WHITE PAPER

THE U.S. DEPARTMENT OF ENERGY VEHICLE TECHNOLOGIES OFFICE AND NATIONAL AERONAUTICS AND SPACE ADMINISTRATION JOINT ASSESSMENT OF THE R&D NEEDS FOR ELECTRIC AVIATION

September 2021

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EXECUTIVE SUMMARY

There is a growing revolution in the world of aviation, from technological innovation to business creation, that aims to launch a new era of flight by transitioning today's aircraft from jet engines to electric motors. Driving factors are the promise of lower fuel and maintenance costs, decreased noise and air pollution, and the possibility of unique aircraft designs enabled by distributed propulsion. Further, concepts around urban air mobility as a means of reducing congestion have accelerated the move to electrification. A large part of this transition is driven by the significant reduction in costs and improvements in performance of lithium-ion (Li-ion) batteries in the last decade. The U.S. Department of Energy (DOE) Vehicle Technologies Office (VTO) and the National Aeronautics and Space Administration (NASA) Glenn Research Center brought together experts for a first-of-its-kind meeting to explore the state of this nascent industry and to understand the research and development (R&D) needs for electric aviation energy storage. These experts from two historically non-overlapping fields—energy storage technologies and advanced aviation—met on December 10–11, 2019, at Argonne National Laboratory to discuss various aspects of the technology and ways to enable leadership in this emerging market. The two-day event drew more than 100 participants from aircraft companies, component makers, battery companies, materials companies, car companies, and academic and national laboratories. The assessment contained herein produced a consensus rubric for where the energy storage advances desired by the electric aviation community could arise and how that overlapped with the sustained and significant activities in the electric light-duty vehicle space. In the near term, participants identified the electric vertical take-off and landing (eVTOL) and short-range consumer aircraft usage cases as opportunities that are benefiting from electric vehicle (EV) battery R&D and commercial deployment. At the opposite end of the spectrum, the holy grail of carbon-free transoceanic flight was identified as (1) having no current electric aviation path forward and (2) representing a strong case for a longer-term, government-supported program to build such electrochemical energy storage solutions.

The body of this report details electric aviation technologies, battery chemistries, and major subjects discussed, as well as the key areas of battery R&D required as a function of the use case (Figure ES-1). The product of this assessment should be considered the initiating draft of a roadmap for the R&D needed to support strong and world-leading U.S. electric aviation industries. Future meetings are in the planning stage and this assessment will continue to evolve.

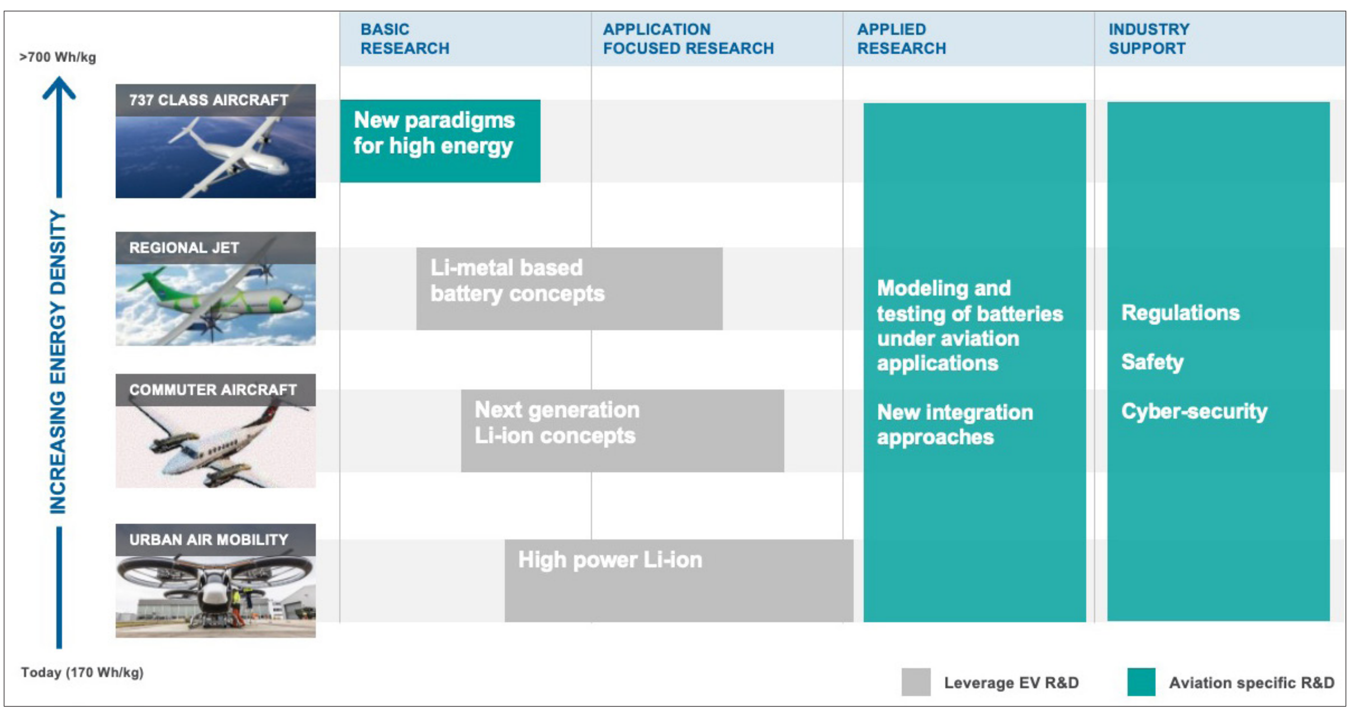


Figure ES-1. Electric aviation energy storage R&D needs.

INTRODUCTION AND BACKGROUND

The numerous advantages offered by electric propulsion have resulted in a dramatic increase in interest and excitement around this concept. These include lower fuel and maintenance costs, decreased noise and air pollution, and unique aircraft design enabled by distributed propulsion concepts. Although the projected market size varies significantly based on analysis by different groups, the trend is clear: there will be significant growth in the market for electric aircraft.

For example, estimates suggest that a new mode of aviation services called Urban Air Mobility (UAM) or sometimes, Advanced Air Mobility (AAM), will be a $9 billion market by 2030 and could be an $80 billion market by 2041. Electric Vertical Take-Off and Landing (eVTOL) aircraft will be the vehicle technology that enables UAM, providing intracity passenger, cargo and emergency services operated by electric-powered aircraft, either remotely piloted or under autonomous control. Many established aerospace companies (including Boeing, Airbus, Rolls, General Electric [GE], United Technologies, Embraer, Bell, etc.) are now making significant investments. Further, numerous startup companies in the United States are now focused on electric aviation innovation. Examples include Elevate, a highly publicized air taxi service started in 2016 by Uber and now owned by Joby Aviation that aims to provide affordable shared flights by 2023 with electrification as its core principle. Also, automotive companies, including Daimler, Toyota, Hyundai, and Porsche, are getting involved in aviation startups.

These announcements and enhanced interest are driven by the prospect that presently available electric vehicle (EV) Li-ion batteries, derived from continued DOE investments over the past three decades, have reached performance levels that allow electrification of VTOL and similar aircraft, albeit with limited operational capability. Planned DOE investments in battery technology will expand the capability of electric aircraft beyond their initial market introduction; however, realization of the full market potential for the electric aircraft market will require significant advances in battery technology beyond the current level of investment, with focuses needed on reducing battery costs and realizing higher energy and power density and longer battery life.

To explore the state of this nascent industry, and to understand the research and development (R&D) needs for batteries for electric aviation, the U.S. Department of Energy (DOE) Vehicle Technologies Office (VTO), along with the National Aeronautics and Space Administration (NASA) Glenn Research Center, brought together experts across the R&D spectrum on December 10–11, 2019, at Argonne National Laboratory. Close to 100 participants from aircraft companies, aircraft propulsion component manufacturers, battery companies, battery materials companies, car companies, and academic and national laboratories spent a day and a half discussing the various aspects of the technology and the ways to enable leadership in this emerging market (see the Appendix for agenda and attendee list). Keynote speakers laid out the state of the aircraft industry and the needs for the future, along with the history and recent developments in EV battery technology. Breakout sessions were used to dig deeper into the different electric aviation concepts, the battery needs for these applications, the R&D gaps, and the differences between battery needs for electric cars and those for electric aviation.

The meeting of these two different communities aided in establishing a shared language and in ensuring that the deep knowledge gained from the electrification of ground transport can accelerate the transition for aircraft. There was clear consensus among the participants that electric aviation is inevitable and is poised to take off within the next 5 to 10 years. The innovations that researchers are already pursuing for EV batteries will play a significant role in enabling electric aviation, especially in the near term. However, differences exist between the two applications that require dedicated focus on mission-specific use of the batteries and the unique requirements that this usage drives, while leveraging some of the advantages offered by aviation-specific missions. In the long term, the energy density needs for electric aviation far outstrip the goals of current DOE and industry investments and are so high that they require strategic thinking around the best approaches to enable this future. It was clear to participants that application of this nascent technology is in its early days, and no country can claim leadership in inventing the future of electric aviation. The United States has the critical mass of expertise needed—in batteries, aviation, propulsion, manufacturing, and system integration—to invent the power source for the next 100 years of aviation.

SUMMARY OF THE WORKSHOP

The day and a half of keynote presentations and discussions in the breakout sessions yielded a clear description of the requirements for batteries for different aircraft designs, along with near-term and long-term needs. Further, discussions centered around the battery innovations being pursued and the opportunities for energy density improvements that can help drive the long-term electrification needs for all classes of aircraft and various target ranges. Summaries of the various discussions follow.

BATTERY REQUIREMENTS FOR VARIOUS AIRCRAFT DESIGNS

The attendees discussed different designs for aircraft, including the near-term eVTOL to the long-term, single-aisle 737-class aircraft. Figure 1 shows the energy density requirements for these four different design concepts that emerged as important to consider:

(i) eVTOL

(ii) 9– to 20-passenger commuter aircraft for thin-haul air transport

(iii) 50-passenger regional aircraft

(iv) 150-passenger 737-class aircraft.

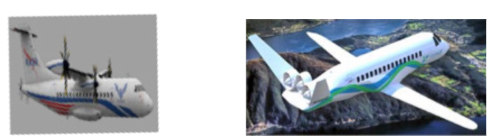
Battery Pack Specific Energy	Potential Missions	Potential Market Introduction
> 700 Wh/kg		Single aisle, 150-passenger single-aisle aircraft, long range
500 Wh/kg		Expansion to various classes of hybrid-electric regional aircraft, short-range 150-passenger, single aisle hybrid-electric aircraft
400 Wh/kg Sweet spot for eVTOL		Desired capability for all-electric eVTOL urban air mobility, long-range all-electric commuter, Initial version of small hybrid-electric regional
300 Wh/kg		All-electric eVTOL urban air mobility with 4 passenger and 50+ mile range: 20-passenter all-electric commuter
SOA (150-170 Wh/kg)		Initial commercial introduction possible for all-electric with limited range and payload, extended capability with hybrid-electric

Figure 1. Impact of improving battery performance in enabling different electric airplane concepts (originally developed by NASA Glenn Research Center).

Energy densities of today's Li-ion batteries, approximately 150–170 Wh/kg*pack* (i.e., at the pack level), allow initial demonstrations and are close enough to enable near-term eVTOL and 9- to 20–passenger, thin-haul applications with limited range capability. Increasing the pack-specific energy to 300–400 Wh/kg*pack*, which is achievable within the current DOE research framework, will enable the desired range capability for eVTOL and 9- to 20–passenger, thin-haul all-electric aircraft, while at the same time making it possible for initial introduction of electrified regional aircraft with short-haul capability. On the other hand, full expansion of the electrified aircraft market to regional and 737-class aircraft requires battery energy densities greater than 500 Wh/kg*pack*, which is beyond the current battery technology capabilities. The most challenging is the energy density requirements for 737-class, single-aisle aircraft that go far beyond those in the R&D pipeline and require the consideration of new approaches.

The group also discussed other metrics beyond energy density for these various designs and the innovations in the pipeline that can be used to satisfy the requirements, as detailed below.

BATTERY INNOVATIONS IN THE PIPELINE TO SATISFY AIRCRAFT REQUIREMENTS

The workshop participants discussed battery chemistries spanning next-generation Li-ion chemistries (i.e., high-energy cathodes and silicon-based anodes), to beyond Li-ion chemistries (i.e., Li/intercalation cathodes, Li-Sulfur, Li-air) to beyond lithium-based concepts (e.g., sodium-ion, magnesium-ion). Figure 2 shows the notional performance improvements with each concept. DOE is nurturing many of these concepts, which will enable further penetration of electrification as the chemistries mature.

The group also discussed other research, such as the effort around all solid-state batteries, which could allow for safer operation and higher packing density with the potential for only 10% loss in energy density from cell to pack. Further, fast-charge research being pursed for EVs could also play a role in helping to reduce the downtime of aircraft between flights. Discussions also centered around the fact that while many topics are well covered by the battery researchers, the focus is on solving challenges in EV and grid storage. Aviation brings new challenges that are not common to EVs or the grid and require a dedicated focus.

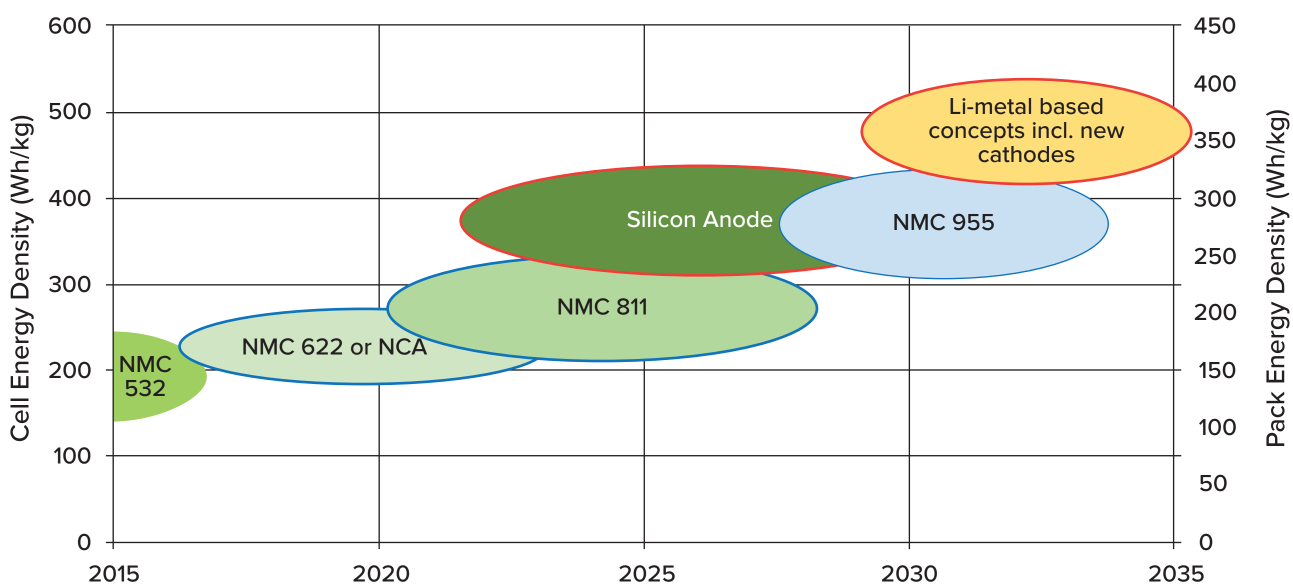


Figure 2. Projected improvement in specific energy at the cell and pack level (originally developed by DOE-VTO).

AVIATION SPECIFIC BATTERY REQUIREMENTS

The group also discussed battery requirements driven by the unique needs of the aviation industry. While the energy density of batteries is a key attribute, other battery performance metrics exist for electric aircraft based on unique mission requirements. An example is the high power demand during takeoff and landing of eVTOLs, wherein the power requirements are ca. 2-3x that typically needed for EVs for as long as 90 s (3x longer than EV power draws); these requirements represent a significant burden for today's EV batteries. Table 1 summarizes differences in battery requirements or needs between EV and electric aircraft.

Table 1. Differences in battery requirements between EVs and electric aircraft.

	Electric Vehicle	Electric Aviation
Mission profiles	Mission profiles are well established using decades of analysis by DOE and U.S. Advanced Battery Consortium and translated from system to material scale.	Mission profiles need to be codified and different battery chemistries need to be evaluated under these conditions.
Maximum discharge rates	The maximum discharge rates are short pulses (2–10 s) at moderate rates until 80% depth of discharge (DOD).	The maximum discharge rate for aircraft is 2x the rate for EVs (sustained for 90 s) at 80% DOD.
Operating temperature	EV batteries need to operate at low temperatures, below -30°C.	Higher temperature is acceptable and may be desired, allowing exploration of high-temperature batteries (e.g., solid polymer).
Cycle and calendar life	The standards are 1000 cycles with a calendar life of 8 years.	Calendar life requirements are less stringent but require 1000–4000 cycles. Limited calendar life may allow use of systems such as Si anodes.
Battery swapping	Swapping has been attempted at the small scale but has been limited by infrastructure cost and lack of standardization.	The opportunity exists to build the aviation market with swapping in mind. However, challenges related to safety need to be solved.
Novel packaging to maximize energy density at the module	Approximately 50% loss from moving from cell to pack occurs, with the possibility for further reduction from better integration into vehicles.	Trade-offs (increased safety requirements, reducing cooling loads, etc.) need to be better defined to quantify packaging needs.
Energy density enhancements	Electric automobiles may not need energy density greater than 200 Wh/kg*pack*; cost reduction will be key driver for EVs (increased Wh/kg often leads to lower $/kWh, thus higher Wh/kg is still being pursued).	Full-scale commercialization of eVTOL and expansion of the electric aircraft market segment to a broad class of aircraft will require energy density greater than 300 Wh/kg*pack*.

The spider charts in Figure 3 capture the comparison of the performance of state-of-the-art, Li-ion batteries compared to targets for EVs, eVTOLs, and 737-class aircraft. The targets for aviation are still preliminary, and researchers need more detailed analysis to firm up the numbers. The charts show the changing requirements among the applications and the increasing demand for high energy.

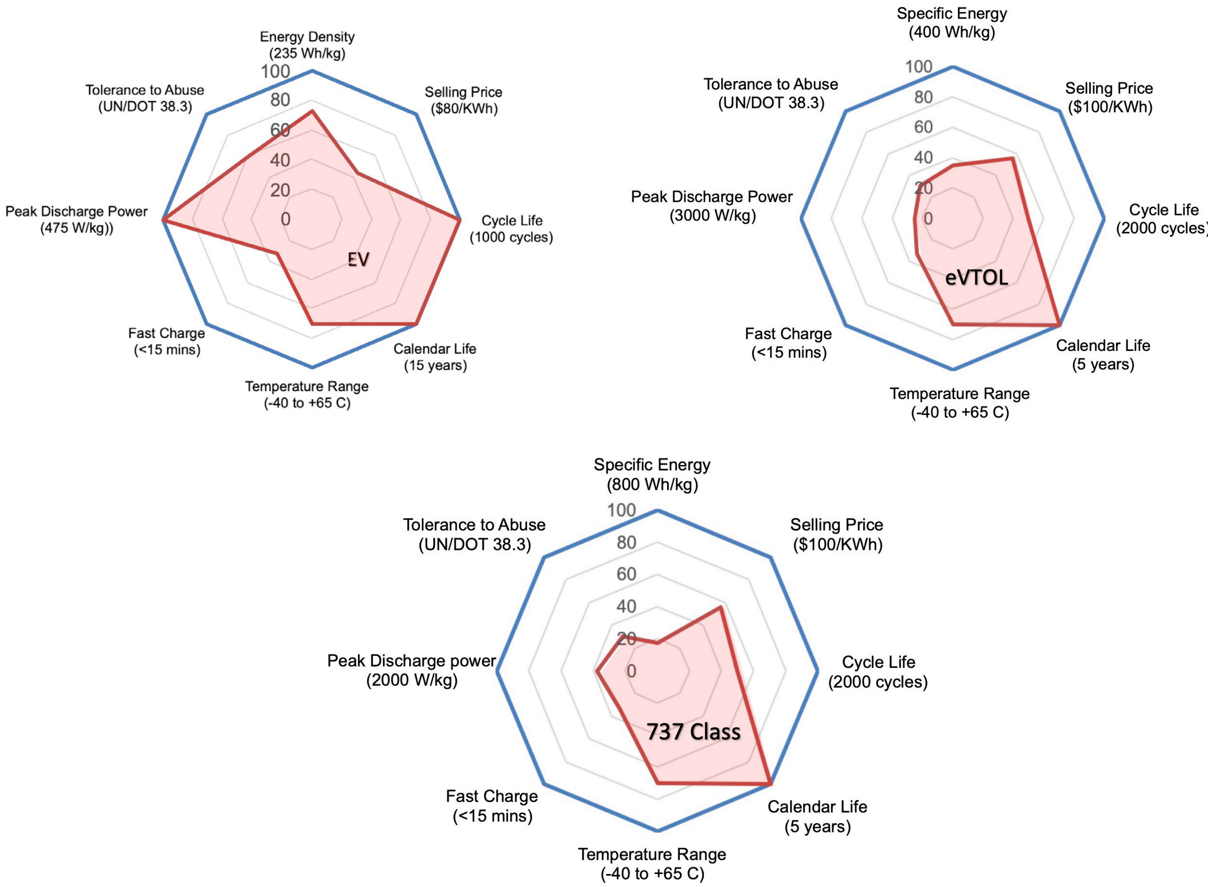


Figure 3. Spider charts capturing the targets for different metrics and the present status of Li-ion batteries. Three applications are captured, namely EVs, eVTOLs, and 737-class aircraft. Note that numbers for aviation applications are preliminary and more analysis is needed to ascertain the targets.

POSSIBILITY FOR 3-5X INCREASES IN ENERGY DENSITY

The discussion also covered the possibility of inventing chemistries that go far beyond those being examined for EV applications. Attendees examined the feasibility of very high energy density primary batteries (such as lithium sulfuryl chloride or lithium metal fluoride) with the aim of establishing their ability to be recharged. Participants also discussed lithium oxygen and lithium sulfur batteries, which are being researched for EVs, as possibilities, assuming fundamental limitations could be solved. Finally, participants also examined fuel-cell systems, wherein the fuel can either be electrochemically or chemically reserved using hydrogen, ammonia, or other synthetic molecules.

R&D NEEDS FOR ELECTRIC AVIATION BATTERIES

Based on the presentations and breakout discussions, the group identified four aircraft concepts on which to focus, namely, (1) eVTOL, (2) 20-passenger commuter aircraft, (3) 50-passenger regional jet, and (4) 150–passenger, single-aisle 737-class aircraft. For each concept, the discussion yielded a clear set of R&D needs to enable commercialization and to push innovation in this emerging area. DOE and NASA could jointly embark on defining the pathways to resolving these challenges. These areas are to:

1. Evaluate high-discharge operation of Li-ion cells, especially focused on eVTOL applications, and develop possible solutions to enable this near-term opportunity.
2. Evaluate next-generation Li-ion (silicon, advanced cathode, Li metal) under aviation conditions and examine the failure modes and safety concerns that emerge to open possibilities that may fully unlock the market for eVTOL and the commuter aircraft market.
3. Augment R&D in solid-state batteries to examine new designs, manufacturing approaches, high-temperature operation, etc., to open new opportunities that enable 50-passenger regional electrified aircraft.
4. Study possible systems with 3–5x higher energy density, including of the potential for enabling high-energy primary batteries, sulfur-based chemistries, and hydrogen carriers, with the aim of providing solutions for large regional and 737-class aircraft.

In addition to these, some cross-cutting R&D needs for all aircraft concepts emerged, including to:

5. Identify a reference mission for each aircraft class and conduct system analysis to pinpoint opportunities as a function of battery energy density.
6. Define mission-specific test protocols and use the national laboratory testing facilities to define the failure modes under these different operating conditions.
7. Link aircraft propulsion models to battery performance and life models to better define battery targets, integration opportunities, etc., under aviation conditions.
8. Develop efficient designs to package cells to modules and packs, taking advantage of emerging approaches such as bipolar designs.

In the short term, significant progress can be made by leveraging EV battery R&D and adapting this for aviation requirements. Testing under aviation-specific requirements will allow identification of the bottlenecks and drive R&D toward solutions. An important aspect of progress will be the continuous evaluation of the status of storage technologies and developing a roadmap, similar to that shown in Figure 2 but for aviation applications. Based on the workshop, Figure 4 shows a notional progression of energy densities that starts with leveraging EV advancements, while slowly pushing on aviation-specific requirements. We will continue to develop this notional roadmap as further studies shed light on this emerging application for batteries.

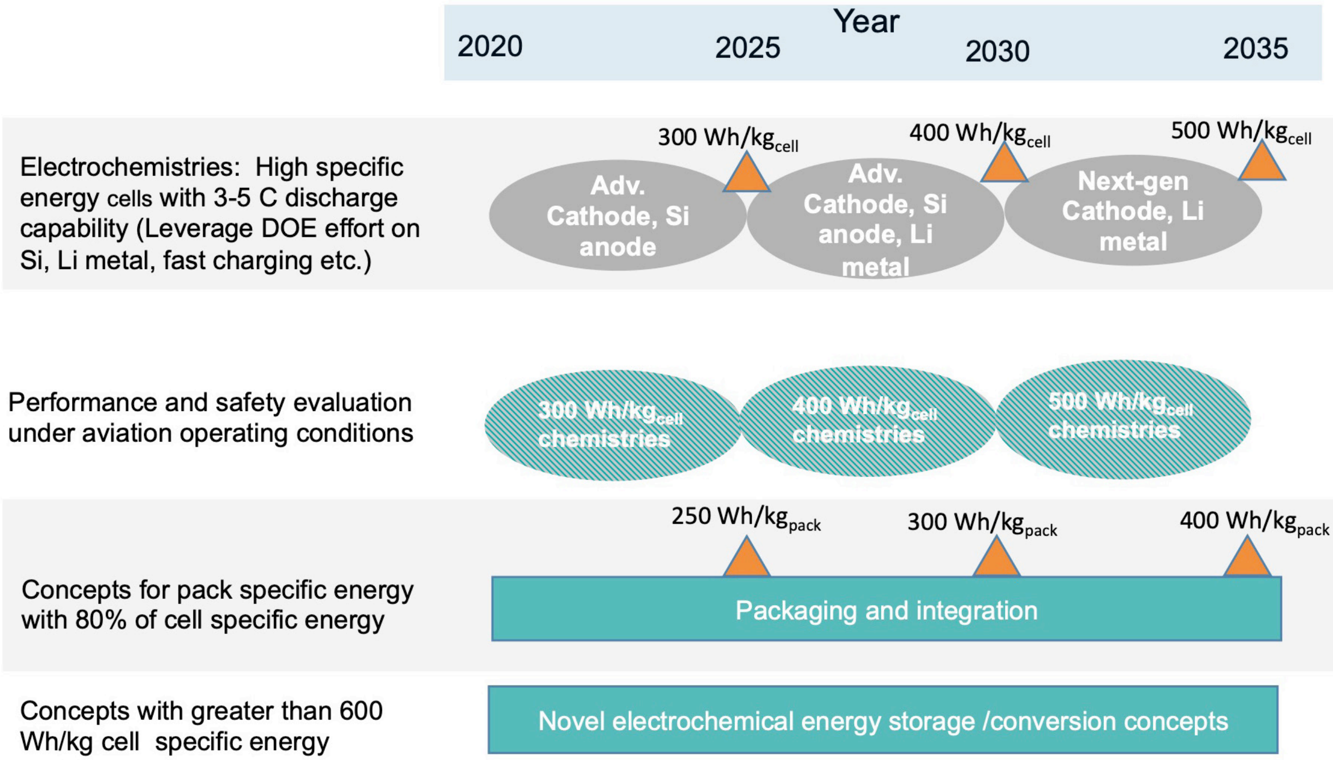


Figure 4. Notional progression of electric aviation batteries that leverages EV battery R&D while simultaneously pushing on aviation-specific R&D.

Beyond the efforts that fall within the scope of DOE and NASA, the aviation industry has a large role to play beyond concept development, working with other federal agencies (e.g., Federal Aviation Administration, U.S. Department of Transportation), including a focus on regulatory aspects, cyber security concerns, etc.

NEXT STEPS

The assessment opens the door to a number of different approaches to further define the opportunity around electric aviation. These might include that:

1. NASA will examine means to enable R&D to better define the aircraft battery needs and ensure that standards are developed.
2. DOE will include requirements for aircraft in future Federal Opportunity Announcements (FOA) and National Laboratory funding calls.
3. DOE and NASA will consider organizing a brainstorming session to identify pathways for very-high-energy-density electrochemical energy storage/conversion that will enable electric propulsion for large aircraft.
4. NASA and DOE will organize brainstorming dedicated to standardizing battery packs for aircraft and easing the supply chain of cells/packs.
5. DOE and NASA will organize the next session of this assessment in 2021 to continue to bring together the different communities dedicated to commercializing electric aviation.

APPENDIX

Meeting Agenda and Participant List

Meeting Agenda:

Tuesday, December 10, 2019

8:30 – 9:00 a.m.	**Registration**
9:00 – 9:30 a.m.	Welcome and Introductions • Suresh Sunderrajan, Associate Laboratory Director, Argonne National Laboratory • Dave Howell, Acting Director, DOE Vehicle Technologies Office • Rickey Shyne, Director of Research and Engineering, NASA Glenn Research Center
9:30 – 11:00 a.m.	**Plenary Presentations** *Electric Aircraft Opportunities, Challenges, and Enabling Battery Requirements: A Boeing Perspective* • Dr. Marty Bradley, Technical Fellow, Commercial Airplanes and Advanced Concepts, Boeing *Electric Vertical Takeoff and Landing (eVTOL) – The Future is Now* • Mike Ryan, Chief Engineer – NEXUS, Bell *Pipistrel Perspective on Electric Aviation – What Kills Innovation* • Dr. Tine Tomažič, Director of Research and Development, Pipistrel
11:00 – 11:15 a.m.	**Break**
11:15 – 12:00 p.m.	**Plenary Presentations (Cont.)** *Energy Storage Research and Development for Electric Aviation – Challenges and Opportunities* • Ajay Misra, Deputy Director of Research and Engineering, NASA Glenn Research Center *DOE Battery R&D – The Future of the Electrification of Transportation* • Peter Faguy, Manager, Applied Battery Research Program, DOE Vehicle Technologies Office
12:00 – 12:15 p.m.	**Setting the Stage for Breakouts:** • Venkat Srinivasan, Director, Argonne Collaborative Center for Energy Storage Science (ACCESS)
12:15 – 1:00 p.m.	**Working Lunch**
1:00 – 2:30 p.m.	**Concurrent Breakout Sessions** Location: Building 240, Rooms 1404, 1405, 1406 and 1407 **Breakout Session #1:** Facilitators: Vince Sprenkle (PNNL), Ralph Jansen (NASA) **Breakout Session #2:** Facilitators: Tony Burrell (NREL), Anil Duggal (GE Research) **Breakout Session #3:** Facilitators: Venkat Viswanathan (CMU), Brian German (GA Tech)
2:30 – 3:00 p.m.	**Break**
3:00 – 4:30 p.m.	**Breakout Sessions (Cont.)**
4:30 – 6:00 p.m.	**Poster Session and Reception**
6:00 p.m.	**Adjourn**

Meeting Agenda and Participant List Continued.

Meeting Agenda:

Wednesday, December 11, 2019

8:45 – 9:00 a.m.	**Recap of Day 1 and Welcome** • Venkat Srinivasan
9:00 – 9:30 a.m.	**Opening Keynote** *History of the Lithium-based Electrochemical Energy Storage* • George Blomgren, Owner, Blomgren Consulting Service
9:30 – 10:00 a.m.	**Second Keynote** *Lessons Learned from the Electrification of Vehicles* • Peter Savagian, Electrification Leader, Ampaire
10:00– 10:30 a.m.	**Break**
10:30 – 11:45 a.m.	**Readouts and Recommendations from Three Breakout Sessions along with Q&A**
12:00 – 12:45 p.m.	**Lunch and Open Discussion**
12:45 – 1:30 p.m.	**Next Steps**
1:45 – 4:00 p.m.	**Optional Tours: Argonne Battery Facilities**

Attendee List

Full Name	Company
Adduci, Joseph	Argonne National Laboratory
Anders, Scott	NASA
Ansell, Phillip	University of Illinois at Urbana-Champaign
Aramanda, Gregg	GE Aviation, LLC
Belharouak, Ilias	Oak Ridge National laboratory
Belt, Jeffrey	EP Systems
Bennett, William	NASA
Bheemireddy, Sambasiva	Argonne National Laboratory
Blomgren, George	Blomgren Consulting Services Ltd.
Bradley, Marty	Boeing
Brooks, David	General Motors
Brzowski, Rita	Argonne National Laboratory
Bugga, Kumar	NASA JPL / Caltech
Burrell, Anthony	National Renewable Energy Laboratory
Button, Robert	NASA Glenn Research Center
Cagle, Dawson	IARPA
Cai, Mei	General Motors
Canova, Marcello	The Ohio State University
Cavolowsky, John	NASA
Chao, Emil	Rivian
Cheng, Lei	Argonne National Laboratory
Chiang, Yet-ming	MIT
Chin, Jeffrey	NASA Glenn Research Center
Clifford, Megan	Argonne National Laboratory
Clites, Mallory	U.S. Dept. of Energy
Crabtree, George	Argonne National Laboratory
Darling, Robert	United Technologies Research Center
D'arpino, Matilde	The Ohio State University
Demattia, Brianne	NASA Glenn Research Center
Dominguez, Vince	Boeing

Full Name	Company
Dong, James	Navitas Systems
Dufek, Eric	Idaho National Laboratory
Duggal, Anil	GE Research
Duong, Tien	U.S. Dept. of Energy
Faguy, Peter	U.S. Dept. of Energy
Fellner, Joseph	Air Force Research Laboratory
Follen, Gregory	NASA Glenn Research Center
Fuller, Thomas	Georgia Institute of Technology
German, Brian	Georgia Institute of Technology
Goodrich, Grant	Case Western Reserve University
Grant, Allan	LAVLE USA Inc.
Greszler, Thomas	Saft America
Hafidi, Kawtar	Argonne National Laboratory
He, Meinan	General Motors
Heidet, Aude	Volta Energy Technologies
Hillebrand, Donald	Argonne National Laboratory
Howell, David	U.S. Dept. of Energy
Ingle, Bill	Argonne National Laboratory
Jansen, Ralph	NASA Glenn Research Center
Jenks, Cynthia	Argonne National Laboratory
Karbowski, Dominik	Argonne National Laboratory
Kearns, Paul	Argonne National Laboratory
Kim, Ji Hyun	LG Chem
Krumdick, Greg	Argonne National Laboratory
Lampert, Jordan	BASF Corporation
Lawson, John	NASA Ames Research Center
Liu, I-han	Argonne National Laboratory
Liu, Meilin	Georgia Institute of Technology
Lovelace, Edward	Aurora Flight Sciences, A Boeing Company
Loyselle, Patricia	NASA Glenn Research Center

Full Name	Company
Lu, Dongping	Pacific Northwest National Laboratory
Lundgren, Cynthia	CDCC Army Research Lab
Lvovich, Vadm	NASA Glenn Research Center
Mattis, Wenjuan	Microvast Inc
Mccartney, Timothy	NASA Glenn Research Center
Mehta, Vineet	Tesla
Misra, Ajay	NASA Glenn Research Center
Ovan, Milos	Navitas Systems
Padgett, Elliot	U.S. Dept. of Energy
Peterson, Norm	Argonne National Laboratory
Prakash, Vikas	Case Western Reserve University
Rousseau, Aymeric	Argonne National Laboratory
Ryan, Michael	Bell
Sakamoto, Jeff	University of Michigan
Savagian, Peter	Ampaire, Inc.
Schnulo, Sydney	NASA
Schwartz, Daniel	University of Washington
Segura Martinez de Ilarduya, Leire	Airbus
Shyne, Rickey	NASA Glenn Research Center
Siu, Carrie	Argonne National Laboratory
Spierling, Todd	United Technologies
Sprenkle, Vincent	Pacific Northwest National Laboratory
Srinivasan, Venkat	Argonne National Laboratory
Stefan, Constantin	Amprius, Inc.
Su, Chi Cheung	Argonne National Laboratory
Sunderrajan, Suresh	Argonne National Laboratory
Surampudi, Subbarao	NASA
Swanson, Eric	Argonne National Laboratory
Takeuchi, Esther	Stony Brook University, Brookhaven National Laboratory
Thoemmes, Carl	Silatronix

Full Name	Company
Tomazic, Tine	Pipistrel
Tomczyk, Anna Marie	Argonne National Laboratory
Toney, Michael	SLAC National Accelerator Laboratory
Torelli, Roberto	Argonne National Laboratory
Tran, Thanh Tuan	Rivian Automotive
Tschopp, Mark	Army Research Laboratory
Viggiano, Rocco	NASA
Viswanathan, Venkat	Carnegie Mellon University
Wang, Chunsheng	University of Maryland
Wang, Enoch	USG
Wang, Francis	NanoGraf Corporation
Whitman, Chase	United Technologies Research Center
Wilhelm, Luke	Uber Technologies
Wood, David	Oak Ridge National Laboratory
Wu, James	NASA Glenn Research Center
Xu, Guiliang	Argonne National Laboratory
Zachos, Lee	Argonne National Laboratory
Zhu, Yu	University of Akron

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