of aircraft and propulsion technologies that utilize electric power instead of traditional petroleum-based fossil fuel engines. The primary types of electric propulsion systems include:

- **Battery electric:** Relies entirely on onboard batteries to supply power to electric motors, offering zero-emission flight.
- **Series hybrid electric:** Uses a reciprocating engine to generate electricity, which then powers electric motors for propulsion.
- **Fuel cell electric:** Converts hydrogen into electricity through a fuel cell system, which then powers electric motors.

Each propulsion type presents unique advantages and challenges in terms of energy efficiency, range, weight, and infrastructure requirements. See **Appendix B** for additional information on electric propulsion and support technologies.




*Depiction of a Series Hybrid Electric engine, courtesy of Ampaire Inc.*

### AIRCRAFT BATTERIES AND CHARGERS

Chargers are essential components in the operation of electric aircraft, serving the critical function of delivering power to onboard batteries. Battery capacity and charging capabilities vary by aircraft model. Importantly, charging performance is not solely determined by a charger's maximum output; each aircraft battery also has defined limits for how quickly it can accept a charge. These limits typically include a maximum rate for alternating current (AC) charging—constrained by the aircraft's onboard inverter—and a maximum rate for direct current (DC) charging, which is governed by the design of the aircraft's battery and electrical system.

Charging stations are categorized by levels which indicate the rate at which they can deliver power. The three primary types are Level 1, Level 2, and DC Fast Charging (DCFC, often referred to as "Level 3").

#### LEVEL 1:

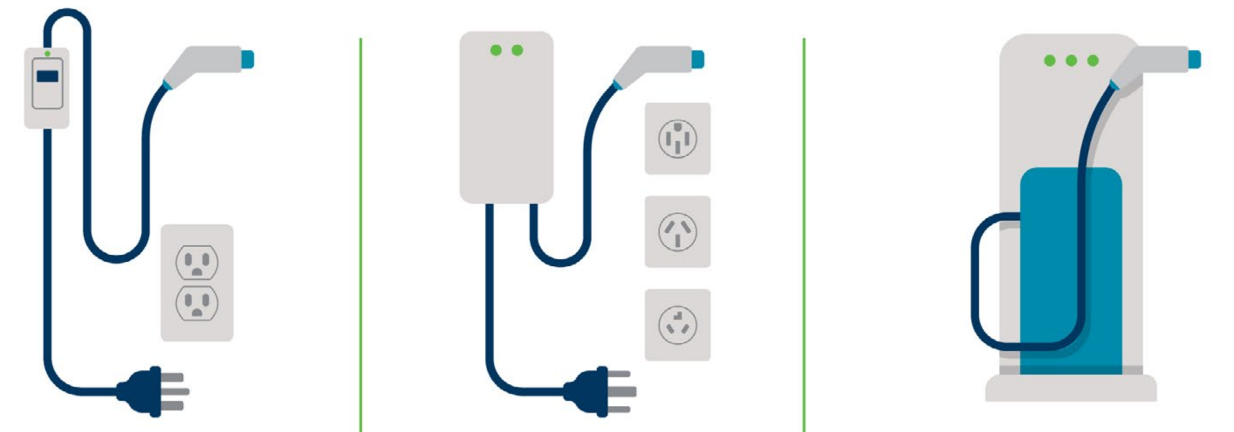
Utilizes a standard 120-volt outlet, similar to a household power socket. With a power output of approximately 1 kilowatt (kW), Level 1 chargers offer the slowest charging speeds—typically suitable for overnight charging of electric vehicles (EVs)—and are generally considered inadequate for charging electric aircraft.

#### LEVEL 2:

Operates on a 240-volt outlet with a power output of approximately 20 kW, significantly increasing charging speeds depending on the specific aircraft and charger used. These chargers are often equipped with monitoring and management capabilities. They are generally considered sufficient to support overnight charging of electric aircraft.

#### DC FAST CHARGING:

The fastest and most power-intensive charging option, utilizing DC to charge batteries more efficiently than other charging solutions. These chargers typically feature advanced monitoring, diagnostics, and load management capabilities. DC Fast Charging is widely regarded as the preferred solution for electric aviation, as it delivers the high power and rapid turnaround necessary to efficiently recharge large aircraft batteries between flights.




*Courtesy of BETA Technologies*

Electric aircraft have unique charging requirements based on their design specifications. At the time of writing, OEM data indicates that peak DC Fast Charging power for electric aircraft can range from 300 kW to 1,000 kW, with battery capacities spanning from 130 kilowatt hours (kWh) to over 300 kWh. These high-capacity systems demand robust charging infrastructure and careful planning to ensure safe, efficient, and reliable operation. A more detailed discussion of required infrastructure can be found in **Section 2.3**.

## WHERE DO HYBRID-ELECTRIC AIRCRAFT FIT IN?

**Throughout the MEAN Study, many stakeholders expressed interest in the role and infrastructure requirements of hybrid-electric aircraft. Some OEMs are prioritizing a hybrid-electric approach. These aircraft, which combine internal combustion engines with electric propulsion systems, can operate independently of ground-based charging infrastructure—making them particularly well-suited for early-stage operations during infrastructure buildout. While the MEAN Study primarily focuses on identifying airports suitable for supporting battery electric aircraft charging systems, hybrid-electric aircraft still benefit from future charging infrastructure deployments, even if such systems are not immediately necessary for their operation.**

*Cook Municipal Airport*

## ELECTRICAL GRID CONSIDERATIONS

Supporting electric aircraft charging requires a robust and extensive infrastructure network capable of delivering high levels of electrical power. Electric service providers are typically responsible for operating and maintaining the electrical distribution system, which includes transformers, distribution wiring, and utility meters. At airports, electricity is supplied through the utility network and monitored via utility meters, then distributed through a series of on-site electrical panels. These panels supply power to the necessary equipment—such as chargers—required for aircraft charging.

Given the increased power demands associated with electric aircraft, existing power grids may require significant upgrades. These enhancements could include new or higher-capacity transformers, expansion of transmission and distribution lines to handle greater electrical loads, and increased generation capacity at power plants. Implementing such upgrades is often complex, involving long-term planning, coordination among stakeholders, and extensive construction efforts that may span several years. As a result, it is essential to identify and initiate necessary improvements as early as possible to ensure infrastructure readiness for electric aviation.

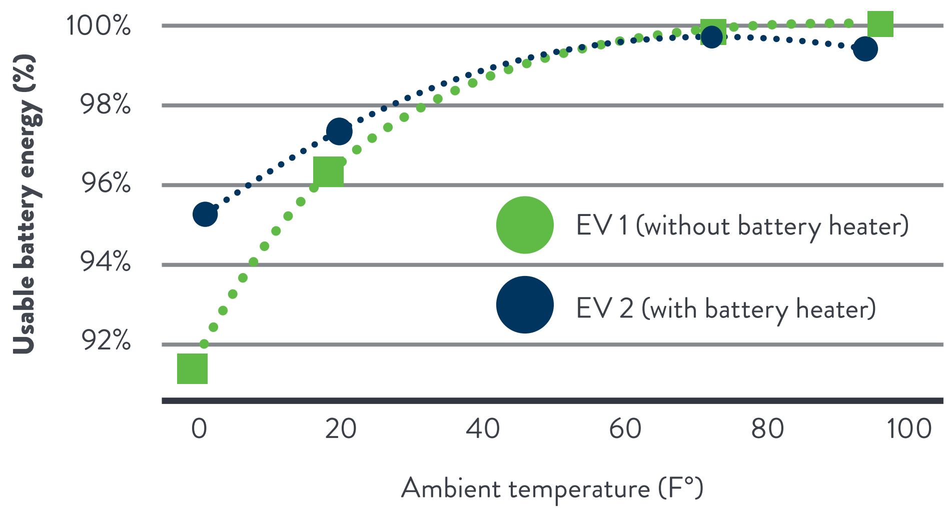
## COLD WEATHER CONSIDERATIONS

Cold weather presents several challenges for electric aircraft, particularly in relation to battery performance and overall energy efficiency. Low temperatures hinder the chemical reactions within batteries, reducing output voltage and available capacity. This results in diminished usable energy and, consequently, a noticeable decrease in aircraft range. For example, data indicates that electric vehicles (EV) can experience up to a 41% drop in efficiency at 20°F, compared to only a 10% reduction for internal combustion engine vehicles[1]. A significant portion of this loss stems from the energy demands of electric heating and cooling systems—such as heat pumps and radiant heaters—used for cabin heating, battery thermal management, and anti-icing functions.

To mitigate these cold weather effects, several strategies have been proposed. One effective approach is preheating the battery while the aircraft is connected to a hangar charger. This reduces the loss of battery capacity at startup. For example, as illustrated in **Figure 1**, an EV retained approximately 4% more battery capacity by preheating in 0°F conditions. Similarly, preheating the aircraft cabin while still connected to the power source can yield energy savings of up to 20%, as shown in **Figure 2**. Additionally, storing electric aircraft in a temperature-controlled environment, such as a heated aircraft hangar, can offer added protection and improve overall battery performance.

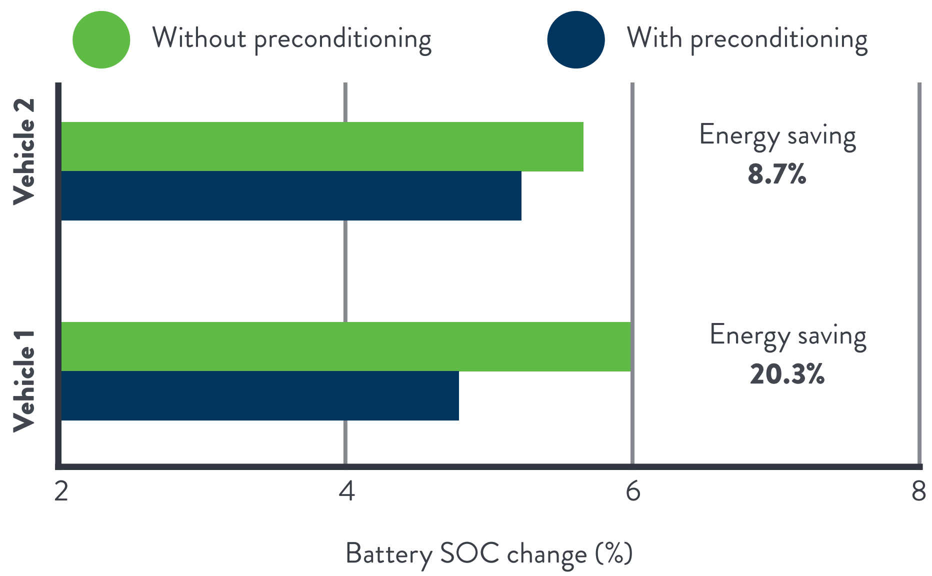
[1] *U.S. Department of Energy. (2024, September 12). Impact of cold ambient temperatures and extreme conditions on electric vehicles (Program Record).*

**Figure 1:** *Battery preheating impact on usable battery energy percentage*




*U.S. Department of Energy. (2024, September 12). Impact of cold ambient temperatures and extreme conditions on electric vehicles (Program Record).*

**Figure 2:** *Cabin preheating impact on battery state of charge (soc)*




*U.S. Department of Energy. (2024, September 12). Impact of cold ambient temperatures and extreme conditions on electric vehicles (Program Record).*


## 1.3 MEAN STUDY APPROACH

Developing an electric aviation network across Minnesota requires a system-level perspective—one that considers not only individual airports, but also the broader connectivity that emerges as a network of airports takes shape. Airports identified through this study as "electric aviation ready" will serve as nodes in the MEAN.

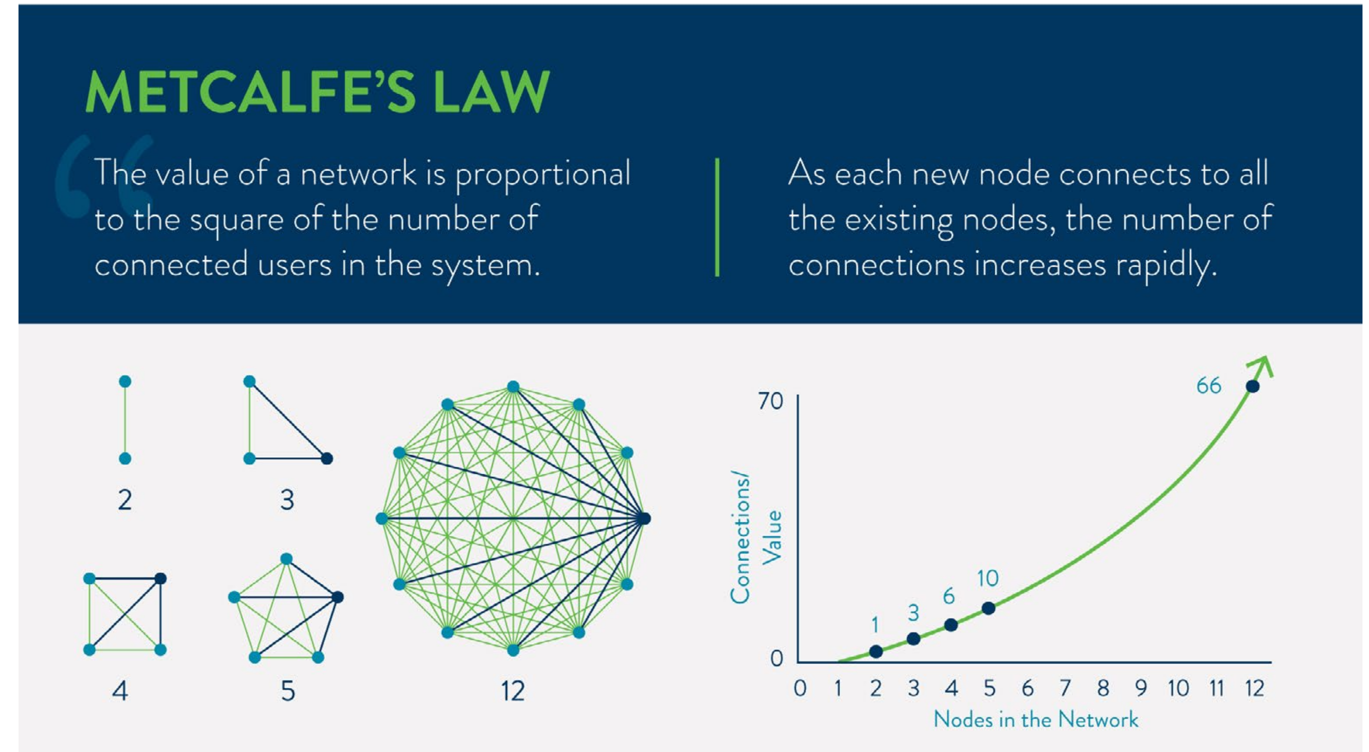
Metcalfe's Law offers a framework for understanding the exponential benefits of a well-integrated electric aviation network. The law states that the value of a network grows exponentially with each added node. In other words, every airport added to the network creates an outsized value for everyone connected to the network. Every airport added increasingly multiplies the number of potential direct connections, enhances route flexibility, operational redundancy, and economic vitality.

As illustrated in **Figure 3**, each additional airport added to the network greatly multiplies the number of potential direct connections. For instance, while a network of four airports enables six direct connections, expanding the network to 12 airports increases that number to 66. This exponential growth significantly enhances route flexibility, operational redundancy, and economic viability for future electric aircraft operators.

For MnDOT, this principle is essential in guiding early-stage infrastructure planning. Rather than focusing solely on high-traffic hubs, the greatest statewide value can be achieved by strategically selecting a diverse mix of initial nodes, including rural and regional airports, that collectively optimize network connectivity. This network-centric strategy also supports phased scalability, both within Minnesota and across state lines. By modeling how each airport contributes to the overall system value, infrastructure investments—such as charging stations, grid upgrades, and maintenance facilities—can be prioritized to accelerate network maturity and maximize long-term economic impact.

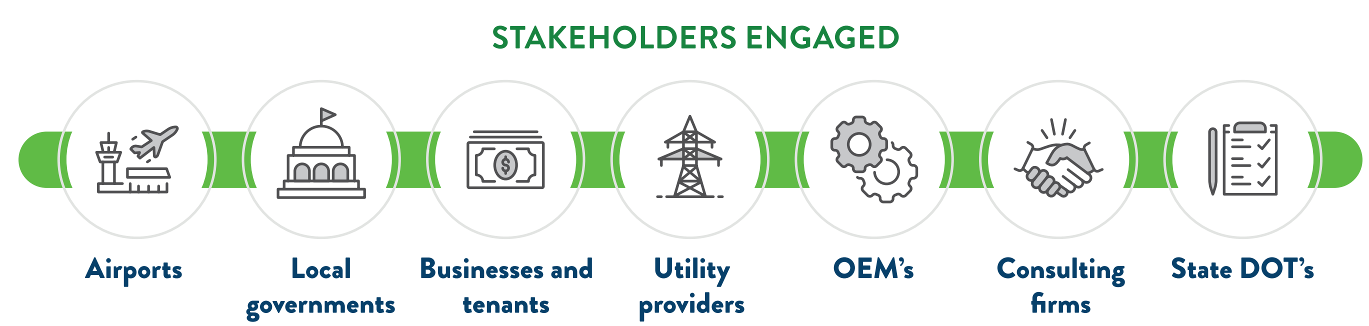
Given the rapidly evolving nature of electric aviation, the MEAN Study adopts a 10-year planning horizon. This timeframe balances the urgency of preparing for emerging technologies with industry uncertainties, including the absence of established regulatory frameworks, limited infrastructure funding mechanisms, evolving battery technologies, and the need for workforce preparedness. By focusing on the near term, the MEAN Study avoids overcommitting to speculative or unproven scenarios. Instead, it establishes a flexible foundation that can adapt as the industry matures, positioning Minnesota to respond decisively when electric aviation becomes commercially viable.

**Figure 3:** *Metcalfe's law*




## 1.4 STAKEHOLDER ENGAGEMENT

Stakeholder engagement is a foundational element of the MEAN Study. With the study's focus on emerging technologies and infrastructure needs, it is essential to incorporate the perspectives, insights, and concerns of those most likely to be impacted by or involved in electric aviation in Minnesota. Key stakeholders engaged include airport sponsors and staff, local governments, on-airport businesses and tenants, electricity providers, OEMs, consulting firms, neighboring state departments of transportation, and the Federal Aviation Administration.



## ENGAGEMENT OVERVIEW

Stakeholder input was instrumental in shaping the MEAN Study's evaluation criteria and overall approach. To promote transparency and encourage broad participation, the project team developed a centralized online resource on MnDOT's *Let's Talk Transportation* platform. This dedicated webpage served as the primary hub for project information and included an introductory video outlining the study's purpose and methodologies, regular updates on study progress, details about the stakeholder engagement process, and access to the airport inventory data collection survey.

To ensure a comprehensive and inclusive process, stakeholder engagement was conducted through multiple mechanisms listed below designed to capture a wide range of perspectives.

This multi-faceted approach ensured that the MEAN Study was informed by both technical expertise and real-world operational perspectives from those on the frontlines of electric aircraft development and aviation in Minnesota.

**Stakeholder engagement methods**

### MEAN SURVEY

Distributed electronically to airports, aviation businesses, consultants, and other relevant stakeholders to gather baseline data on infrastructure and interest in electric aviation.

### OEM COLLABORATIONS

Conducted with representatives from Minnesota airports and OEMs of electric aircraft, propulsion systems, and charging infrastructure.

### USE CASE EXPLORATION INTERVIEWS

Held with aviation business owners and other stakeholders to gather insights on operational needs, market readiness, and potential use cases.

### IN-PERSON WORKSHOPS

Six workshops were facilitated across the state to engage a broad cross-section of stakeholders and collect localized input.



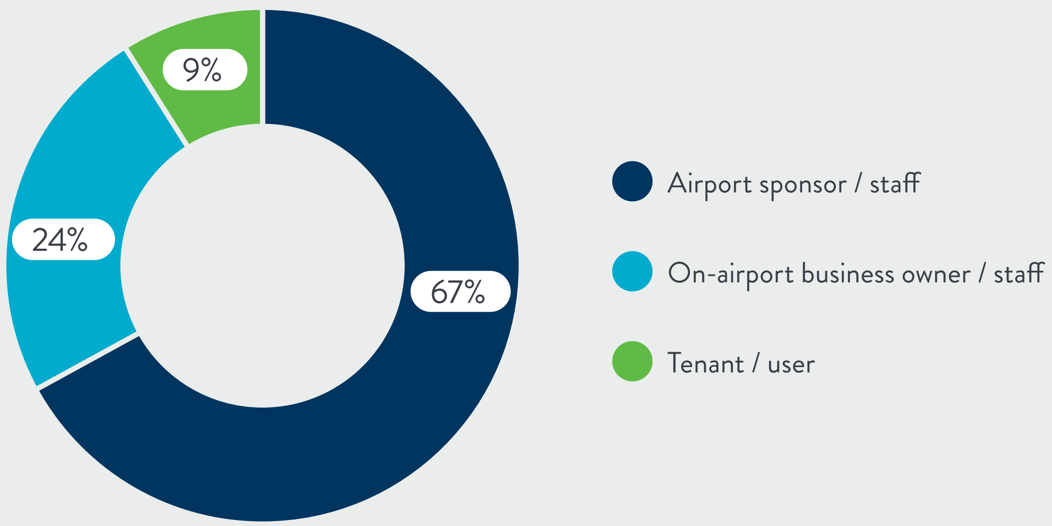

## STAKEHOLDER SURVEY

To support the MEAN Study's objectives, the project team developed and deployed an airport inventory survey as a foundational tool for collecting key data to inform the study's airport evaluations.

A wide range of stakeholders—including airport sponsors, tenants, and business users—contributed input on existing infrastructure and the potential for electric aviation integration across Minnesota's public-use airports. The survey was distributed electronically via email and hosted on the MEAN Study website to ensure broad accessibility. Follow-up phone calls were made, as needed, to clarify responses and complete missing sections. All data was compiled into a centralized database, which served as a core input for evaluating Minnesota airports.

A total of 110 stakeholders completed the survey, representing a diverse cross-section of Minnesota's aviation community, as shown in **Figure 4**. This broad participation ensured the MEAN Study reflects a comprehensive and representative view of electric aviation perspectives across the state.

**Figure 4:** *MEAN survey responses by relationship to airport*




The MEAN survey focused on two primary elements: existing airport infrastructure and stakeholder interest in electric aviation.

Topics related to airport infrastructure included:

- Electrical utility provider contact information
- Availability and specifications of heated aircraft hangars
- Aircraft Rescue and Firefighting (ARFF) facilities and mutual aid agreements
- On-site fuel services
- Terminal and fixed base operator (FBO) facilities

Topics related to electric aviation interest included:

- General interest in electric aircraft technologies
- Potential use cases and business models
- Opportunities for electric aviation integration at specific airports
- Ongoing and/or planned initiatives related to electric aviation and/or AAM

The data received from the MEAN survey were ultimately utilized as inputs into the MEAN evaluation of airports, as described in **Section 2** of this report. Survey responses related to electric aviation interest offered valuable insights that informed assessments of demand at individual airports. These insights were integral to the evaluation approach detailed in **Section 2.2**, helping to identify airports with the strongest business cases for electric aviation. Additionally, responses concerning airport infrastructure played a key role in analyzing each airport's physical readiness to support electric aviation operations in the near term. These inputs were central to the methodology outlined in **Section 2.3**.

## SUMMARY OF OEM FEEDBACK

As part of the MEAN Study's research efforts, the project team conducted a series of virtual meetings with OEMs involved in the development of electric aircraft and supporting infrastructure. These discussions were designed to gather insights into the current state and future of electric aviation, with a focus on certification timelines, operational use cases, charging infrastructure, climate adaptability, and market scalability.

The OEMs engaged represent a broad cross-section of the electric aviation ecosystem, including developers of fixed-wing aircraft, eVTOL aircraft, electric and hybrid-electric propulsion systems, and battery and charging technologies. MnDOT thanks the following OEMs for collaborating with the team during the development of the MEAN Study:

- **Electric Power Systems, Inc. (EPS)**
- **magniX Technologies Pty Ltd**
- **Electro.Aero Pty Ltd**
- **Ampaire, Inc.**
- **BETA Technologies, Inc.**
- **Bye Aerospace, Inc.**
- **Joby Aviation, Inc.**
- **Textron eAviation, Inc. / Pipistrel**

The insights gathered through OEM engagement offer a critical foundation for understanding how Minnesota can proactively align its infrastructure, policy, and planning efforts to support the growth of electric aviation and position itself as a leader in this emerging industry. The following information summarizes the OEM feedback received by the project team related to:

- Market readiness
- Use cases and market applications
- Charging infrastructure and power requirements
- Cold weather operations and thermal management

**Although perspectives varied depending on the OEM, aircraft type, and intended use cases, this summary reflects the overall sentiment expressed throughout the OEM engagement process.**

### OEM MARKET READINESS

A central focus of the MEAN Study is identifying and supporting near-term opportunities for deploying electric aviation technologies in Minnesota. Encouragingly, participating OEMs shared a common perspective: while electric aviation remains in its early stages, it holds strong potential for rapid growth. Several key factors contribute to this optimism:

- **Cost reductions:** As technology matures and infrastructure scales, both equipment and charging costs are expected to decline, making electric aviation increasingly competitive with conventional fuel-based operations.
- **Market expansion:** As aircraft progress through the certification process, manufacturers plan to expand their reach, either by retrofitting existing aircraft or targeting underserved regions that could benefit from more accessible and sustainable air service.
- **Public acceptance:** OEMs are actively partnering with airlines, emergency response providers, consumer brands, and other corporations to build trust and familiarity with electric aviation. These collaborations aim to normalize electric flight and increase public interest and confidence.

Although optimism is high, timing to market is dependent on regulatory certification. Certification timelines are largely influenced by the readiness of industry partners and the pace of regulatory approvals rather than by the speed of technological development itself. As a result, OEMs anticipate achieving certification and initiating operations within a range of one to five years while still expressing some uncertainty as to how the certification process will unfold.

### USE CASES AND MARKET APPLICATIONS

As previously noted, OEMs identified a wide range of potential use cases for electric aviation, many of which align closely with Minnesota's transportation needs and its network of regional airports. Cargo and medical transport emerged as key focus areas as both use cases stand to benefit from faster response times, reduced operating costs, and the ability to reach remote areas more reliably.

Flight training also stood out as a strong early market opportunity due to the cost advantages of electric aircraft. OEMs see flight schools as well positioned to benefit from lower operating costs and reduced environmental impact.

Additionally, there is growing interest in passenger transportation as a long-term application, particularly for regional routes and frequent short-haul services. Examples include airport shuttles and travel to entertainment destinations—services expected to expand as infrastructure improves and public acceptance grows.

Collectively, these OEM perspectives suggest that Minnesota's regional airports could play a pivotal role in the early adoption and scaling of electric aviation, supporting both commercial and specialized operations across the state.

### CHARGING INFRASTRUCTURE AND POWER REQUIREMENTS

A consistent theme heard from all participating OEMs was a strong preference for direct charging over battery swapping. However, charging power requirements vary significantly depending on aircraft size and operational needs, typically ranging from 200 kW to 1 megawatt (MW), according to the OEMs engaged for the MEAN Study.

The availability of three-phase power at airports was identified as a critical infrastructure factor. In particular, the distance between the transformer and the charging location on the airfield is key. Ideally, three-phase power should be available on-site or within close proximity. If a transformer is located more than 2,000 feet from the charging point, further evaluation is needed to assess the cost and feasibility of extending power to that location.

### COLD WEATHER OPERATIONS AND THERMAL MANAGEMENT

Minnesota's climate presents unique challenges for electric aviation, making reliable aircraft performance in low temperatures a critical consideration. OEMs are actively developing strategies to address these conditions and ensure consistent operational reliability during winter months.

Most OEMs are developing pre-conditioning systems for aircraft batteries and cabins to enable efficient thermal management before flight. These systems, which are generally integrated with ground charging infrastructure, help optimize battery performance and maintain cabin comfort. Each OEM is pursuing distinct solutions tailored to their respective aircraft designs. While heated hangars are not strictly required for storing electric aircraft, OEMs generally recommend them to preserve battery health and reduce energy demands during pre-flight preparation.

Overall, OEMs expressed confidence that, with proper battery care, thermal management, and operational planning, electric aircraft can perform reliably in cold climates such as Minnesota's winter conditions.




*Courtesy of Joby Aviation. © Joby Aero, Inc.*

## OEM FEEDBACK – KEY TAKEAWAYS

The OEM engagement process provided a comprehensive view of the electric aviation landscape and its relevance to Minnesota. Key takeaways include:

- Certification and commercial operations are expected within the next one to five years, aligning with the MEAN Study's near-term focus.
- Use cases such as cargo, medical transport, and pilot training are well suited to Minnesota's geography, infrastructure, and robust industries.
- Charging infrastructure must be scalable and capable of supporting increased power demands to accommodate a growing fleet of electric aircraft and other on-airport electrical needs.
- Cold weather operations are feasible with appropriate thermal management and facility planning.
- The industry is poised for significant growth, and thoughtful planning and preparation will be essential to unlocking its full potential.

**Table 1** summarizes key information about aircraft developed by OEMs interviewed during the engagement process, and highlights the specific technologies and aircraft models that are shaping the future of electric aviation. All information is current as of 2025 and is subject to change as technologies evolve and certification processes progress.

**Table 1:** *OEMs interviewed and associated aircraft*

| OEM | Aircraft | Propulsion | Type | Est. range (mi) | MTOW (lbs) | Anticipated certification |
|---|---|---|---|---|---|---|
| Ampaire | Eco Caravan | Hybrid | CTOL | 1,100 | 8,750 | Late 2025 |
| BETA | Alia 250 | Electric | VTOL | 250 | 6,999 | 2027-2028 |
| | Alia CX300 | Electric | CTOL | 300 | 6,999 | 2026 |
| BYE aerospace | eFlyer2 | Electric | CTOL | 250 | 2,000 | 2027-2028 |
| Joby | JAS4-1 | Electric | VTOL | 100 | 5,300 | 2026-2029 |
| Textron eAviation | Pipistrel Velis Electro | Electric | CTOL | 124 | 1,320 | Currently available |

## STAKEHOLDER WORKSHOPS

Between January and February 2025, the MEAN Study team conducted six in-person stakeholder workshops across Minnesota. These sessions were strategically located to ensure regional representation and accessibility and to encourage broad participation from key stakeholders:

1 **St. Paul Downtown Airport (Metro)**
January 31, 2025

2 **City of Alexandria City Hall (Central)**
February 3, 2025

3 **City of Marshall City Hall (Southwest)**
February 6, 2025

4 **MnDOT District 2 HQ, Bemidji (Northwest)**
February 7, 2025

5 **Duluth International Airport (Northeast)**
February 18, 2025

6 **MnDOT District 6 HQ, Rochester (Southeast)**
February 21, 2025

Each session included presentations and discussions on the MEAN Study, aircraft electrification, and data collection needs. Collectively, the workshops hosted over 70 attendees, representing a diverse cross-section of stakeholders, including:

- **26 Airports**
- **11 Businesses**
- **6 Consulting firms**
- **4 Utility providers**
- **3 Neighboring state DOTs**
- **FAA**

These workshops served as a critical platform for two-way dialog, allowing stakeholders to engage directly with the project team, ask questions, and provide detailed feedback. The input gathered was instrumental in refining use cases, airport evaluation criteria, and identifying areas for further research.

## COMMON THEMES FROM STAKEHOLDER WORKSHOPS

The MEAN Stakeholder Workshops provided a nuanced, statewide perspective on electric aviation in Minnesota by highlighting the most immediate opportunities, persistent barriers, and recurring concerns identified by a diverse group of participants.

### OPPORTUNITIES

While stakeholder perspectives varied, several promising opportunities emerged:

- **Near-term use cases:** Short-haul cargo flights and flight training were frequently cited as viable early use for electric aircraft due to their limited range requirements and predictable flight patterns.
- **Renewable energy integration:** Stakeholders expressed strong interest in powering electric aviation infrastructure with renewable energy, particularly solar, aligning with Minnesota's broader sustainability goals.
- **Broader infrastructure benefits:** Participants noted that electric aviation infrastructure could also support other airport operations, including:
  - Electric ground support equipment to reduce emissions and noise
  - EV charging stations for airport fleets and public use
  - Electric transit connections to enhance multimodal airport access

*St. Paul Downtown Airport*

### BARRIERS AND CONCERNS

Despite the enthusiasm, stakeholders identified several key challenges that could impede the adoption of electric aviation:

- **Electric capacity:** Many regional airports may lack the grid infrastructure needed to support high-power charging systems. Upgrades could be costly and time intensive.
- **Aircraft turnaround time:** Longer charging times compared to traditional refueling could disrupt current operational models, particularly for commercial or high-frequency flights.
- **Range anxiety:** Concerns about the limited range of existing and future electric aircraft models and their reliability for route planning were common.
- **Aviation stakeholder perception:** Building trust in the safety, reliability, and value of electric aviation was seen as essential for adoption.
- **Cost and funding:** High upfront costs for aircraft, charging infrastructure, and facility upgrades—combined with limited funding and regulatory uncertainty—were cited as systemic barriers.
- **Fire suppression:** The risks associated with lithium-ion batteries may require new equipment and training for airport fire response teams.
- **Maintenance and workforce readiness:** Electric aircraft require different technical skills than traditional aircraft, highlighting the need for new training programs.
- **Charger operations:** Questions were raised about charger maintenance responsibilities, service frequency, and long-term costs.
- **Other concerns included:**
  - Insurance pricing for electric aircraft remains uncertain.
  - Charger durability in Minnesota's cold winters.
  - Space constraints on aprons and in hangars where accommodating new infrastructure could be challenging.
  - Hangar building codes may need updates to accommodate electric aircraft and charging systems.

> Opportunities, barriers, and concerns raised during the stakeholder workshops underscore the transformative potential of electric aviation for Minnesota's airport ecosystems. However, realizing this potential will require intentional planning, strong cross-sector collaboration, and thoughtful policy development to ensure a safe, sustainable, and equitable transition.

*St. Paul Downtown Airport*

*Section 2*

# METHODOLOGY AND FINDINGS

## TOPICS

- INTRODUCTION TO THE MEAN EQUATION
- DEMAND: THE BUSINESS CASE FOR ELECTRIC AVIATION
- SUPPLY: ELECTRIC AVIATION INFRASTRUCTURE
- MEAN FINDINGS
- STUDY CONCLUSION

## 2.1 INTRODUCTION TO THE MEAN EQUATION

The MEAN Study was developed using a pragmatic framework to evaluate and identify Minnesota airports that may support electric aviation over the next decade. The study's core concept is simple, but meaningful: **Demand + Supply = MEAN**. This equation guided the study's process, enabling the project team to assess both the potential need for electric aviation services and the existing infrastructure capacity to support those services. By focusing on both demand (the business case for electric aviation) and supply (the infrastructure readiness of Minnesota's airports), the study provides a comprehensive foundation for strategic planning and investment. This dual-focus approach ensures that the MEAN Study is both visionary and grounded in practical realities.

The MEAN equation culminated in a synthesis of demand and supply to identify a strategic network of airports best positioned to support electric aviation in the near term. These airports represent the foundational nodes of Minnesota's future electric aviation network.

To ensure the network is both functional and scalable, the study also incorporated a connectivity analysis evaluating how well the identified airports link together to provide efficient, economical service and broad geographic coverage across the state. The goal was to create a network that supports early adoption while enabling long-term growth as electric aviation technologies continue to evolve.

This section explores each component of the MEAN equation in greater detail and presents the key findings of the MEAN Study.

*Courtesy of Joby Aviation. © Joby Aero, Inc.*

> **Within the context of the MEAN equation, "Demand" refers to the current aviation and economic activity occurring at and around Minnesota airports that could translate into viable electric aviation use cases in the future.**



## 2.2 DEMAND: THE BUSINESS CASE FOR ELECTRIC AVIATION

### DEFINING "DEMAND"

The first component of the MEAN equation, **Demand,** focuses on identifying where electric aviation is most likely to gain traction in Minnesota. This analysis focuses on individual airports to evaluate the strategic, operational, and financial rationale for electric aviation, grounded in real-world operations, economic opportunities, and a practical assessment of near-term potential.

Recognizing that demand is dynamic and influenced by a range of factors, the study team approached this analysis as a collaborative and iterative process. It combined quantitative data with qualitative insights gathered through robust stakeholder engagement. The following process was utilized to conduct the demand analysis:

**Evaluate industry trends, data, and emerging technologies.** → **Review viable electric aviation use cases within Minnesota.** → **Engage with airports, businesses, tenants, and OEMs to assess interest and feasibility.** → **Identify Minnesota airports strategically positioned to support these use cases.**

Ultimately, the demand analysis aimed to answer four key questions:

- What are the most viable near-term and future use cases for electric aircraft in Minnesota?
- Where is aviation and economic activity already occurring in Minnesota that could support electric aviation?
- Which Minnesota airports are strategically positioned—geographically and operationally—to support these use cases?
- Which Minnesota airports have already incorporated electric aircraft considerations into their planning efforts?

To answer these questions, the team leveraged stakeholder engagement efforts (see **Section 1.4**), insights from the MnSASP, and additional research. The result was a consolidated list of existing and potential electric aviation use cases, mapped against airport activity and regional economic indicators. This informed the development of an initial "demand map" highlighting airports where electric aviation could be both practical and impactful over the next decade.

*Courtesy of BETA Technologies*

## NEAR-TERM USE CASES

Among the electric aviation use cases discussed in **Section 1.2** , three emerged from the stakeholder engagement and research processes as the most viable for near-term implementation in Minnesota: short-haul cargo, pilot training, and medical transport. These use cases form the foundation of the demand analysis and help define the primary roles electric aviation could play in the state over the next decade.

### SHORT-HAUL CARGO

Short-haul cargo transport refers to the movement of goods over distances typically under 300 miles, often involving frequent, time-sensitive deliveries. This use case was highlighted due to the global growth in air cargo over the past five years and Minnesota's concentration of medical technology companies, which generate substantial demand for air cargo services. Electric aircraft could help meet this growing demand, particularly for short-haul routes across the state.

### PILOT TRAINING

Pilot training encompasses both theoretical instruction and practical flight experience required to obtain pilot certifications. Minnesota's robust aerospace ecosystem, with over 40 flight schools and training programs, makes it an ideal candidate for early adoption. Furthermore, several electric aircraft OEMs are developing FAA-certified, zero-emission, low-noise aircraft specifically for training purposes. Integrating electric aircraft into training programs could help reduce barriers to entry and position Minnesota as a leader in aviation innovation.

### MEDICAL TRANSPORT

Medical transport involves using aircraft to move supplies, equipment, patients, and medical personnel oftentimes in emergency situations. This use case ranked highly in the demand analysis due to Minnesota's strong healthcare sector. Additionally, many airports across the state already support medical transport operations, indicating both existing demand and near-term feasibility for electric alternatives.



## EVALUATION CRITERIA: DEMAND

To guide the demand analysis, a set of evaluation criteria was developed based on stakeholder input and industry trends. These criteria were designed to assess the electric aviation potential of individual airports and to identify those with the highest near-term demand across Minnesota. Shown in **Table 2**, the criteria are organized into four categories:

- Near-term use cases
- Survey responses
- Regional indicators
- Airport activity

The evaluation criteria for the demand analysis are detailed below, while the respective scoring systems for each criterion are highlighted in the following section: **Analysis and methodology: demand.**

**Table 2:** *Evaluation criteria: demand*

| **Near-term use cases** |
|---|
| Pilot training |
| Short-haul cargo |
| Medical transport |
| **Survey responses** |
| Completed survey |
| Indicated near-term opportunities for electric aviation |
| Electric aviation planning stage |
| **Regional indicators** |
| County population |
| Overall economic impact of airport |
| County EV adoption (EV share of cars on road) |
| **Airport activity** |
| Operator route distance |
| Airport operations |


*Courtesy of Ampaire, Inc.*

## NEAR-TERM USE CASES

This category assesses whether an airport currently supports one or more of the three near-term electric aviation use cases identified in the study: short-haul cargo, pilot training, and medical transport. Airports were evaluated based on the presence of tenants, businesses, and/or programs aligned with these activities. The analysis also considered the frequency of these operations and whether the airport hosts a based tenant that regularly provides these services. This deeper review helped distinguish between occasional activity and sustained operational presence, which is more indicative of near-term demand for electric aviation. Data sources for this evaluation included stakeholder input, the MnSASP, and other publicly available datasets.

## SURVEY RESPONSES

Data received via the MEAN survey required careful interpretation due to varying levels of participation and response quality. While some airports, tenants, and stakeholders expressed enthusiasm and identified actionable opportunities, others conveyed skepticism or uncertainty. The following three criteria were evaluated as part of the demand analysis:

- **Completed survey:** Whether an airport submitted a response to the MEAN survey and the nature of that response.
- **Identified near-term opportunities:** Whether an airport indicated specific, actionable opportunities for electric aviation.
- **Electric aviation planning stage:** The extent to which an airport has initiated planning or preparations for electric aviation.

These criteria provide insight into the current level of interest and readiness for electric aviation across Minnesota airports.

## REGIONAL INDICATORS

Regional indicators offer additional context for evaluating electric aviation demand. This category includes:

- **County population:** Larger populations often correlate with greater commercial activity, infrastructure investment, and demand for transportation services. These areas are more likely to adopt new technologies, including electric aviation.
- **Economic impact of the airport:** Airports that contribute significantly to the local economy are more likely to attract investment and support for innovation.
- **County EV adoption:** Higher rates of EV adoption suggest a community's openness to clean technologies and sustainability, serving as a proxy for potential support of electric aviation.

Data sources for these criteria include the American Community Survey 5-Year Estimates, the EValuateMN EV adoption database from Atlas Public Policy (2023), the MnDOT Statewide Airport Economic Impact Study (2019), the MSP Economic Impact Report (2016), and the Economic Impact of Reliever Airports Report (2018).[2]

*[2] The most recent available data on economic activity has been used in this analysis. While some figures may be dated, they remain the latest officially reported values and are included to provide the best possible context for interpretation and comparison.*

## AIRPORT ACTIVITY

This category focuses on operational metrics that reflect an airport's current usage and alignment with electric aircraft capabilities:

- **Operator route distance:** Utilizing origin and destination data, this evaluates the prevalence of routes within the 300-mile range anticipated for electric aircraft in the market over the next decade. Airports with a high volume of short-haul routes are better suited for early electric aviation deployment. Thus, aircraft operators in Minnesota were classified as one of the below categories. Airports were then evaluated by type of operator activity.
  - **Good fit** for electric aviation: Operators where at least 90% of total recorded flights were 300 miles or less.
  - **Moderate fit** for electric aviation: Operators where between 70% and 89% of total recorded flights were 300 miles or less.
  - **Poor fit** for electric aviation: Operators where less than 70% of total recorded flights were 300 miles or less.
- **Airport operations (2023):** Includes total takeoffs and landings, indicating overall airport activity. Higher operational volumes suggest more robust infrastructure, established operator relationships, and greater potential for innovation.

Data for these criteria were sourced from the FAA's Traffic Flow Management System Counts and the 2024 Terminal Area Forecast.

*Tower Municipal Airport*

Southwest Minnesota Regional Airport

## ANALYSIS METHODOLOGY: DEMAND

This section outlines the methodology used to evaluate and rank Minnesota airports based on the demand criteria for electric aviation. The analysis employed a structured scoring and weighting system—summarized in **Table 3**—developed through collaboration with OEMs and industry stakeholders. The final rankings were derived by aggregating weighted scores across all evaluation categories.

### WEIGHTING SYSTEM

In consultation with OEMs and industry stakeholders, varying weights were assigned to each evaluation criteria category based on its relevance and overall importance to electric aviation demand. This weighting approach ensures that the most influential factors are prioritized in the final analysis.


### SCORING SYSTEM

Within each category, individual criteria were scored on a scale from 0 to 3, based on how well each airport aligns with the specific characteristics associated with electric aviation. The scoring methodology for each criterion is detailed in **Table 3** and reflects both quantitative data and qualitative insights.

**Table 3:** *Demand analysis scoring key*

| | Category | Weight | 0 Points | 1 Point | 2 Points | 3 Points |
|---|---|---|---|---|---|---|
| Near-term use cases | Pilot training | 35% | No flight school or program | Flight school with one based aircraft | Flight school with two to four based aircraft | Flight school with five or more based aircraft |
| | Short-haul cargo | | No operations | Monthly or seasonal operations | Weekly operations | Daily operations |
| | Medical transport | | No service | Service conducted but not based at the airport | *No 2-point option; based operations are considered a strong indicator of electric aviation readiness.* | Service based at the airport |
| Survey response | Competed survey | 15% | No response or expressed disinterest | Survey completed | *Binary criterion; no 2- or 3-point options* | |
| | Indicated near-term opportunities for electric aviation | | No opportunities identified | *Binary criterion; no 1- or 3-point options* | Specific near-term opportunities identified | Binary criterion; no 1- or 3-point options |
| | Electric aviation planning stage* | | No planning | Preliminary planning | Planning in development | Comprehensive planning |
| Regional indicators | County population † | 15% | Bottom 25% of the dataset | Lower-middle 25% | Upper-middle 25% | Top 25% |
| | Economic impact of the airport † | | Bottom 25% of the dataset | Lower-middle 25% | Upper-middle 25% | Top 25% |
| | County EV adoption † | | Bottom 25% of the dataset | Lower-middle 25% | Upper-middle 25% | Top 25% |
| Airport activity | Operator route distance‡ | 35% | Only "Poor Fit" operators | One "Moderate Fit" operator | Multiple "Moderate Fit" or one "Good Fit" operator | Multiple "Good Fit" operators |
| | Airport operations (based on total takeoffs and landings)† | | Bottom 25% of the dataset | Lower-middle 25% | Upper-middle 25% | Top 25% |

**This includes input or actions taken by the airport sponsor, airport tenants, and/or business users operating at the airport.*
*†Scoring based on quartile distribution of respective datasets.*
*‡TFMSC data was utilized to identify origin and destination airports of aircraft operators in Minnesota. Airports were classified by the total percentage of flights at their facility that are less than or equal to 300 miles—the anticipated range of electrical aircraft over the next decade.*

## DEMAND MAP

To visualize the results of the demand analysis, a ranking system was developed using the cumulative scores from each evaluation criterion, weighted according to the methodology outlined in the previous sections. Airports with the highest total scores were identified as having the greatest near-term demand for electric aviation. **Figure 5** illustrates the outcome of this analysis.

Each grey circle represents a public-use airport in Minnesota, while the blue circles highlight the top 30 ranked airports in the demand analysis. The size of each blue circle is proportional to the airport's rank—larger circles indicate higher demand scores.

**Figure 5:** *Demand analysis results map*

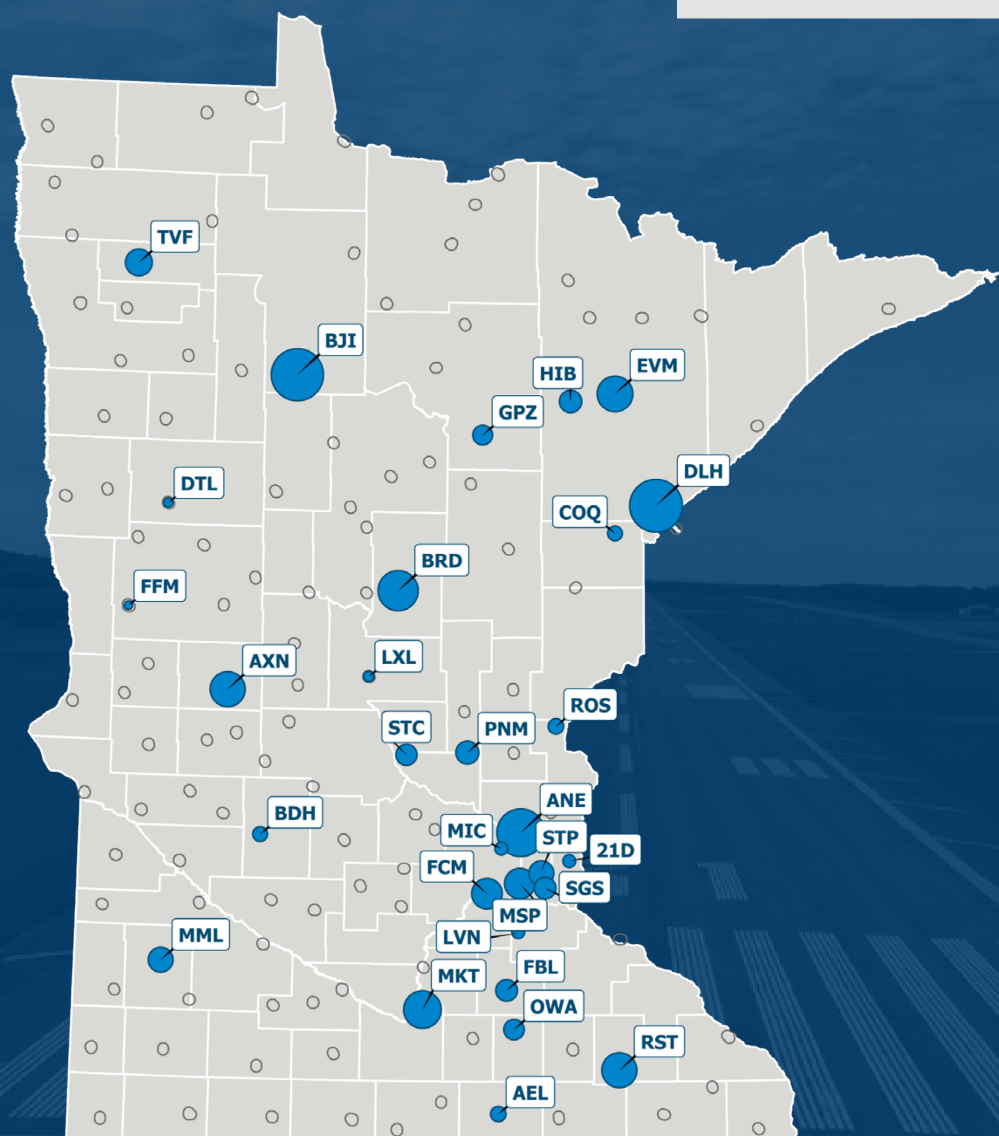



**Table 4** lists the 30 highest-ranking airports based on their demand scores. Highlighting the top 30 allows for a representative sample of airports that demonstrate strong alignment with electric aviation use cases, operational readiness, and stakeholder support.

**Table 4:** *Airport demand analysis rank (top 30)*

| Rank | Score | FAA ID | Airport name | Rank | Score | FAA ID | Airport name |
|---|---|---|---|---|---|---|---|
| 1 | 6.75 | DLH | Duluth International | 16 | 4.30 | SGS | South St. Paul Municipal |
| 2 | 6.70 | BJI | Bemidji Regional | 17 | 4.30 | FBL | Faribault Municipal |
| 3 | 6.35 | ANE | Anoka County-Blaine | 18 | 4.25 | STC | Saint Cloud Regional |
| 4 | 5.75 | BRD | Brainerd Lakes Regional | 19 | 4.20 | OWA | Owatonna Degner Regional |
| 5 | 5.55 | MKT | Mankato Municipal | 20 | 4.15 | GPZ | Grand Rapids-Itasca County |
| 6 | 5.40 | EVM | Eveleth-Virginia Municipal | 21 | 3.80 | AEL | Albert Lea Municipal |
| 7 | 5.35 | AXN | Alexandria Municipal | 22 | 3.80 | ROS | Rush City Municipal |
| 8 | 5.35 | RST | Rochester International | 23 | 3.75 | BDH | Willmar Municipal |
| 9 | 5.00 | MSP | Minneapolis-St. Paul Int'l | 24 | 3.75 | COQ | Cloquet-Carlton County |
| 10 | 5.00 | FCM | Flying Cloud | 25 | 3.60 | 21D | Lake Elmo |
| 11 | 4.70 | TVF | Thief River Falls Regional | 26 | 3.60 | LVN | Airlake |
| 12 | 4.55 | MML | Marshall-Southwest Minnesota Regional | 27 | 3.60 | MIC | Crystal |
| 13 | 4.55 | STP | Saint Paul Downtown | 28 | 3.40 | LXL | Little Falls-Morrison County |
| 14 | 4.40 | PNM | Princeton Municipal | 29 | 3.30 | DTL | Detroit Lakes |
| 15 | 4.35 | HIB | Range Regional | 30 | 3.25 | FFM | Fergus Falls Municipal |

It is important to note that this ranking reflects only the demand side of the analysis. The supply analysis, covered in **Section 2.3** , evaluates each airport's capacity to support electric aviation infrastructure. Together, these perspectives provide a comprehensive view of electric aviation readiness at airports across Minnesota.

## 2.3 SUPPLY: ELECTRIC AVIATION INFRASTRUCTURE

### DEFINING "SUPPLY"

Within the context of the MEAN equation, **Supply** refers to the current readiness of Minnesota's airport infrastructure to support electric aviation.

The supply analysis evaluates the physical and technical capabilities of airports to accommodate electric aircraft. This includes assessing the infrastructure necessary to support charging, maintenance, and safe operations. The supply analysis focused on the following primary infrastructure components:

- **Electrical elements:** Energy capacity and access to three-phase power for fast charging.
- **Aviation elements:** Airfield facilities, hangar space, and emergency response capabilities.

Unlike the demand analysis, which incorporated both quantitative data and qualitative stakeholder insights, the supply analysis is more technical in nature. It answers the question: What does an airport need to support electric aviation operations? The result is an inventory of infrastructure assets across Minnesota's public-use airports. This inventory provides a clear picture of where investment may be required to enable electric aviation and where airports are already well-positioned to support these emerging technologies.

### EVALUATION CRITERIA: SUPPLY

A set of evaluation criteria was developed based on feedback from OEMs and the study team's knowledge of aviation and electrical infrastructure. These criteria were designed to identify which airports are best positioned to support electric aircraft operations in the near term. The evaluation criteria, summarized in **Table 5**, are organized into two primary categories: Electrical Elements and Aviation Elements.

The evaluation criteria for the supply analysis are detailed on the following pages, while the respective scoring systems for each criterion are highlighted in the following section: **Analysis and Methodology: Supply.**

**Table 5:** *Supply analysis evaluation criteria*

| | Category |
|---|---|
| Electrical elements | Existing electrical capacity |
| | Availability and location of three-phase power |
| | Opportunities for utility expansion |
| Aviation elements | Paved runway |
| | Runway length |
| | Instrument approaches |
| | Access to heated hangars |
| | Fire suppression and emergency response |
| | FBO, terminal, and crew amenities |



*Courtesy of BETA Technologies*

### ELECTRICAL ELEMENTS

This category evaluates the presence and state of key electrical infrastructure components. These elements are critical for determining the feasibility, cost, and timeline for deploying electric aircraft charging systems. The three primary criteria are:

- **Existing electrical capacity:** Refers to the total electrical power an airport can currently draw from the grid, typically limited by the size and rating of on-site utility transformers. Higher capacity reduces the need for costly upgrades and accelerates charger deployment. This metric is more reliable than building size alone, as some facilities may use non-electric systems, resulting in lower actual electrical demand.
- **Availability and location of three-phase power:** Three-phase power is essential for high-capacity electric aircraft chargers. This criterion assesses whether three-phase power is already available on-site and, if not, the complexity and cost of extending it to the airport based on location.
- **Opportunities for utility expansion:** Energy demands will continue to increase as airport electric needs increase. This criterion evaluates whether the utility has excess capacity, or plans to increase capacity, to support future charging demands.

To ensure accurate and consistent data collection, and with permission from airport sponsors, the study team conducted direct outreach to utility providers serving Minnesota airports. Utility representatives completed a structured survey designed to capture the following:

- **Transformer specifications and locations:** Identification of all on-site transformers, including their capacities (sizes) and locations.
- **Three-phase power availability:** Confirmation of whether existing transformers are configured for three-phase power.
- **Proximity to three-phase power:** For sites lacking on-site three-phase power, identification of the nearest accessible connection point. This helps estimate the scope and cost of potential infrastructure upgrades.
- **Capacity for future load increases:** Evaluation of the utility's ability to support an additional 1 MW of electrical load in the near term. This also includes any planned grid enhancements or capacity expansion projects in the surrounding area that could facilitate future electrification efforts.

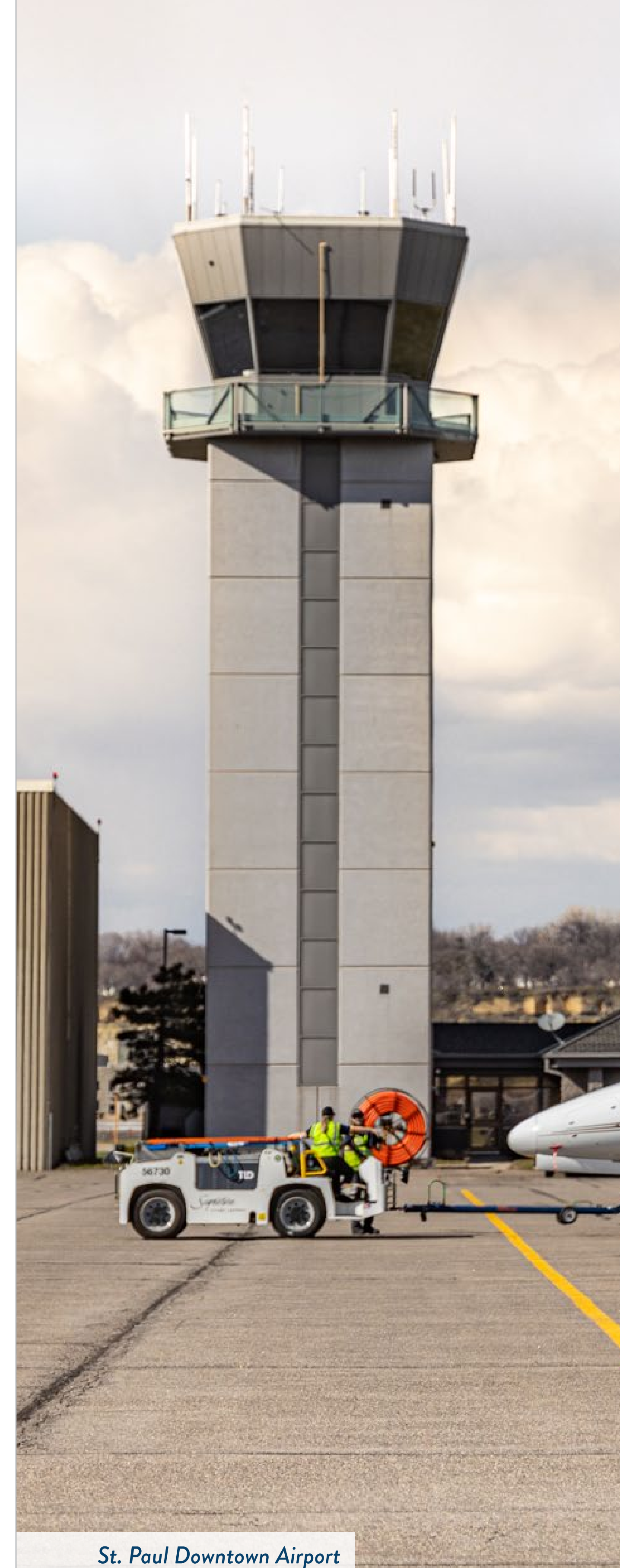
### AVIATION ELEMENTS

This category evaluates the presence of aviation-specific infrastructure relevant to electric aircraft operations. Based on insights from OEMs and industry stakeholders, these criteria reflect the operational requirements of electric aircraft and the facilities needed to support them. Data sources for this information includes the MnSASP, FAA Forms 5010 – Airport Master Records, airport layout plans (ALPs), master plans, aerial imagery, and stakeholder input. The criteria within this include:

- **Paved runway:** Required for electric conventional takeoff and landing (eCTOL) aircraft, which rely on wheeled landing gear and require smooth, paved surfaces for safe operations.
- **Runway length:** Ensures sufficient distance for eCTOL aircraft to take off and land safely, accounting for the unique performance characteristics of electric propulsion systems.
- **Instrument approach procedures:** Necessary for reliable operations in poor weather conditions, especially for use cases like cargo and medical transport that require consistent service. Some electric aircraft are expected to be certified for operations under instrument flight rules (IFR), including flight into known icing (FIKI) conditions.
- **Access to heated hangars:** Recommended in cold climates like Minnesota, where battery thermal management is essential. Heated hangars help maintain optimal battery temperatures and reduce pre-flight energy consumption.
- **Fire suppression and emergency response:** Electric aircraft introduce unique fire risks, particularly from battery systems. Airports must have appropriate ARFF capabilities and/or emergency response agreements in place.
- **FBO, terminal, and crew amenities:** Charging times for electric aircraft can range from 30 minutes to several hours. During this time, pilots, crew, and passengers require access to facilities for rest, work, or waiting—especially in extreme weather conditions.

*Rochester International Airport*



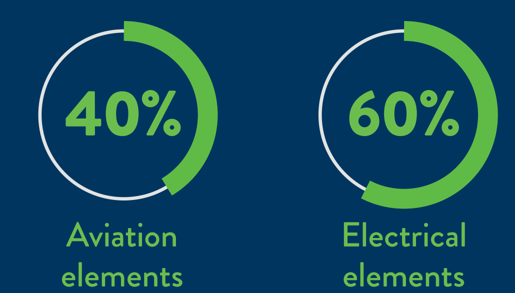

*St. Paul Downtown Airport*

## ANALYSIS METHODOLOGY: SUPPLY

This section outlines the methodology used to evaluate and rank Minnesota airports based on their infrastructure readiness to support electric aviation. Like the demand methodology, this analysis employed a structured scoring and weighting system, summarized in **Table 6** on the following page, which was developed in collaboration with OEMs and industry stakeholders. Each airport was assessed against a set of criteria grouped into two main categories: Aviation Elements and Electrical Elements. The final rankings of airports based on their supply readiness were derived by aggregating weighted scores across all evaluation categories.

### WEIGHT SYSTEM

A weight was assigned to each category based on its relative importance to electric aviation infrastructure. The weighting system prioritizes the most critical infrastructure components for electric aviation. In consultation with OEMs and industry stakeholders, the following weights were assigned:




This weighting reflects the foundational importance of electrical infrastructure. Without sufficient electrical capacity and access to three-phase power, the deployment of electric aircraft charging systems becomes significantly more complex and costly. As such, electrical readiness was given greater emphasis in the final analysis.

## SCORING SYSTEM

### ELECTRICAL ELEMENTS

Each criterion within the Electrical Elements category was scored on a scale from 0 to 3, based on the presence and state of key infrastructure components as shown in **Table 6**. These scores were derived from data collected during the utility outreach process and reflect each airport's current capabilities to support electric aviation infrastructure.

**Table 6:** *Supply analysis scoring key*

| | Category | Weight | 0 Points | 1 Point | 2 Points | 3 Points |
|---|---|---|---|---|---|---|
| Electrical elements | **Existing electrical capacity** Evaluates the total apparent power capacity of the airport site, measured in kilovolt-amperes (kVA), which provides a reliable indicator of the site's ability to support electric aircraft charging systems. Sites with higher capacity are typically equipped with three-phase transformers and are better positioned for electrification. | 60% | No existing three-phase transformers on site | Total site capacity of three-phase transformers < 100 kVA | Total site capacity between 100–500 kVA | Total site capacity > 500 kVA |
| | **Availability and location of three-phase power** Assesses the feasibility of accessing three-phase power, which is essential for high-capacity charging systems. Based on input from OEMs, scoring reflects the proximity of the nearest accessible three-phase power source. | | Three-phase power located >2,500 feet from airport property OR three-phase power unavailable | Three-phase power located between 1,500-2,500 feet from airport property | Three-phase power located <1,500 feet from airport property | Three-phase power available on airport |
| | **Opportunities for utility expansion** Evaluates the potential for future utility support based on planned increases in electrical capacity by utility providers. Reflects the likelihood of cost-sharing opportunities or subsidized upgrades that could accelerate infrastructure deployment. | | No planned future capacity exceeding 1 MW | Planned upgrades to exceed 1 MW | Planned capacity between 1–3 MW | Planned capacity exceeding 3 MW |

### AVIATION ELEMENTS

Each criterion within the Aviation Elements category was scored on a scale from 0 to 3, based on the presence of aviation infrastructure at each airport as shown in **Table 6**.

**Table 6:** *Supply analysis scoring key (continued)*

| | Category | Weight | 0 Points | 1 Point | 2 Points | 3 Points |
|---|---|---|---|---|---|---|
| Aviation elements | **Paved runway** An airport is equipped, or it is not. | 40% | No paved runway | | | Paved runway present |
| | **Runway length** A critical factor for eCTOL aircraft. Based on OEM input, the following scoring was applied. | | Runway length < 3,000 feet | Runway length 3,000–3,499 feet | Runway length 3,500–3,999 feet | Runway length ≥ 4,000 feet |
| | **Instrument approaches** While not essential for all early electric aircraft, instrument approach procedures enhance operational reliability. This criterion was capped at two points to reflect its moderate influence. | | Airport is equipped with visual approaches only | Non-precision instrument approaches | Precision instrument approaches | |
| | **Access to heated hangars** Recommended for battery thermal management in cold climates. Scoring reflects both the presence and near-term availability of heated hangars. | | No heated hangar space | <15,000 sq. ft., fully occupied or unavailable | ≥15,000 sq. ft., fully occupied or unavailable | Any amount of heated hangar space currently or soon available |
| | **Fire suppression and emergency response** Given the unique fire risks associated with electric aircraft, this criterion emphasizes preparedness. A one-point option was intentionally excluded. | | No ARFF and no emergency agreement with local agency | | Formal emergency agreement with local agency | On-site ARFF facility |
| | **FBO, terminal, and crew amenities** Reflects the need for passenger/crew facilities and amenities during aircraft charging periods. | | No FBO, terminal, or crew amenities | | | FBO, terminal, or crew amenities present |

*Courtesy of BETA Technologies*

## ELECTRICAL ELEMENTS ASSUMPTION-BASED SCORING METHODOLOGY

Despite extensive outreach and follow-up efforts, complete electrical infrastructure data could not be obtained for all airports due to one or more of the following reasons:

- Lack of authorization from airport sponsors to contact their utility providers
- Unresponsive utility providers
- Incomplete or unsubmitted permission forms required by property owners

To address these gaps, the study team conducted at least three follow-up attempts with airport representatives and/or utility providers. In cases where data remained unavailable, assumptions were made based on observable site characteristics. These assumptions were informed by aerial imagery, building attributes, and standard utility practices.

## OBSERVABLE SITE CHARACTERISTICS

Assumptions were guided by the following observable characteristics:

- **Number of structures:** A greater number of buildings at an airport generally indicates higher electrical demand due to lighting; heating ventilation, and air conditioning; and equipment use.
- **Size of structures:** Larger buildings generally require more electrical capacity. Smaller buildings were assumed to use approximately 5 kVA and operate on single-phase power.
- **Type of structures:** The function of a building influences its power needs. Passenger terminals and industrial facilities typically require more power than storage units or hangars.



For each Electrical Element criterion, this assumption-based methodology outlined in **Table 7** was used to assign a score ranging from 0 to 3 for airports where complete utility data was unavailable.

**Table 7:** *Supply analysis scoring key (electrical elements assumptions-based methodology)*

| | Category | 0 Points | 1 Point | 2 Points | 3 Points |
|---|---|---|---|---|---|
| Assumptions by electrical element | **Existing electrical capacity**<br>Where utility transformers were visible in aerial imagery, service size was estimated using standard utility practices. If no transformer was visible, capacity was inferred from the number, size, and type of buildings. | Fewer than three small buildings on airport property: assumed no three-phase power | Up to 15 small buildings: assumed <100 kVA | Presence of medium/large buildings: assumed 100–500 kVA | Multiple medium/large buildings: assumed >500 kVA |
| | **Availability and location of three-phase power**<br>Assessed based on building types and their likely electrical demands. | Airport buildings limited to small, relatively simple structures (e.g., storage units, basic hangars) | | | Presence of buildings with high electrical loads (e.g., passenger terminals, maintenance facilities, industrial buildings) |
| | **Opportunities for utility expansion**<br>Airport's proximity to urban or industrial development was used as a proxy for potential utility grid expansion. | Airport located in a rural area with no assumed expansion potential | Airport located within two miles of a town or industrial area | Airport located within one mile of a town or industrial area | No airport evaluated using assumptions was awarded three points due to the absence of confirmed utility expansion plans |

These assumptions were applied only after all reasonable efforts to obtain direct data had been exhausted. This included multiple outreach attempts to airport representatives and utility providers, as well as efforts to secure the necessary permissions from property owners. **Assumption-based scoring was used solely as a last resort to maintain continuity and completeness in the statewide infrastructure readiness analysis.**

## SUPPLY MAP

To visualize the results of the supply analysis, a ranking system was developed by aggregating the weighted scores from each evaluation criterion. This system was used to identify Minnesota airports with the greatest existing infrastructure capacity to support electric aviation. **Figure 6** illustrates the outcome of this analysis.

Each grey circle represents a public-use airport included in the study in Minnesota, while the yellow circles highlight the top 30 ranked airports in the supply analysis. The size of each yellow circle is proportional to the airport's rank—larger circles indicate higher supply scores.

**Figure 6:** *Infrastructure supply analysis results map*

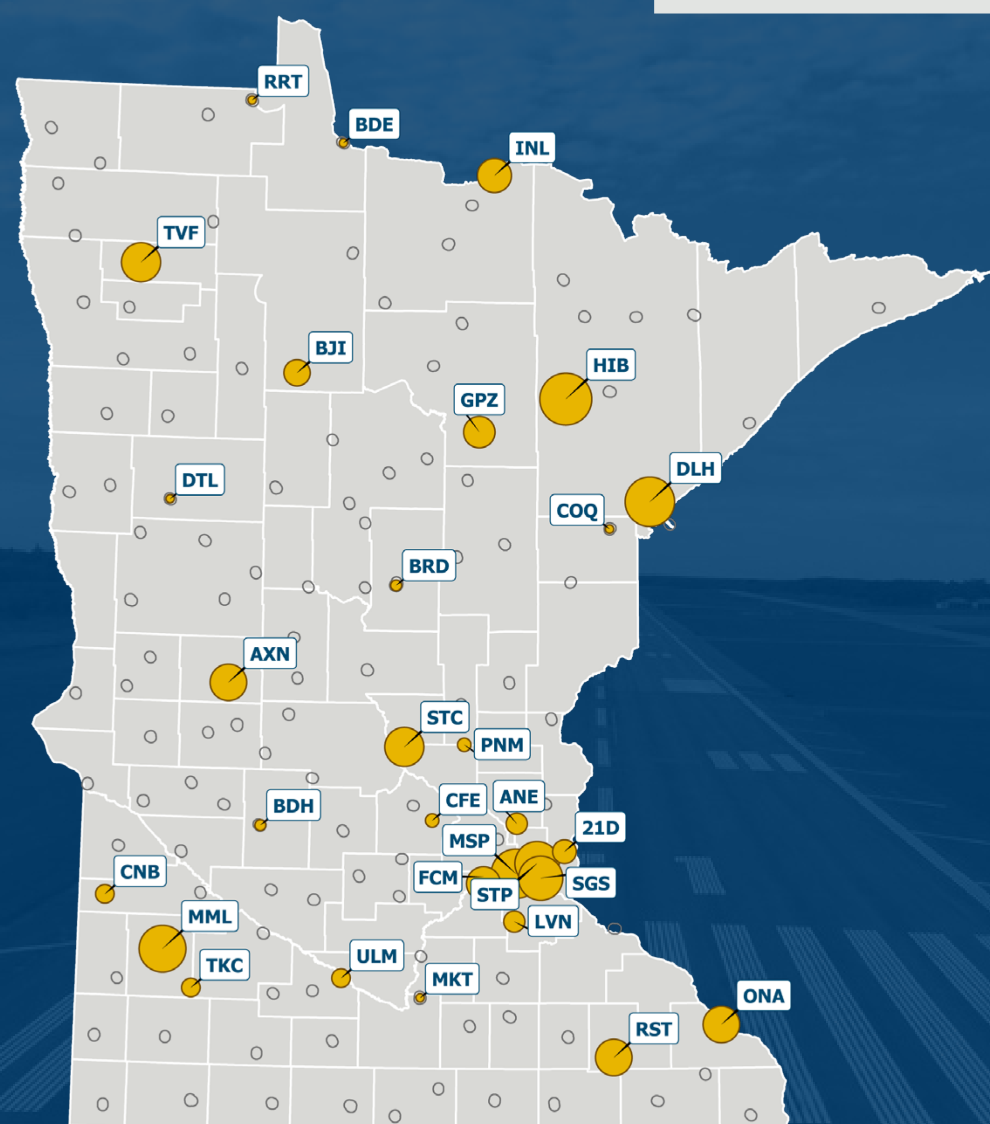



**Table 8** lists the 30 highest-ranking airports based on their supply scores. Like the demand scores, highlighting the top 30 provides a representative sample of airports that demonstrate strong alignment with electric aviation infrastructure needs.

**Table 8:** *Airport supply rank (top 30)*

| Rank | Score | FAA ID | Airport name | Rank | Score | FAA ID | Airport name |
|---|---|---|---|---|---|---|---|
| 1 | 2.95 | HIB | Range Regional | 16 | 2.4 | 21D | Lake Elmo |
| 2 | 2.9 | DLH | Duluth International | 17 | 2.35 | ANE | Anoka County-Blaine |
| 3 | 2.9 | MSP | Minneapolis-St. Paul Int'l | 18 | 2.35 | LVN | Airlake |
| 4 | 2.85 | MML | Marshall-Southwest Minnesota Regional | 19 | 2.3 | ULM | New Ulm Municipal |
| 5 | 2.8 | STP | Saint Paul Downtown | 20 | 2.3 | TKC | Tracy Municipal |
| 6 | 2.8 | SGS | South St. Paul Municipal | 21 | 2.3 | CNB | Canby Municipal |
| 7 | 2.7 | TVF | Thief River Falls Regional | 22 | 2.2 | PNM | Princeton Municipal |
| 8 | 2.7 | STC | Saint Cloud Regional | 23 | 2.2 | CFE | Buffalo Municipal |
| 9 | 2.65 | AXN | Alexandria Municipal | 24 | 2.15 | BRD | Brainerd Lakes Regional |
| 10 | 2.65 | RST | Rochester International | 25 | 2.15 | BDH | Willmar Municipal |
| 11 | 2.65 | ONA | Winona Municipal | 26 | 2.1 | MKT | Mankato Municipal |
| 12 | 2.6 | FCM | Flying Cloud | 27 | 2.1 | COQ | Cloquet-Carlton County |
| 13 | 2.6 | INL | Falls International | 28 | 2.1 | MIC | Crystal |
| 14 | 2.55 | GPZ | Grand Rapids-Itasca County | 29 | 2.1 | DTL | Detroit Lakes |
| 15 | 2.45 | BJI | Bemidji Regional | 30 | 2.1 | RRT | Warroad International |

It is important to emphasize that these results reflect only the findings of the supply analysis component of the study. The complementary demand analysis, presented in **Section 2.2**, evaluates the potential demand for electric aviation services and represents the other core dimension of the MEAN.

Duluth International Airport

## 2.4 MEAN FINDINGS

To identify the MEAN, the project team conducted a comprehensive evaluation that combined the results of the demand analysis (**Section 2.2**) and the supply analysis (**Section 2.3**). Those that demonstrated strength in both areas were considered strong candidates for inclusion in the MEAN. Following this evaluation, a connectivity analysis was performed to ensure that the final network supports efficient travel, minimizes redundancy, and provides broad geographic coverage across the state. The outcome of this process is a finalized list of airports that comprise the MEAN.

### DRAFT MEAN

To identify candidate airports for the MEAN, each airport was assigned a total MEAN score, which was calculated by summing the results of the demand and supply analyses. Airports were then ranked numerically based on their total MEAN scores.[3]

Importantly, the demand and supply scores are based on different evaluation criteria, scoring methodologies, and weighting strategies. As a result, the maximum possible score for an airport in the demand analysis is 7.95, while the maximum score in the supply analysis is 3. This means, with a total possible MEAN score of 10.95, the demand analysis accounts for approximately 73% of a "perfect" MEAN score, with the supply analysis contributing the remaining 27%. This intentional imbalance reflects a key strategic insight: **while infrastructure (supply) can often be developed through public or private investment, demand—driven by viable business cases and early adopter scenarios—is significantly harder to manufacture.** Consequently, airports with strong demand potential are considered more likely to support successful electric aviation deployment in the near term.

Based on the ranked scores, the top 25% of airports in the Minnesota system were identified as MEAN candidates. This selection resulted in a list of 33 top-scoring airports, presented in **Table 9** and visualized in **Figure 7**. Inclusion in this group indicates that an airport demonstrates a strong combination of existing or attainable infrastructure and a compelling business case for electric aviation within the next decade.

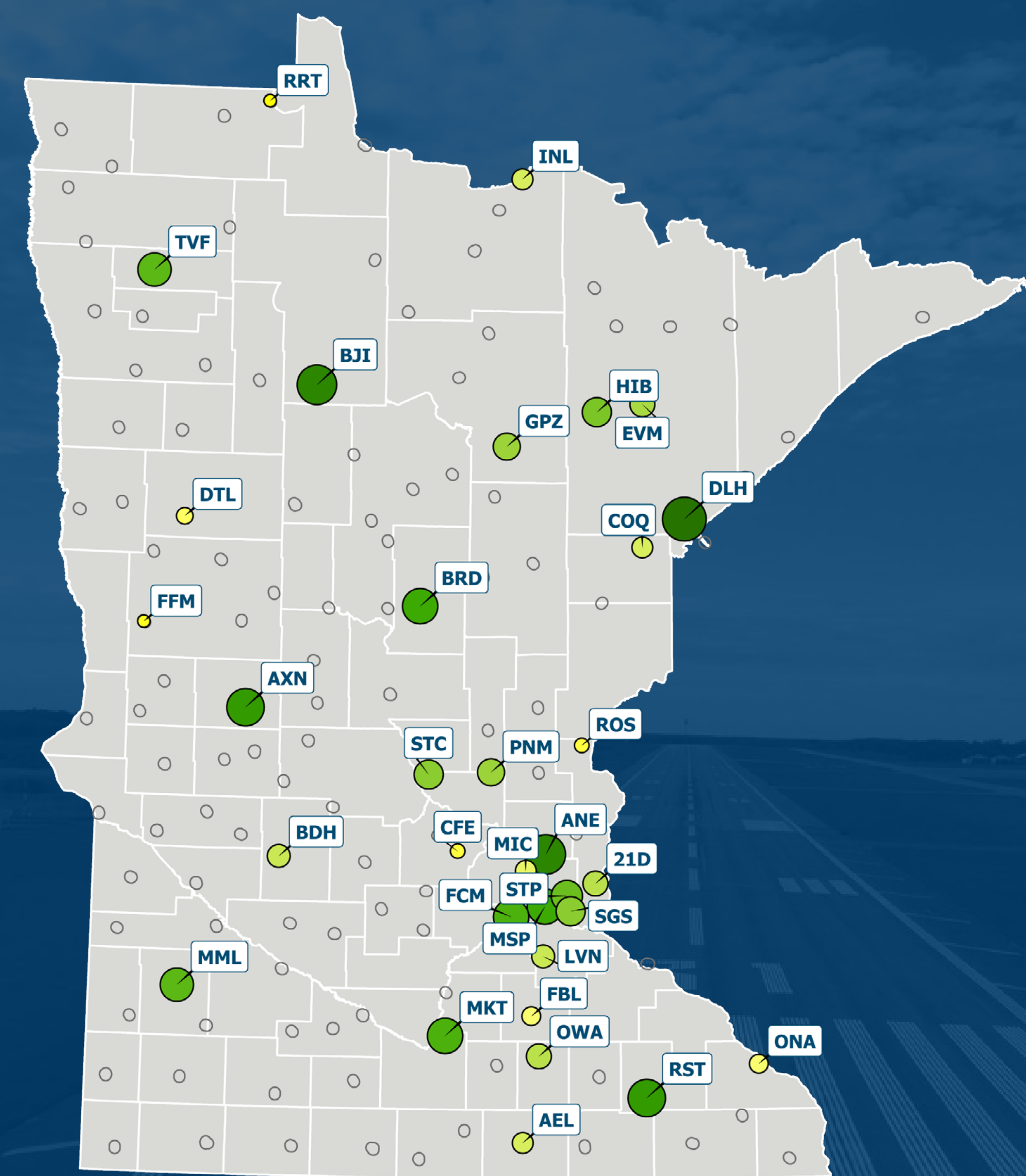
[3] *This ranked list includes Minnesota's public-use airports. Two airports declined participation, resulting in a pool of 130 airports.*

**Table 9:** *MEAN candidate airports*

| Rank | Score | FAA ID | Airport name |
|---|---|---|---|
| 1 | 9.65 | DLH | Duluth International |
| 2 | 9.15 | BJI | Bemidji Regional |
| 3 | 8.70 | ANE | Anoka County-Blaine |
| 4 | 8.00 | AXN | Alexandria Municipal |
| 5 | 8.00 | RST | Rochester International |
| 6 | 7.90 | BRD | Brainerd Lakes Regional |
| 7 | 7.90 | MSP | Minneapolis-St. Paul Int'l |
| 8 | 7.65 | MKT | Mankato Municipal |
| 9 | 7.60 | FCM | Flying Cloud |
| 10 | 7.40 | MML | Marshall-Southwest Minnesota Regional |
| 11 | 7.40 | TVF | Thief River Falls Regional |
| 12 | 7.35 | STP | Saint Paul Downtown |
| 13 | 7.30 | HIB | Range Regional |
| 14 | 7.10 | SGS | South St. Paul Municipal |
| 15 | 6.95 | STC | Saint Cloud Regional |
| 16 | 6.70 | GPZ | Grand Rapids-Itasca County |
| 17 | 6.60 | PNM | Princeton Municipal |
| 18 | 6.40 | EVM | Eveleth-Virginia Municipal |
| 19 | 6.00 | 21D | Lake Elmo |
| 20 | 6.00 | OWA | Owatonna Degner Regional |
| 21 | 5.95 | LVN | Airlake |
| 22 | 5.90 | BDH | Willmar Municipal |
| 23 | 5.85 | COQ | Cloquet-Carlton County |
| 24 | 5.80 | INL | Falls International |
| 25 | 5.80 | AEL | Albert Lea Municipal |
| 26 | 5.70 | MIC | Crystal |
| 27 | 5.60 | FBL | Faribault Municipal |
| 28 | 5.55 | ONA | Winona Municipal |
| 29 | 5.40 | DTL | Detroit Lakes |
| 30 | 5.30 | CFE | Buffalo Municipal |
| 31 | 5.25 | ROS | Rush City Municipal |
| 32 | 5.05 | FFM | Fergus Falls Municipal |
| 33 | 4.80 | RRT | Warroad International |



**Figure 7:** *MEAN candidate airports*



## CONNECTIVITY ANALYSIS

While infrastructure and demand are critical components of electric aviation readiness, they are not sufficient on their own. For electric aviation to be viable and impactful at a statewide level, the selected airports must also form a cohesive, cost-effective, and geographically comprehensive network. To address this, a connectivity analysis was conducted to evaluate how well the 33 candidate airports would function as part of an integrated system. This additional layer of analysis refined the candidate list by prioritizing airports that not only scored highly in demand and supply, but also contributed meaningfully to a statewide network that supports efficient travel and accessibility.

### NETWORK VALUE AND STRATEGIC PLACEMENT

As discussed in **Section 1.3**, Metcalfe's Law provides a theoretical foundation for evaluating network value, stating that the value of a network increases approximately with the square of the number of connected nodes. This principle highlights the importance of strategic airport placement to maximize overall utility of the MEAN:

- **Strategic deployment:** Prioritizing airports that unlock new connections enhances network efficiency.
- **Network effects:** A single, well-placed airport can enable multiple new routes, improving accessibility.
- **Investment justification:** Demonstrating how each new node increases total network value strengthens the case for funding and development.

Accordingly, the connectivity analysis focused on two key questions:

- Are there geographic gaps where a MEAN airport is needed to connect underserved or isolated areas?
- Are there locations where MEAN airports are redundant due to close proximity?

### DISTANCE ANALYSIS AND REDUNDANCY REVIEW

To assess spatial connectivity, the Pipistrel Velis Electro was selected as the baseline aircraft due to its near-term feasibility for short-range electric aviation. Although not yet fully FAA-certified, it received a special airworthiness exemption in 2024 for Light-Sport Aircraft (LSA) operations, making it the most practical fully electric reference aircraft currently available.

**Performance assumptions for the Velis Electro:**

- **Average flight time (including reserves):** ~50 minutes
- **Operational range:** ~45–60 miles under typical weather conditions

Given these parameters, a 30-mile flight is reliably achievable in any weather, making 30 miles a suitable minimum node separation to avoid redundancy in the network.

To determine the maximum node separation, the average range of electric aircraft listed in **Table 1**, or 205 miles, was used. Any airport beyond this distance would be considered "isolated" and require an additional nearby node to maintain network connectivity.

**Established distance thresholds for MEAN airport network:**

- **Minimum node separation:** 30 miles (to prevent overlap)
- **Maximum node separation:** 205 miles (to ensure statewide coverage)

Distances between each candidate airport and its nearest neighbor were calculated. All airports fell within a range of 6 to 85 miles, satisfying the maximum separation requirement. However, airports located within 30 miles of another candidate airport were identified for potential redundancy. These airports are listed in **Table 10**.

**Table 10:** *Identified airports for redundancy review*

| MEAN score | FAA ID | Airport | Miles to nearest candidate airport | Nearest candidate airport |
|---|---|---|---|---|
| 7.35 | STP | Saint Paul Downtown | 5.51 | SGS |
| 7.10 | SGS | South St. Paul Municipal | 5.51 | STP |
| 7.90 | MSP | Minneapolis-St. Paul Int'l | 8.54 | STP |
| 5.70 | MIC | Crystal | 9.01 | ANE |
| 8.70 | ANE | Anoka County-Blaine | 9.01 | MIC |
| 6.00 | 21D | Lake Elmo | 10.89 | STP |
| 7.60 | FCM | Flying Cloud | 12.33 | MSP |
| 5.60 | FBL | Faribault Municipal | 14.31 | OWA |
| 6.00 | OWA | Owatonna Degner Regional | 14.31 | FBL |
| 6.40 | EVM | Eveleth-Virginia Municipal | 16.13 | HIB |
| 7.30 | HIB | Range Regional | 16.13 | EVM |
| 5.95 | LVN | Airlake | 17.47 | MSP |
| 9.65 | DLH | Duluth International | 17.72 | COQ |
| 5.85 | COQ | Cloquet-Carlton County | 17.72 | DLH |
| 6.60 | PNM | Princeton Municipal | 21.79 | STC |
| 6.95 | STC | Saint Cloud Regional | 21.79 | PNM |
| 5.30 | CFE | Buffalo Municipal | 24.77 | MIC |


*Sky Harbor Airport and Seaplane Base*

To ensure the MEAN is both efficient and geographically optimized, two approaches were used to reduce redundancy among closely located candidate airports:

1. **MAC Node consolidation:** In this study, a node is defined as a functional unit within the MEAN network, typically represented by an individual airport. However, in metropolitan areas where multiple airports are operated under a single governing authority, nodes may be consolidated to reflect operational and administrative efficiencies. Specifically, the Metropolitan Airports Commission (MAC) operates seven airports in the Minneapolis-St. Paul metropolitan area. For the purposes of this analysis, these airports are treated as a single "MAC node" to avoid redundancy when developing the network. This consolidation reflects the shared governance, overlapping service areas, and potential for coordinated infrastructure planning across these facilities.
   - Minneapolis–St. Paul International Airport (MSP)
   - Saint Paul Downtown Airport (STP)
   - Crystal Airport (MIC)
   - Anoka County-Blaine Airport (ANE)
   - Lake Elmo Airport (21D)
   - Flying Cloud Airport (FCM)
   - Airlake Airport (LVN)
2. **Score-based elimination:** Based on the distance analysis, **Table 11** lists airport pairs located within 30 miles of each other. A previously noted, all MAC airports are grouped into a single "node" and treated as one facility in the connectivity analysis. To address proximity-based redundancy, a score-based elimination method was applied: for each airport pair, the airport or node with the lower total MEAN score was excluded from initial network eligibility.

**Airports removed through the connectivity analysis remain strong candidates for future electric aviation deployment and may be reconsidered as the network evolves.**

**Table 11:** *Redundancy resolution summary*

| Airports retained | | | | Airports removed | | |
|---|---|---|---|---|---|---|
| MEAN score | FAA ID | Airport name | Miles between | MEAN score | FAA ID | Airport name |
| 8.70† | | MAC Node (STP) | 5.51* | 7.10 | SGS | South St. Paul Municipal |
| 6.00 | OWA | Owatonna Degner Regional | 14.31 | 5.60 | FBL | Faribault Municipal |
| 7.30 | HIB | Range Regional | 16.13 | 6.40 | EVM | Eveleth-Virginia Municipal |
| 9.65 | DLH | Duluth International | 17.72 | 5.85 | COQ | Cloquet-Carlton County |
| 6.95 | STC | Saint Cloud Regional | 21.79 | 6.60 | PNM | Princeton Municipal |
| 8.70† | | MAC Node (MIC) | 24.77* | 5.30 | CFE | Buffalo Municipal |

**Distance from nearest MAC Node airport.*
*†Score of highest ranking MAC Node airport.*

## FINAL MEAN

The final MEAN includes 27 airports, grouped into 21 distinct nodes, as shown in **Table 12** and illustrated in **Figure 8**. This network represents the highest-ranking airports identified through a combined analysis of demand, supply, and connectivity. For reference, a comprehensive list of all 132 public-use airports evaluated in this study—along with their respective supply, demand, and overall MEAN scores—is provided in **Appendix A**.

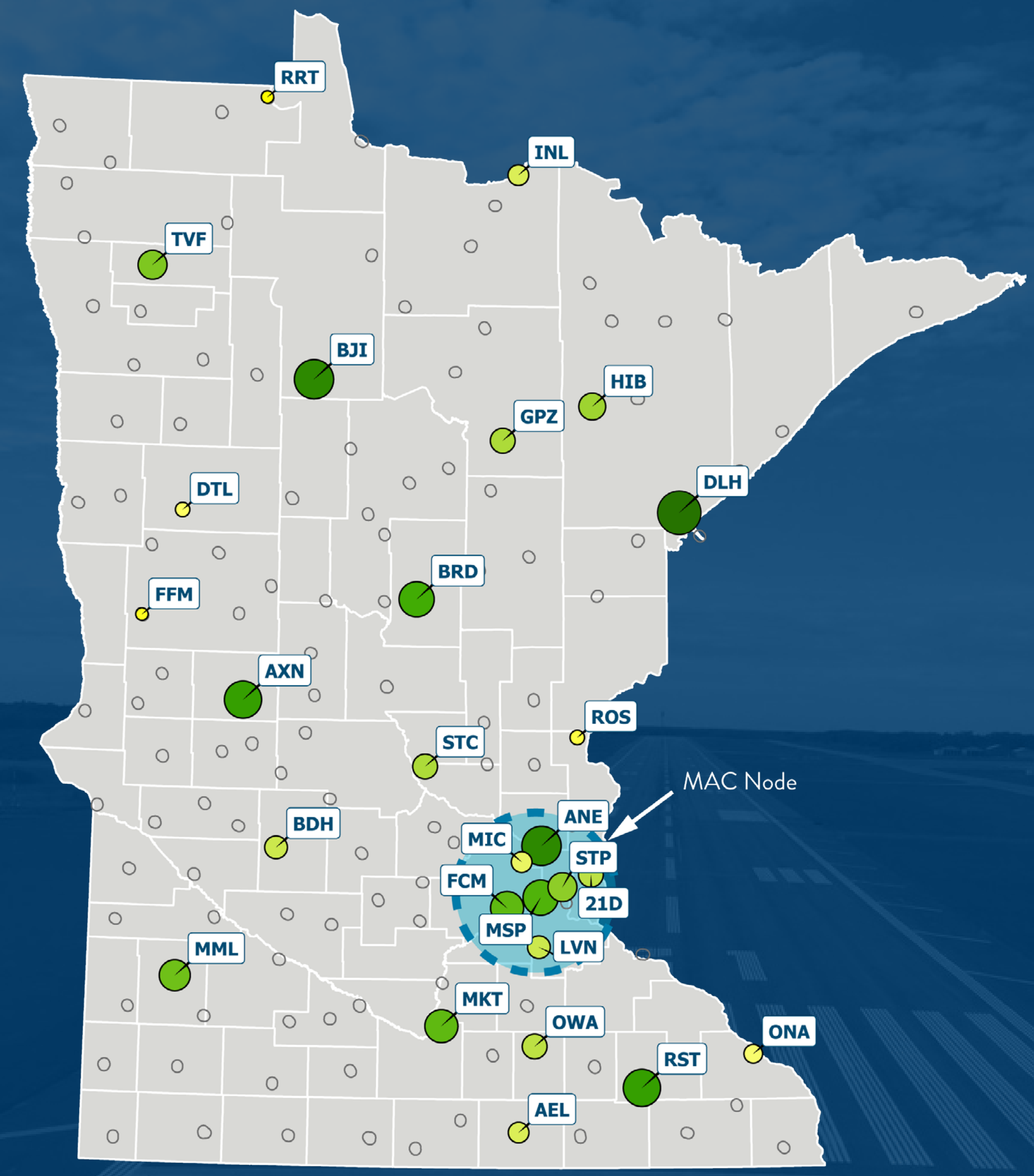
The MEAN is designed to deliver comprehensive statewide coverage, ensuring that electric aviation infrastructure is both strategically located and operationally viable. The selected airports support the most promising early use cases for electric aircraft, reflect strong stakeholder interest in emerging aviation technologies, and possess the necessary infrastructure to support electric aircraft charging. This network lays a strong foundation for the scalable and sustainable deployment of electric aviation across Minnesota and the Upper Midwest.

**Table 12:** *Final MEAN airports*

| Rank | Score | FAA ID | Airport name | Rank | Score | FAA ID | Airport name |
|---|---|---|---|---|---|---|---|
| 1 | 9.65 | DLH | Duluth International | 14 | 6.95 | STC | Saint Cloud Regional |
| 2 | 9.15 | BJI | Bemidji Regional | 15 | 6.70 | GPZ | Grand Rapids-Itasca County |
| 3 | 8.70 | ANE | Anoka County/Blaine | 16 | 6.00 | 21D | Lake Elmo |
| 4 | 8.00 | AXN | Alexandria Municipal | 17 | 6.00 | OWA | Owatonna Degner Regional |
| 5 | 8.00 | RST | Rochester International | 18 | 5.95 | LVN | Airlake |
| 6 | 7.90 | BRD | Brainerd Lakes Regional | 19 | 5.90 | BDH | Willmar Municipal |
| 7 | 7.90 | MSP | Minneapolis-St. Paul Int'l | 20 | 5.80 | INL | Falls International |
| 8 | 7.65 | MKT | Mankato Municipal | 21 | 5.80 | AEL | Albert Lea Municipal |
| 9 | 7.60 | FCM | Flying Cloud | 22 | 5.70 | MIC | Crystal |
| 10 | 7.40 | MML | Marshall-Southwest Minnesota Regional | 23 | 5.55 | ONA | Winona Municipal |
| 11 | 7.40 | TVF | Thief River Falls Regional | 24 | 5.40 | DTL | Detroit Lakes |
| 12 | 7.35 | STP | Saint Paul Downtown | 25 | 5.25 | ROS | Rush City Municipal |
| 13 | 7.30 | HIB | Range Regional | 26 | 5.05 | FFM | Fergus Falls Municipal |
| | | | | 27 | 4.80 | RRT | Warroad International |

MAC node airports

**Figure 8:** *Final MEAN map*



## 2.5 STUDY CONCLUSION

### UNDERSTANDING THE ROLE OF THE MEAN STUDY

The MEAN Study is a foundational research effort—meant as a starting point to build upon and evolve as this exciting new industry grows to serve Minnesotans. It is not a policy directive, infrastructure plan, or funding program. Its purpose is to inform, not to prescribe. This distinction is essential for understanding how the findings should be interpreted and applied.

As a study rather than a plan, the MEAN Study does not establish any formal commitments by MnDOT to implement electric aviation infrastructure, nor does it initiate a grant program or regulatory framework. Rather, it provides a data-driven, stakeholder-informed framework to support future decision-making by a wide range of stakeholders, including airport sponsors, local governments, private investors, OEMs, and aviation businesses. **Importantly, while the study identifies a network of airports, exclusion from this network does not preclude any airport from pursuing electric aircraft infrastructure or operational readiness.**

In addition to offering a robust foundation for future efforts, the MEAN Study also underscores the importance of continued research and collaboration. Several topics emerged throughout the study that represent additional opportunities for research and warrant further exploration. These topics are outlined in **Appendix D**.

### CLARIFYING THE PURPOSE AND USE OF THE MEAN STUDY

The MEAN Study was developed to:

- Identify airports with strong potential to support electric aviation based on current infrastructure and anticipated demand.
- Provide a framework for evaluating electric aviation readiness using transparent, replicable criteria.
- Support local and regional planning efforts by offering a statewide perspective on electric aviation opportunities.
- Encourage stakeholder dialogue and foster collaboration across sectors.

The MEAN Study is intended to be a resource for a broad range of stakeholders. Each group may find different value in the findings and recommendations:

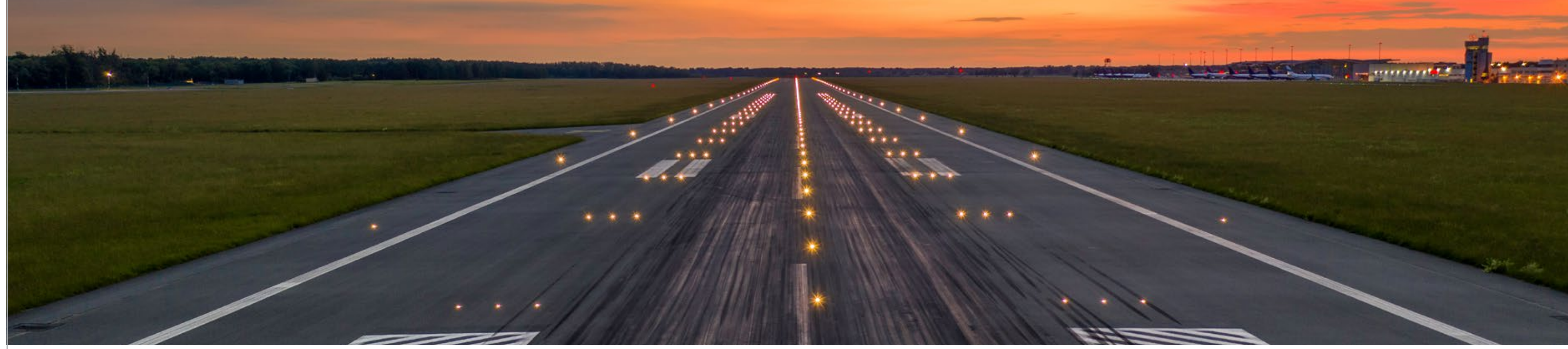
#### FOR AIRPORT SPONSORS AND LOCAL GOVERNMENTS:

- Use the MEAN Study criteria to assess your airport's readiness and identify potential infrastructure gaps. For instance, an airport may discover it needs more electrical capacity and begin discussions with local utilities.
- Engage with community stakeholders to align electric aviation with local economic development or climate action plans.
- Apply MEAN Study insights to pursue funding opportunities or pilot projects with OEMs.

#### FOR PRIVATE INVESTORS AND AVIATION BUSINESSES:

- Use the MEAN Study demand and supply maps to identify high-potential markets for electric aircraft services.
- Explore partnerships with airports and local governments to develop electric charging stations or aircraft hangars.





#### FOR OEMS AND INFRASTRUCTURE PROVIDERS:

- Use the MEAN Study findings to identify airports with favorable conditions for early deployment.
- Collaborate with local stakeholders to conduct feasibility research or demonstration flights.

#### FOR REGIONAL AND STATEWIDE PLANNERS:

- Use the MEAN Study as a reference for integrating electric aviation into transportation and energy planning efforts.
- Coordinate with local, state, and federal agencies to align infrastructure investments and regulatory frameworks.

The MEAN Study is not a definitive list of "approved" or "qualified" airports. Importantly, the absence of an airport from the final MEAN list does not imply that it is unsuitable for electric aviation. Many airports not included in the final MEAN list may still be excellent candidates—particularly if there is a local champion, strong community interest, or compelling use cases such as medical transport, pilot training, or short-haul cargo.

In fact, one of the most important takeaways from this study is that **local initiative matters.** This conclusion emerged from case studies and stakeholder interviews that highlighted how airports with engaged leadership, community support, and a willingness to dialogue with OEMs or utilities were more likely to pursue electric aviation opportunities. For example, airports that had already begun conversations with stakeholders, or had integrated sustainability goals into their strategic plans, demonstrated a higher level of readiness and momentum. These insights underscore the importance of local champions in driving innovation and adoption.

### A PRAGMATIC PATH FORWARD

The MEAN Study is an important first step in preparing Minnesota for the future of aviation. In alignment with the theme of pragmatism, the study's focus is on equipping Minnesota's aviation stakeholders with the knowledge, tools, and partnerships necessary to make informed decisions about electric aviation policy and investment when the time is right.

The research, methodologies, and findings presented here invite stakeholders to engage with MnDOT and industry leaders—guided by data and grounded in local context. Additionally, the study provides a solid foundation for follow-on efforts to identify site-specific infrastructure needs and economic opportunities at airports identified as part of the MEAN.

Ultimately, MnDOT envisions this study as a contribution to Minnesota's continued leadership in sustainable and forward-thinking transportation. As the aviation industry evolves, so too must the state's approach to innovation. The MEAN Study supports this evolution and provides a thoughtful and strategic foundation for advancing electric aviation across the Upper Midwest and beyond.

*Duluth International Airport*

*Appendix A*

# COMPLETE MEAN SCORES BY AIRPORT

# COMPLETE MEAN SCORES BY AIRPORT

| Rank | FAA ID | Airport Name | State Classification | Demand Score | Supply Score | MEAN Score |
|---|---|---|---|---|---|---|
| 1 | DLH | Duluth International Airport | Key Commercial Service | 6.75 | 2.90 | 9.65 |
| 2 | BJI | Bemidji Regional Airport | Key Commercial Service | 6.70 | 2.45 | 9.15 |
| 3 | ANE | Anoka County-Blaine Airport | Key General Aviation | 6.35 | 2.35* | 8.70 |
| 4 | AXN | Alexandria Municipal Airport | Key General Aviation | 5.35 | 2.65 | 8.00 |
| 5 | RST | Rochester International Airport | Key Commercial Service | 5.35 | 2.65 | 8.00 |
| 6 | BRD | Brainerd Lakes Regional Airport | Key Commercial Service | 5.75 | 2.15* | 7.90 |
| 7 | MSP | Minneapolis-St. Paul International | Key Commercial Service | 5.00 | 2.90* | 7.90 |
| 8 | MKT | Mankato Municipal Airport | Key General Aviation | 5.55 | 2.10* | 7.65 |
| 9 | FCM | Flying Cloud Airport | Key General Aviation | 5.00 | 2.60* | 7.60 |
| 10 | MML | Marshall-Southwest Minnesota Regional Airport | Key General Aviation | 4.55 | 2.85 | 7.40 |
| 11 | TVF | Thief River Falls Regional Airport | Key Commercial Service | 4.70 | 2.70 | 7.40 |
| 12 | STP | Saint Paul Downtown Airport | Key General Aviation | 4.55 | 2.80* | 7.35 |
| 13 | HIB | Range Regional Airport | Key Commercial Service | 4.35 | 2.95 | 7.30 |
| 14 | SGS | South St. Paul Municipal Airport | Intermediate Large | 4.30 | 2.80* | 7.10 |
| 15 | STC | Saint Cloud Regional Airport | Key Commercial Service | 4.25 | 2.70 | 6.95 |
| 16 | GPZ | Grand Rapids-Itasca County | Key General Aviation | 4.15 | 2.55 | 6.70 |
| 17 | PNM | Princeton Municipal Airport | Intermediate Large | 4.40 | 2.20 | 6.60 |
| 18 | EVM | Eveleth-Virginia Municipal Airport | Intermediate Large | 5.40 | 1.00 | 6.40 |
| 19 | 21D | Lake Elmo Airport | Intermediate Small | 3.60 | 2.40* | 6.00 |
| 20 | OWA | Owatonna Degner Regional | Key General Aviation | 4.20 | 1.80* | 6.00 |
| 21 | LVN | Airlake Airport | Intermediate Large | 3.60 | 2.35* | 5.95 |
| 22 | BDH | Willmar Municipal Airport | Key General Aviation | 3.75 | 2.15 | 5.90 |
| 23 | COQ | Cloquet-Carlton County Airport | Intermediate Large | 3.75 | 2.10 | 5.85 |
| 24 | INL | Falls International Airport | Key Commercial Service | 3.20 | 2.60 | 5.80 |
| 25 | AEL | Albert Lea Municipal Airport | Key General Aviation | 3.80 | 2.00 | 5.80 |
| 26 | MIC | Crystal Airport | Intermediate Small | 3.60 | 2.10* | 5.70 |
| 27 | FBL | Faribault Municipal Airport | Intermediate Large | 4.30 | 1.30 | 5.60 |
| 28 | ONA | Winona Municipal Airport | Key General Aviation | 2.90 | 2.65* | 5.55 |
| 29 | DTL | Detroit Lakes Airport | Intermediate Large | 3.30 | 2.10 | 5.40 |
| 30 | CFE | Buffalo Municipal Airport | Intermediate Small | 3.10 | 2.20* | 5.30 |
| 31 | ROS | Rush City Municipal Airport | Intermediate Large | 3.80 | 1.45 | 5.25 |
| 32 | FFM | Fergus Falls Municipal Airport | Key General Aviation | 3.25 | 1.80* | 5.05 |
| 33 | RRT | Warroad International Airport | Key General Aviation | 2.70 | 2.10 | 4.80 |
| 34 | ULM | New Ulm Municipal Airport | Key General Aviation | 2.25 | 2.30 | 4.55 |
| 35 | RGK | Red Wing Regional | Key General Aviation | 2.90 | 1.50* | 4.40 |
| 36 | HCD | Hutchinson Municipal Airport | Intermediate Large | 2.30 | 1.95 | 4.25 |
| 37 | RWF | Redwood Falls Municipal Airport | Intermediate Large | 2.15 | 2.05 | 4.20 |
| 38 | JKJ | Moorhead Municipal Airport | Intermediate Large | 2.20 | 2.00 | 4.20 |
| 39 | LXL | Little Falls-Morrison County Airport | Intermediate Large | 3.40 | 0.75 | 4.15 |
| 40 | ROX | Roseau Municipal Airport | Intermediate Large | 2.55 | 1.45 | 4.00 |
| 41 | ELO | Ely Municipal Airport | Key General Aviation | 2.05 | 1.90 | 3.95 |
| 42 | AUM | Austin Municipal Airport | Key General Aviation | 2.60 | 1.35* | 3.95 |
| 43 | CQM | Cook Municipal Airport | Intermediate Large | 2.50 | 1.35 | 3.85 |
| 44 | CNB | Canby Municipal Airport | Intermediate Large | 1.50 | 2.30 | 3.80 |
| 45 | CKN | Crookston Municipal Airport | Intermediate Large | 2.00 | 1.75 | 3.75 |
| 46 | JMR | Mora Municipal Airport | Intermediate Large | 1.65 | 2.05 | 3.70 |
| 47 | OTG | Worthington Municipal Airport | Key General Aviation | 2.15 | 1.55* | 3.70 |
| 48 | DYT | Duluth-Sky Harbor Airport & Seaplane Base | Intermediate Small | 2.05 | 1.65 | 3.70 |
| 49 | AIT | Aitkin Municipal Airport | Intermediate Large | 2.35 | 1.30 | 3.65 |
| 50 | HCO | Hallock Municipal Airport | Intermediate Large | 1.65 | 1.95 | 3.60 |
| 51 | MOX | Morris Municipal Airport | Intermediate Large | 2.50 | 1.05 | 3.55 |
| 52 | 12Y | Le Sueur Municipal Airport | Intermediate Small | 1.50 | 1.95 | 3.45 |
| 53 | FRM | Fairmont Municipal Airport | Key General Aviation | 1.65 | 1.65 | 3.30 |
| 54 | BDE | Baudette International Airport | Key General Aviation | 1.20 | 2.10* | 3.30 |
| 55 | MVE | Montevideo-Chippewa County Airport | Intermediate Large | 1.35 | 1.95* | 3.30 |
| 56 | TWM | Two Harbors-Richard B. Helgeson Airport | Intermediate Large | 1.45 | 1.70 | 3.15 |
| 57 | GDB | Granite Falls Municipal Airport | Intermediate Large | 1.60 | 1.50 | 3.10 |
| 58 | LJF | Litchfield Municipal Airport | Intermediate Large | 1.10 | 1.95 | 3.05 |
| 59 | TKC | Tracy Municipal Airport | Intermediate Small | 0.60 | 2.30* | 2.90 |
| 60 | CKC | Grand Marais-Cook County | Key General Aviation | 1.95 | 0.95 | 2.90 |
| 61 | XVG | Longville Municipal Airport | Intermediate Small | 0.95 | 1.90* | 2.85 |
| 62 | D42 | Springfield Municipal Airport | Intermediate Small | 0.75 | 2.10* | 2.85 |
| 63 | MWM | Windom Municipal Airport | Intermediate Small | 1.10 | 1.65 | 2.75 |
| 64 | 12D | Tower Municipal Airport | Intermediate Small | 1.05 | 1.70* | 2.75 |
| 65 | 25D | Forest Lake Airport | Intermediate Small | 1.65 | 1.05 | 2.70 |
| 66 | PQN | Pipestone Municipal Airport | Intermediate Large | 1.15 | 1.50* | 2.65 |

| Rank | FAA ID | Airport Name | State Classification | Demand Score | Supply Score | MEAN Score |
|---|---|---|---|---|---|---|
| 67 | 16D | Perham Municipal Airport | Intermediate Large | 1.25 | 1.40 | 2.65 |
| 68 | 10D | Winsted Municipal Airport | Landing Strip Turf | 1.30 | 1.30* | 2.60 |
| 69 | ORB | Orr Regional Airport | Intermediate Large | 1.40 | 1.15 | 2.55 |
| 70 | LYV | Luverne Municipal Airport | Intermediate Large | 1.30 | 1.20* | 2.50 |
| 71 | FKA | Preston Fillmore County Airport | Intermediate Large | 1.50 | 1.00* | 2.50 |
| 72 | 04Y | Hawley Municipal Airport | Intermediate Small | 1.25 | 1.20* | 2.45 |
| 73 | ADC | Wadena Municipal Airport | Intermediate Large | 1.00 | 1.40 | 2.40 |
| 74 | BBB | Benson Municipal Airport | Intermediate Large | 0.80 | 1.55 | 2.35 |
| 75 | PEX | Paynesville Municipal Airport | Intermediate Small | 1.05 | 1.30* | 2.35 |
| 76 | MJQ | Jackson Municipal Airport | Intermediate Small | 1.15 | 1.15* | 2.30 |
| 77 | 6D1 | Brooten Municipal Airport | Intermediate Small | 1.20 | 1.05* | 2.25 |
| 78 | FSE | Fosston Municipal Airport | Intermediate Small | 0.80 | 1.40* | 2.20 |
| 79 | SBU | Blue Earth Municipal Airport | Intermediate Small | 1.30 | 0.90* | 2.20 |
| 80 | FOZ | Bigfork Municipal Airport | Intermediate Large | 0.95 | 1.20 | 2.15 |
| 81 | TOB | Dodge Center Municipal Airport | Intermediate Large | 0.60 | 1.50* | 2.10 |
| 82 | CHU | Caledonia-Houston County Airport | Intermediate Small | 0.75 | 1.35 | 2.10 |
| 83 | GHW | Glenwood Municipal Airport | Intermediate Large | 1.10 | 1.00* | 2.10 |
| 84 | ACQ | Waseca Municipal Airport | Intermediate Small | 1.45 | 0.60* | 2.05 |
| 85 | GYL | Glencoe Municipal Airport | Intermediate Small | 1.45 | 0.60* | 2.05 |
| 86 | MGG | Maple Lake Municipal Airport | Intermediate Small | 0.90 | 1.10* | 2.00 |
| 87 | Y63 | Elbow Lake Municipal Airport | Intermediate Small | 0.95 | 1.05* | 2.00 |
| 88 | 14Y | Long Prairie Airport | Intermediate Small | 0.45 | 1.50* | 1.95 |
| 89 | VWU | Waskish Municipal Airport | Landing Strip Turf | 1.20 | 0.70 | 1.90 |
| 90 | MZH | Moose Lake-Carlton County Airport | Intermediate Small | 0.90 | 0.95 | 1.85 |
| 91 | PWC | Pine River Regional Airport | Intermediate Small | 0.95 | 0.90* | 1.85 |
| 92 | D39 | Sauk Centre Municipal Airport | Intermediate Small | 1.20 | 0.60* | 1.80 |
| 93 | JYG | Saint James Municipal Airport | Intermediate Large | 0.80 | 0.90 | 1.70 |
| 94 | OVL | Olivia Regional Airport | Intermediate Small | 0.60 | 1.05* | 1.65 |
| 95 | SAZ | Staples Municipal Airport | Intermediate Small | 0.65 | 0.90* | 1.55 |
| 96 | 63Y | Tyler Municipal Airport | Landing Strip Turf | 0.15 | 1.35* | 1.50 |
| 97 | Y49 | Walker Municipal Airport | Intermediate Small | 0.95 | 0.55* | 1.50 |
| 98 | HZX | McGregor-Isedor Iverson Airport | Intermediate Small | 0.30 | 1.15* | 1.45 |
| 99 | VVV | Ortonville Municipal Airport | Intermediate Small | 0.15 | 1.10* | 1.25 |



| Rank | FAA ID | Airport Name | State Classification | Demand Score | Supply Score | MEAN Score |
|---|---|---|---|---|---|---|
| 100 | 18Y | Milaca Municipal Airport | Landing Strip Turf | 0.60 | 0.65 | 1.25 |
| 101 | 05Y | Henning Municipal Airport | Landing Strip Turf | 0.75 | 0.50* | 1.25 |
| 102 | 1D6 | Hector Municipal Airport | Intermediate Small | 0.80 | 0.45 | 1.25 |
| 103 | Y58 | Sleepy Eye Municipal Airport | Landing Strip Turf | 0.75 | 0.45* | 1.20 |
| 104 | D81 | Red Lake Falls Municipal Airport | Intermediate Small | 0.45 | 0.70* | 1.15 |
| 105 | 3N8 | Mahnomen County Airport | Intermediate Small | 0.15 | 0.95* | 1.10 |
| 106 | AQP | Appleton Municipal Airport | Intermediate Small | 0.45 | 0.65* | 1.10 |
| 107 | 47Y | Pelican Rapids Municipal Airport | Landing Strip Turf | 0.90 | 0.15* | 1.05 |
| 108 | 23D | Karlstad Municipal Airport | Landing Strip Turf | 1.05 | 0.00* | 1.05 |
| 109 | D14 | Fertile Municipal Airport | Intermediate Small | 0.30 | 0.70* | 1.00 |
| 110 | 55Y | Rushford Municipal Airport | Intermediate Small | 0.45 | 0.55* | 1.00 |
| 111 | 7Y3 | Backus Municipal Airport | Landing Strip Turf | 0.45 | 0.55* | 1.00 |
| 112 | DXX | Madison-Lac Qui Parle Airport | Intermediate Small | 0.30 | 0.60* | 0.90 |
| 113 | 9Y2 | East Gull Lake Airport | Landing Strip Turf | 0.75 | 0.15* | 0.90 |
| 114 | ETH | Wheaton Municipal Airport | Intermediate Small | 0.30 | 0.55* | 0.85 |
| 115 | D32 | Starbuck Municipal Airport | Landing Strip Turf | 0.45 | 0.40* | 0.85 |
| 116 | 52Y | Remer Municipal Airport | Landing Strip Turf | 0.60 | 0.25* | 0.85 |
| 117 | DVP | Slayton Municipal Airport | Intermediate Small | 0.00 | 0.80* | 0.80 |
| 118 | D41 | Stephen Municipal Airport | Intermediate Small | 0.30 | 0.50* | 0.80 |
| 119 | 68Y | Wells Municipal Airport | Landing Strip Turf | 0.60 | 0.20* | 0.80 |
| 120 | 9Y0 | Bowstring Airport | Landing Strip Turf | 0.60 | 0.20* | 0.80 |
| 121 | D37 | Warren Municipal Airport | Intermediate Small | 0.15 | 0.60* | 0.75 |
| 122 | 06Y | Herman Municipal Airport | Intermediate Small | 0.30 | 0.45* | 0.75 |
| 123 | 7Y4 | Bagley Municipal Airport | Intermediate Small | 0.00 | 0.60* | 0.60 |
| 124 | D00 | Norman County-Ada/Twin Valley Airport | Intermediate Small | 0.00 | 0.55* | 0.55 |
| 125 | 8Y5 | Clarissa Municipal Airport | Landing Strip Turf | 0.45 | 0.00* | 0.45 |
| 126 | 13Y | Littlefork Municipal/Hanover Airport | Landing Strip Turf | 0.15 | 0.20* | 0.35 |
| 127 | 43Y | Northome Municipal Airport | Landing Strip Turf | 0.15 | 0.20* | 0.35 |
| 128 | 07Y | Hill City-Quadna Mountain Airport | Landing Strip Turf | 0.30 | 0.05* | 0.35 |
| 129 | 3G2 | Grygla Municipal Airport | Landing Strip Turf | 0.00 | 0.20* | 0.20 |
| 130 | 7Y9 | Big Falls Municipal Airport | Landing Strip Turf | 0.15 | 0.05* | 0.20 |

**Complete electrical infrastructure data could not be obtained for airport. Therefore, supply score was developed utilizing assumption-based methodology as described in **Section 2.3**.*

*Appendix B*

# ELECTRIC PROPULSION AND SUPPORTING TECHNOLOGIES

This appendix provides an overview of the primary types of electric propulsion systems and explores emerging technologies that support the advancement of electric flight. These supporting technologies include high-capacity charging systems, wireless charging, battery swapping, and advanced energy storage and load management systems—all of which are critical to enabling scalable and efficient electric aviation operations.

*Courtesy of Ampaire, Inc.*

# TYPES OF ELECTRIC PROPULSION

Electric aviation encompasses a broad spectrum of aircraft and propulsion technologies that rely on electric power rather than conventional internal combustion engines fueled by fossil fuels. The primary types of electric propulsion include:

- Turboelectric
- Series Hybrid Electric
- Battery Electric
- Fuel Cell Electric

Each system offers unique advantages and challenges, depending on aircraft size, mission profile, and technological maturity.[1]

## TURBOELECTRIC PROPULSION

Turboelectric propulsion is a hybrid system that combines traditional fuel-based turbines with electric drive systems. As illustrated in **Figure B.1**, fuel is combusted in a turbine engine, which drives an electric generator. This generator converts mechanical energy into electricity, which then powers one or more electric motors connected to propellers or fans.

Key characteristics of turboelectric systems include:

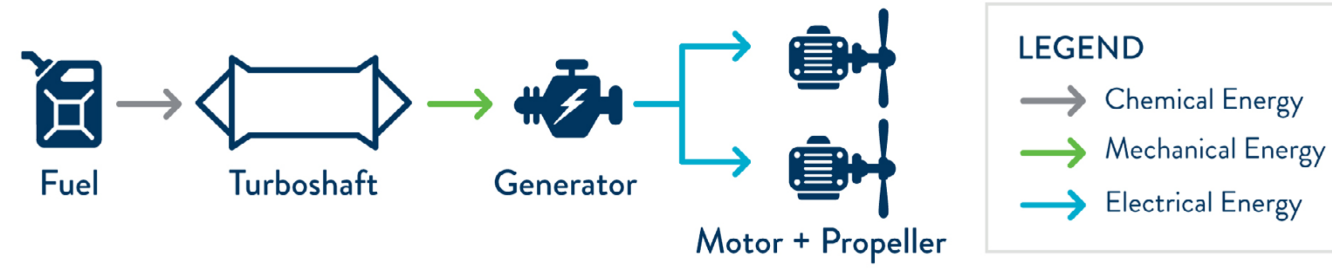
- **High power output:** Leverages the efficiency and reliability of turbine engines.
- **Distributed propulsion potential:** Enables multiple electric motors to be placed across the airframe, allowing for innovative aircraft designs and improved aerodynamic performance.
- **Fuel efficiency:** Offers reduced fuel consumption compared to conventional propulsion systems.
- **Design complexity:** The integration of mechanical and electrical components increases system complexity and weight, which can impact maintenance and performance.

Turboelectric propulsion is considered a promising near-term solution for larger regional aircraft and single-aisle commercial jets, serving as a transitional technology toward fully electric aviation.

[1] *National Academies of Sciences, Engineering, and Medicine. 2016. Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions. Washington, DC: The National Academies Press. https://doi.org/10.17226/23490.*



**Figure B.1:** *Turboelectric propulsion*

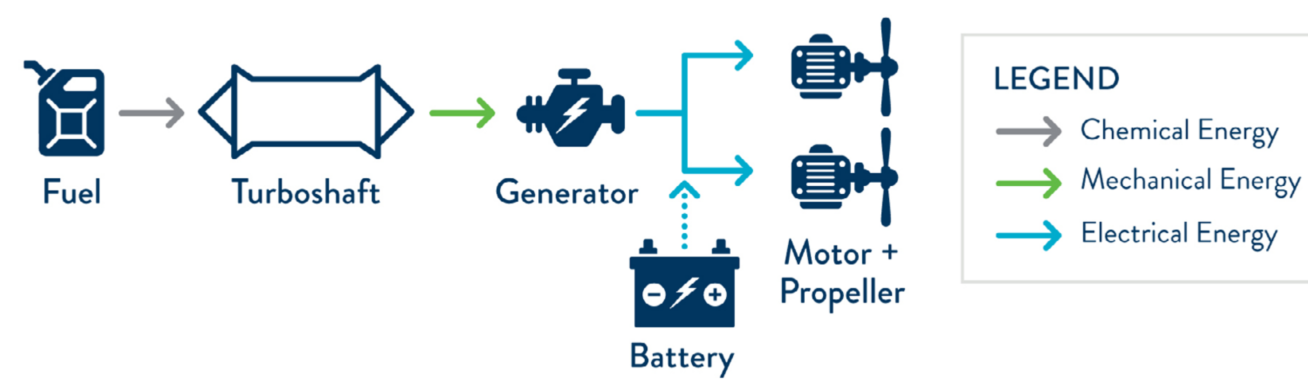



## SERIES HYBRID-ELECTRIC PROPULSION

Series hybrid-electric propulsion combines a traditional internal combustion engine with an electric propulsion system, similar to turboelectric configurations. However, it also incorporates batteries to store additional energy, offering greater operational flexibility and extended range. As shown in **Figure B.2**, the engine powers a generator, which produces electricity to drive the electric motors, while the batteries can supplement power during high-demand phases such as takeoff or climb.

Key advantages of this system include improved fuel efficiency and the ability to optimize engine operation. However, the inclusion of both an engine and battery system increases weight and complexity, which can impact aircraft performance and maintenance requirements.

**Figure B.2:** *Series hybrid-electric propulsion*



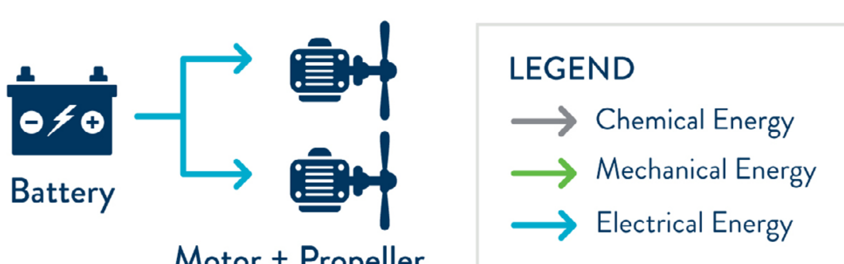
*Courtesy of Joby Aviation. © Joby Aero, Inc.*

## BATTERY ELECTRIC PROPULSION

Battery electric propulsion is a fully electric system that relies exclusively on batteries to store and deliver electrical energy directly to the motors, as illustrated in **Figure B.3**. This configuration eliminates combustion entirely, resulting in zero emissions during operation. The performance of battery electric aircraft is heavily dependent on battery efficiency and energy density. Currently, lithium-ion batteries are the most widely used, though advancements in solid-state batteries and other high-density storage technologies are underway.

Battery electric systems offer several benefits, including lower maintenance due to fewer moving parts, quiet operations when compared to traditional aircraft propulsion systems, and no direct emissions. However, current battery limitations restrict range and payload capacity, and the need for robust charging infrastructure remains a significant barrier to widespread adoption.

**Figure B.3:** *Battery electric propulsion*

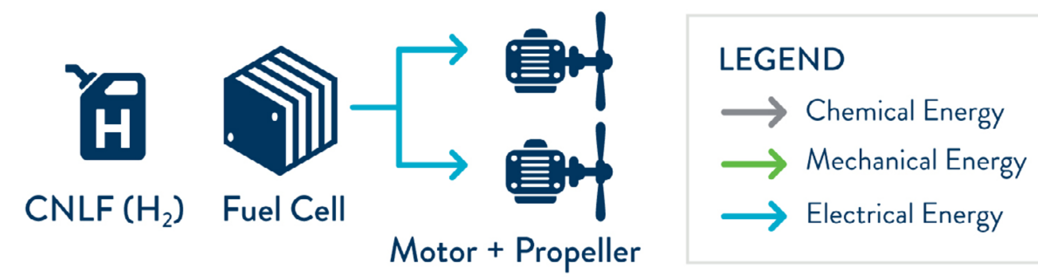





## FUEL CELL ELECTRIC PROPULSION

Fuel cell electric propulsion uses hydrogen fuel cells to convert chemical energy into electricity without combustion, as depicted in **Figure B.4**. When hydrogen is used as a fuel source, the only byproduct is water vapor, making this a zero-emission technology. Fuel cells offer higher energy density than batteries, making them a promising solution for longer-range electric flights. They generate electricity to power electric motors, supporting clean and efficient operation. Additionally, hydrogen refueling can be completed more quickly than battery recharging, offering operational advantages. Despite these benefits, the feasibility of scaling fuel cell technology for commercial use remains to be determined as significant investment in hydrogen production, storage, and refueling infrastructure is required to support widespread adoption.

**Figure B.4:** *Fuel cell electric propulsion*




*Courtesy of BETA Technologies*

# EMERGING CHARGING TECHNOLOGIES

Emerging charging solutions for electric aircraft focus on delivering high-power, efficient, and flexible energy transfer. A selection of these technologies is highlighted within this section.

## MEGAWATT CHARGING SYSTEMS

The Megawatt Charging System (MCS) is a high-performance charging standard designed to rapidly charge large batteries used in electric trucks, buses, and aircraft. Based on the Combined Charging System (CCS), MCS aims to provide a universal solution across multiple vehicle platforms. Capable of delivering up to 3.75 megawatts of power—approximately seven times more than currentcontemporary direct current  (DC) fast chargers—MCS is under active development, with pilot deployments expected in 2025.

## WIRELESS CHARGING PADS

Wireless or inductive charging systems allow aircraft to recharge without physical connectors, reducing wear and enabling faster turnaround times. These systems operate via resonant inductive coupling: an alternating current in a ground-based coil generates an electromagnetic field, which induces a current in a receiver coil on the aircraft. The induced alternating current (AC) is then converted to direct current (DC) to charge the battery. Wireless charging offers operational simplicity and safety benefits, particularly in high-traffic environments.

## BATTERY SWAPPING SYSTEMS

Battery swapping addresses the time constraints of conventional charging by enabling rapid replacement of modular battery packs. Aircraft designed for this approach feature accessible battery compartments, allowing depleted batteries to be quickly removed and replaced with fully charged units. While this method presents challenges related to infrastructure, standardization, and logistics, it holds promise for high-frequency operations and could become a key component of future electric aviation networks.

## ENERGY STORAGE SYSTEMS

Battery Energy Storage Systems (BESS) are critical for managing energy supply at airports. These systems consist of large arrays of battery cells that store electricity during off-peak hours or when renewable energy is abundant. During peak demand or grid outages, BESS can discharge stored energy, converting DC to AC to support airport operations. This reduces reliance on the grid, provides economic benefits, and enhances energy security.

BESS are particularly advantageous for charging electric aircraft due to the high-power input required. The stored energy can be used in combination with main grid power to increase the available power input, which is critical for quick turnaround times.



## LOAD MANAGEMENT SYSTEMS

Load management systems, or load sharing devices, are essential tools for supporting the increased demand for electric vehicle (EV) charging infrastructure. EV load management systems, which can be implemented through either software or hardware solutions, are specifically designed to optimize the charging process when power capacity is limited and for cost -effectiveness by restricting power delivery during peak hours. Their primary goal is to minimize strain on the electrical grid and ensure efficient use of available resources.

These systems continuously monitor and manage the charging process, considering factors such as grid capacity, electricity demand, and individual vehicle requirements. Load balancing allocates the available power among the chargers in a network, ensuring each vehicle gets charged over time without exceeding the overall power limit of the infrastructure.

Load balancing can either distribute equal power to each charger or dynamically adjust the power allocation based on the state of charge of each aircraft's battery. Smart load balancing further enhances efficiency by adapting charging rates in real time, ensuring that aircraft with imminent departures receive priority. This intelligent allocation of resources supports timely readiness and cost-effective operations.

St. Paul Downtown Airport

*Appendix C*

# STAKEHOLDER ENGAGEMENT STRATEGY AND INSIGHTS

The MEAN Study was designed not only as a technical assessment of electric aviation readiness, but also as a platform for initiating meaningful conversations across Minnesota's aviation ecosystem. Stakeholder engagement was a cornerstone of the study, shaping both its methodology and findings. Recognizing that electric aviation is an emerging field filled with both promise and uncertainty, the study team approached engagement with a commitment to transparency, inclusivity, and pragmatism.

This appendix provides a detailed overview of the engagement strategies employed and the insights gained throughout the process. By documenting these experiences, the MEAN Study aims to inform and strengthen future planning efforts in Minnesota and beyond.

## LEADING WITH PRAGMATISM: A FOUNDATION FOR TRUST

From the outset, the study team adopted a pragmatic and grounded approach to stakeholder engagement. Rather than focusing on speculative technologies or distant future scenarios, the team emphasized near-term opportunities based on current capabilities and realistic projections. By clearly framing the MEAN Study as a planning and readiness tool—rather than a funding program or infrastructure mandate—the team fostered open, constructive dialogue. Ongoing feedback helped refine and strengthen the study's methodology and findings.

## MULTI-CHANNEL ENGAGEMENT STRATEGY

To promote broad participation and capture diverse perspectives, the MEAN Study employed a multi-channel engagement strategy. This included:

- A statewide stakeholder survey
- Targeted interviews and roundtables with airport sponsors, tenants, and utility providers
- A series of virtual meetings with electric aircraft and infrastructure OEMs
- In-person workshops across Minnesota

This layered approach allowed stakeholders with varying levels of familiarity and interest in electric aviation to engage in ways that suited their preferences and availability. It also ensured that both technical experts and community voices were represented in the study's development.

## EARLY AND TRANSPARENT COMMUNICATION

Transparency was a guiding principle throughout the engagement process. A dedicated project webpage on MnDOT's *Let's Talk Transportation* platform served as a central hub for information and included an introductory video, project updates, and access to the stakeholder survey. The study team also communicated openly about areas of uncertainty—such as aircraft certification timelines and infrastructure requirements—clearly distinguishing between confirmed data and emerging trends. This approach helped build trust and encouraged deeper stakeholder engagement.

## OEM COLLABORATION

Engagement with electric aircraft, propulsion system, and infrastructure OEMs was instrumental in shaping the MEAN Study's technical foundation. Through a series of structured interviews, the team gathered insights on aircraft performance, charging requirements, certification timelines, cold-weather operations, and other critical infrastructure needs. These conversations helped validate key assumptions, refine evaluation criteria, and ensure that the study's recommendations were grounded in real-world feasibility. OEMs also provided valuable feedback on infrastructure readiness, emphasizing the importance of three-phase power availability, transformer proximity, and scalable charging solutions. These insights directly informed the supply analysis and helped identify Minnesota airports best positioned to support electric aviation over the next decade.




## REGIONAL WORKSHOP ACCESSIBILITY

To enhance geographic equity and capture location-specific insights, the MEAN Study team hosted six in-person workshops across Minnesota. These sessions were held in both urban and rural locations, including St. Paul, Alexandria, Marshall, Bemidji, Duluth, and Rochester. Over 70 stakeholders participated, representing 26 airports, 11 businesses, 6 consulting firms, 4 utility providers, 3 neighboring state DOTs, and the FAA.

This regional format allowed stakeholders to discuss electric aviation in the context of their local infrastructure, economic priorities, and community needs, surfacing unique challenges such as rural grid limitations and space constraints at commercial airports.

## INTEGRATION OF STAKEHOLDER INPUT INTO METHODOLOGY

Stakeholder feedback was actively integrated into the MEAN Study's methodology. For example, input from airport sponsors and tenants helped identify the most viable near-term use cases for electric aviation in Minnesota: pilot training, short-haul cargo, and medical transport. These use cases became foundational elements of the demand analysis. Similarly, feedback from utility providers and OEMs shaped the supply evaluation criteria, particularly around electrical capacity and charging infrastructure. This participatory approach enhanced the study's credibility and ensured that the final MEAN network reflected both technical feasibility and stakeholder priorities.

## OPTIMIZING SURVEY DESIGN AND INTERPRETATION

The stakeholder survey was a valuable tool for gathering baseline data on infrastructure and interest in electric aviation. As with many surveys in emerging fields, some variability in responses and interpretation challenges were encountered. To address this, the team supplemented survey data with follow-up interviews and cross-referenced responses with existing datasets. This triangulation helped validate findings, improve response quality and consistency, and ensure that the demand analysis was both robust and representative.

## ENHANCING ENGAGEMENT THROUGH VISUAL AND SCENARIO-BASED TOOLS

To help demystify electric aviation concepts and foster more informed dialogue, the study team made extensive use of visual aids and real-world examples during stakeholder workshops and presentations. For example, maps illustrating potential electric aviation networks and diagrams of charging infrastructure enabled stakeholders to visualize how electric aircraft could operate within their communities. Additionally, tools such as scenario planning exercises, interactive maps, and other visual resources helped participants better understand the practical implications of electric aviation and engage more meaningfully in planning discussions.

*Courtesy of Joby Aviation. © Joby Aero, Inc.*

*Appendix D*

# OPPORTUNITIES FOR ADDITIONAL RESEARCH

The MEAN Study highlights the rapid evolution of electric aviation, a field filled with both promise and uncertainty. While this study establishes a foundational framework for assessing infrastructure readiness and identifying near-term use cases in Minnesota, it also reveals several critical knowledge and regulatory gaps that must be addressed to support the safe, scalable deployment of electric aircraft across the US and beyond.

Several topics emerged throughout the course of the MEAN Study as areas where standards, technologies, and policies are still developing. Each of the following topics represent opportunities for MnDOT, research institutions, and industry partners to explore further through pilot programs, regulatory development, and applied research.

*Courtesy of BETA Technologies*

## FAA SEPARATION STANDARDS FOR CHARGING SYSTEMS

The integration of high-capacity electric aircraft chargers introduces new spatial and safety considerations at airports. However, FAA guidance on separation distances between chargers, aircraft, fuel systems, and other infrastructure is still under development. Future research and operational data will be essential to inform evidence-based standards that ensure safety without unnecessarily limiting airport design flexibility.

## BUILDING CODES FOR ELECTRIC AIRCRAFT STORAGE AND CHARGING

Electric aircraft introduce new requirements for hangar design, including fire safety, ventilation, and electrical integration. Existing building codes were not developed with these technologies in mind. There is a growing need to evaluate how current codes apply—or fall short—and to develop best practices tailored to electric propulsion systems.

## FIRE SUPPRESSION STANDARDS

The fire behavior of lithium-ion batteries differs significantly from that of conventional fuels, posing new challenges for Aircraft Rescue and Firefighting (ARFF) teams. Aviation-specific suppression standards are still emerging. Research into suppression agents, response protocols, and training requirements will be critical to ensure emergency preparedness evolves alongside electric aircraft deployment.

## DEICING STANDARDS AND CONSIDERATIONS

Cold weather operations are a defining challenge for electric aviation in Minnesota. While OEMs are developing thermal management systems, the energy demands of deicing and the lack of standardized procedures for electric aircraft remain concerns. Further research is needed to understand aircraft and charging performance in icing conditions and to develop infrastructure and operational strategies that mitigate cold-weather impacts.

## IMPACTS ON INSURANCE COSTS

The insurance landscape for electric aviation is still developing. With limited operational history, insurers face uncertainty in pricing policies for aircraft, charging infrastructure, and related liabilities. As more aircraft enter service, data-driven research will be essential to understand risk exposure and to guide the development of sustainable insurance models.



## IMPACT OF RENEWABLE ENERGY ON PEAK DEMAND COSTS

Many stakeholders envision powering electric aviation infrastructure with renewable energy, particularly solar. However, the interaction between intermittent generation, peak demand charges, and grid reliability is complex. Research into how battery energy storage systems (BESS), smart load management, and utility rate structures affect electric aviation operations will help airports and utilities plan cost-effective, resilient energy strategies.

## USER AND PUBLIC PERCEPTION OF ELECTRIC AVIATION

Public acceptance will be critical to the success of electric aviation. Yet, little is known about how travelers, pilots, and communities perceive electric aircraft in terms of safety, reliability, and value. Social science research—including surveys, focus groups, and pilot programs—can help uncover barriers to acceptance and inform effective outreach strategies.

## PILOT EXPERIENCE AND TRAINING IN ELECTRIC AIRCRAFT

Electric aircraft differ from conventional aircraft in propulsion behavior, energy management, and emergency procedures. As these aircraft enter training fleets, flight schools and regulators will need to adapt curricula and certification standards. Research into pilot performance, simulator fidelity, and training outcomes will be essential to prepare the next generation of pilots for the unique demands of electric aviation.


*Courtesy of Joby Aviation. © Joby Aero, Inc.*

# MINNESOTA ELECTRIC AVIATION NETWORK

# M.E.A.N.

# STUDY

DEPARTMENT OF TRANSPORTATION
AERONAUTICS