



Electrified Aircraft Propulsion Flight Project Battery Industry Day

November 30, 2020

Virtual Meeting

Accelerate transition of 1MW class powertrain systems to US transport aircraft fleet

Agenda



Start	End	Session	Speaker
10:00 AM	10:05 AM	Welcome	Gaudy Bezos-O'Connor
10:05 AM	10:20 AM	NASA Intro	Ralph Jansen
10:20 AM	10:40 AM	NASA Battery Intro	Ajay Misra
10:40 AM	11:00 AM	Q&A	
11:00 AM	11:15 AM	Break	
11:15 AM	11:30 AM	Aircraft 1	Ampaire
11:30 AM	11:45 AM	Aircraft 2	Boeing
11:45 AM	12:00 PM	Aircraft 3	Wright Electric
12:00 PM	12:30 PM	Lunch 1 (East Coast)	
12:30 PM	12:45 PM	Battery 1	Amprius
12:45 PM	1:00 PM	Battery 2	CRG/Lectratek
1:00 PM	1:15 PM	Battery 3	Cuberg
1:15 PM	1:30 PM	Battery 4	Eagle Picher
1:30 PM	1:45 PM	Break	
1:45 PM	2:00 PM	Battery 5	EP Systems
2:00 PM	2:15 PM	Battery 6	Navitas
2:15 PM	2:30 PM	Battery 7	Sion Power
2:30 PM	2:45 PM	Battery 8	Solid Power
2:45 PM	3:30 PM	Lunch 2 (West Coast)	
3:30 PM	3:45 PM	Battery 9	Teledyne
3:45 PM	4:00 PM	Battery 10	GLX Power
4:00 PM	4:15 PM	Battery 11	Ionic Materials
4:15 PM	4:30 PM	Battery 12	Mobius Energy
4:30 PM	4:45 PM	Break	
4:45 PM	5:00 PM	Battery 13	Ford
5:00 PM	5:15 PM	Battery 14	Romeo Power
5:15 PM	5:30 PM	Battery 15	General Atomics
5:30 PM	5:45 PM	Battery 16	Lavle
5:45 PM	6:00 PM	Closing Remarks	



Why is Electrified Propulsion important?

- **EP enables favorable direct operating cost (DOC) trades**
 - Total Energy
 - Maintenance
- **EP creates a flexible design space opportunities**
 - Boundary layer ingestion
 - Distributed architectures
 - Reduced turbofan core sizes
- **EP coupled with advanced airframe architectures**
 - May enable functionally silent and ultra low emission flight
- **EP is synergistic with low emission airport infrastructure changes**

5-year EPFD Project start in FY21

Agency and ARMD Strategic Plan Flow Down to EPFD Project



Agency Goal

3.0 Address national challenges and catalyze economic growth

3.2: Transform Aviation Through Revolutionary Technology Research, **Development, and Transfer**

AERONAUTICS
STRATEGIC
THRUST

Thrust 3: Ultra Efficient Subsonic Transports

Realize revolutionary improvements in economics and environmental performance for subsonic transports with opportunities to transition to alternative propulsion and energy

AAVP and IASP
CRITICAL
COMMITMENT

Critical Commitment 3.1 - Demonstrate **practical vehicle-level integration of MW-class electrified aircraft propulsion** systems, leveraging advanced airframe systems to **reinvigorate the regional and emerging smaller aircraft markets and strengthen the single-aisle aircraft market.**

Technical
Challenges

TC 5.2: Establish viable concept for 5-10 MW hybrid gas-electric propulsion system for a single-aisle class vehicle with reduced fuel burn, emissions and noise (TRL2)
Finished in FY19
(AATT)

TC 10.1: Demonstrate representative hybrid electric powertrain having a total power of at least 3X the state-of-the-art that meets fault management, redundancy, and power quality requirements (TRL 4) and develop key components to TRL 6.
(AATT with EPFD Enhancements)

TC 14.1: Achieve 20% power extraction at altitude from a modern commercial turbofan engine with the thrust, efficiency, operability, and durability to enable the benefits of electrified aircraft propulsion at a vehicle level.
(AATT with EPFD Enhancements)



EPFD Approach

- **Accelerate US industry technology readiness of integrated MW-class electrified powertrain systems**
 - Facilitate jump to new aviation industry S – curve by focusing on integrated MW-class powertrain system technology
 - Focus on next generation single aisle (150 – 200 passenger seat class) commercial transport aircraft
 - Ensure an appropriate mix of potentially disruptive concepts and commercial transport products
 - Commercial thin haul transport aircraft can potentially disrupt hub and spoke system
 - Directly engage propulsion companies to facilitate timely integrated MW-class powertrain system development and transition
- **Plan and Conduct at least two integrated MW-class powertrain system flight demonstration**
 - Identify and address regulation and standards gaps
 - Identify and retire barrier technical and integration risks
- **Employ right-sized project management and procurement rigor for efficient execution and timely funding expenditures:** highly leveraging industry processes and practices with significant NASA insight to make informed decisions at periodic reviews
- **Coordinate closely with ARMD programs to fully leverage prior and ongoing ARMD electrified powertrain system investments**

Objectives of Battery Industry Day

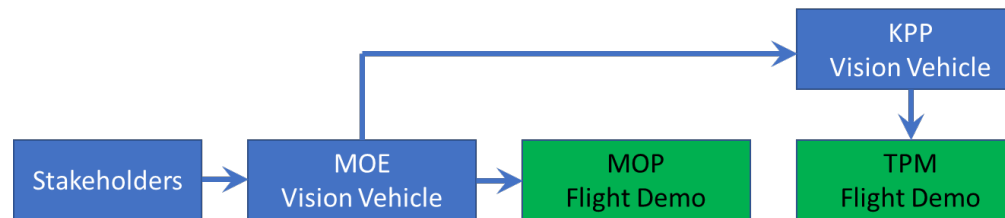


- Connect U.S. aircraft and propulsion companies with U.S. battery companies with interest in MW class Electrified Aircraft Propulsion
- Provide awareness of upcoming Electrified Aircraft Propulsion Project Request for Proposals and related project performance objectives
- Provide awareness of battery challenges for MW class Electrified Aircraft Propulsion
- Provide summary of NASA-DOE workshops related to battery technologies for electrified aircraft



Formulation Studies

- **Study contracts have been completed with six companies to define:**
 - The largest market opportunities for MW-Class EAP
 - A Vision Vehicle (potential product) for that market
 - Barrier Technical Risks that need to be overcome for the Vision Vehicle
 - Technology maturation needed for Vision Vehicle
 - A proposed flight demonstration to reduce the Barrier Technical Risks and increase the Technology Readiness levels for Integrated MW-class powertrain systems
 - Probabilistic assessments of cost and schedule for the proposed flight demonstration



Formulation studies informed the objectives and performance goals of the Electrified Powertrain Flight Demonstration project

Technical Measures of Effectiveness



- The EPFD project has established a draft set of Technical Measures of Effectiveness

MOE #	Measure of Effectiveness (MOE)
MOE-1	Establish at least two Vision Vehicles that address the single-aisle, regional, or thin haul markets.
MOE-2	Define a viable path that accelerates U.S. Industry product introduction of the Vision Vehicle and execute the part of the path that requires government participation.
MOE-3	Identify and reduce Barrier Technical Risks to the introduction of the Vision Vehicle through ground and flight tests.
MOE-4	Reduce regulations and standards barriers to the introduction of Vision Vehicles with Integrated MW-Class Powertrain Systems into the air fleet.
MOE-5	Collect the data defined in the Data and Intellectual Property Management (DIPM) plan to verify Key Performance Parameters and support regulations and standards work.

KPPs and TPMs



- Draft Key Performance Parameters for the Vision Vehicle and draft Technical Performance Parameters for the flight demonstration have been established.

Key Performance Parameter (KPP)#	Key Performance Parameter (KPP)	Full Success Single Aisle Part 25	Minimum Success 19 PAX Thin Haul Part 23
KPP-1	Total Power level of the Integrated MW-Class Powertrain System	2MW	500kW
KPP-2	Power Level of individual electrical components	1MW	250kW
KPP-3	Operating Voltage of the Integrated MW-Class Powertrain System	1000V	500V
KPP-4	Altitude Capability of the Integrated MW-Class Powertrain System	40,000 ft.	20,000 ft.
KPP-5	Specific Power of the Integrated MW-Class Powertrain System	1.25 kW/kg	0.5 kW/kg
KPP-6	End to End loss of the Integrated MW-Class Powertrain System	20%	
KPP-7	Mission Fuel Burn/Energy Reduction	4% for Part 25 Transport Aircraft	10% for Part 23 Transport Aircraft

Technical Performance Parameter (TPM)#	Technical Performance Parameter (TPM)	Full Success	Minimum Success
TPM-1	Total Power level of the Integrated MW-Class Powertrain System	1.5MW	500kW
TPM-2	Power level of individual electrical components	1MW	250kW
TPM-3	Operating Voltage of the Integrated MW-Class Powertrain System	1000V	500V
TPM-4	Altitude Capability of the Integrated MW-Class Powertrain System	30,000 ft.	15,000 ft.
TPM-5	Specific Power of the Integrated MW-Class Powertrain System	1.25 kW/kg	0.5 kW/kg
TPM-6	End to End loss of the Integrated MW-Class Powertrain System	20%	25%



Barrier Technical Risks

- **Barrier Risks**
 - Overarching risks applicable to future commercial transport applications by US Industry that the project will reduce over the life of the project
- **Six Barrier Technical Risks have been identified.**
- **The EPFD project intends to reduce these barrier technical risks to EAP Vision Vehicles through the execution of two or more U.S. Industry flight demonstration of integrated MW-class powertrains.**
- **Battery performance and airworthiness is one of the six barrier risks. The industry day is being held to foster connections between battery suppliers and aircraft and propulsion companies.**

Risk ID	Risk Title	Statement	Project Specific Risk
EPFD-028	Barrier Risk- Battery System Performance Shortfall	Given that the battery pack requirement exceeds current state of the art technology, there is a possibility that the battery system design does not meet performance requirements, resulting in a decrease in time per flight, increasing the total number of flight tests needed, impacting the cost and schedule.	EPFD-039: Battery Airworthiness



EPFD Draft Request for Proposals has been posted

- **Draft Request for Proposal has been posted.**

- Link: https://beta.sam.gov/opp/09c460e4b5b14e22b43c4b60ae4010dc/view?keywords=80afrc21r0009&sort=-relevance&index=&is_active=true&page=1

- **Description**

- Attached is the DRAFT Request for Proposal (DRFP) for the Electrified Powertrain Flight Demonstration. The objective of this requirement is to plan, manage, and conduct appropriate ground tests and flight tests of an integrated MW-class Powertrain System that enables the offeror's vision system, that meets the described needs, goals and objectives identified in the attached Statement of Objectives, and that are in alignment with system and data requirements defined in the System Requirements Document (SRD) and Data Requirements Document (DRD). See the attached Statement of Objectives for additional information. The DRDs and SRD will be provided via an amendment to this DRFP. Potential Offerors shall monitor [bata.SAM.gov](https://beta.sam.gov) for amendments to this DRFP.
- Potential Offerors are encouraged to review all aspects of the DRFP, including the requirements, schedules, proposal instructions, and evaluation approaches. Potential Offerors should provide questions and/or comments and identify any unnecessary or inefficient requirements relating to the DRFP no later than 2:00 pm Pacific, Dec 16, 2020.
- An Industry Day will be held Dec 10, 2020. A registration link for the Industry Day will be provided.



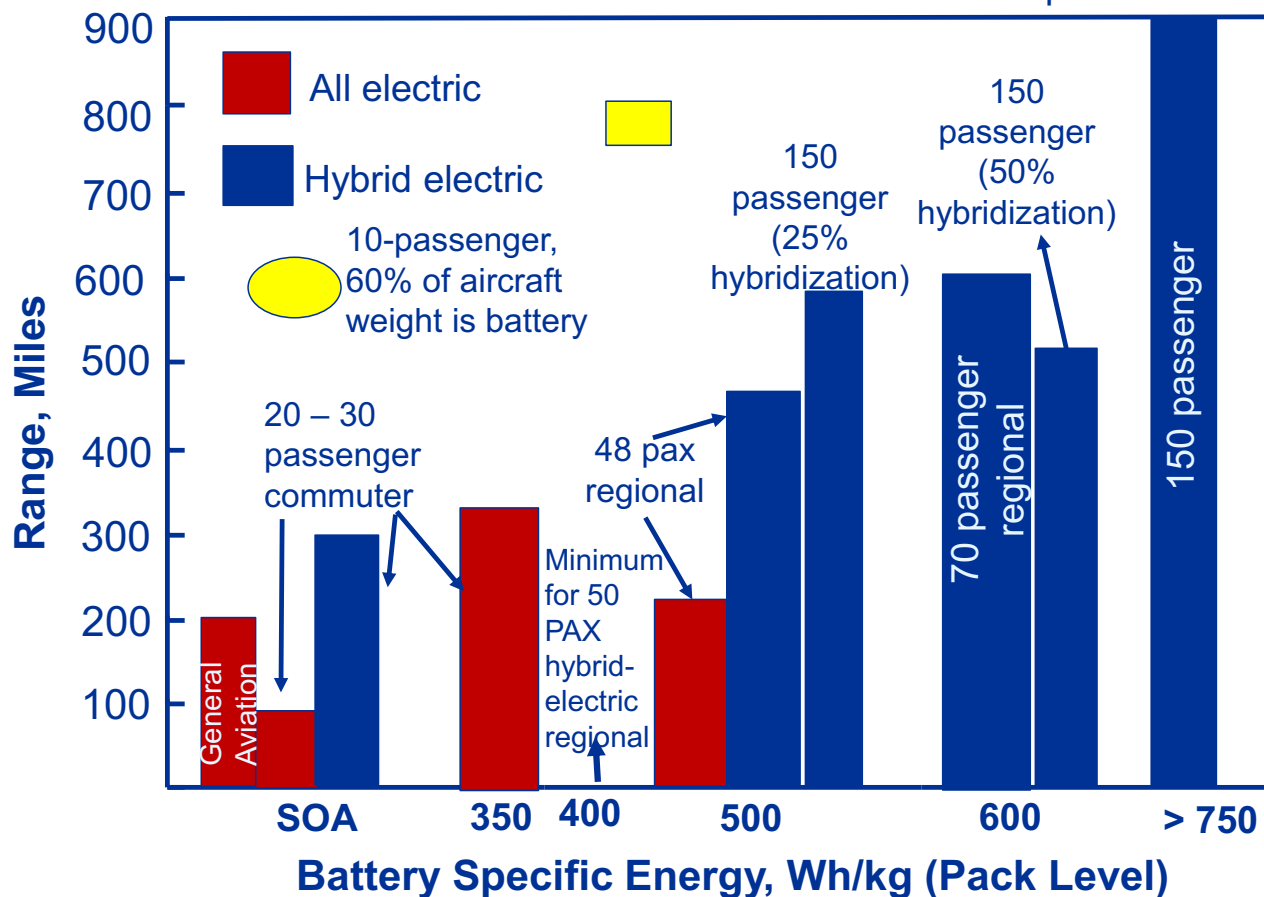
Battery Technology for MW Class Electrified Aircraft Propulsion

Dr. Ajay Misra (NASA)

Battery Specific Energy Requirement for Conventional Takeoff and Landing Electrified Aircraft



- Taken from different sources with different assumptions



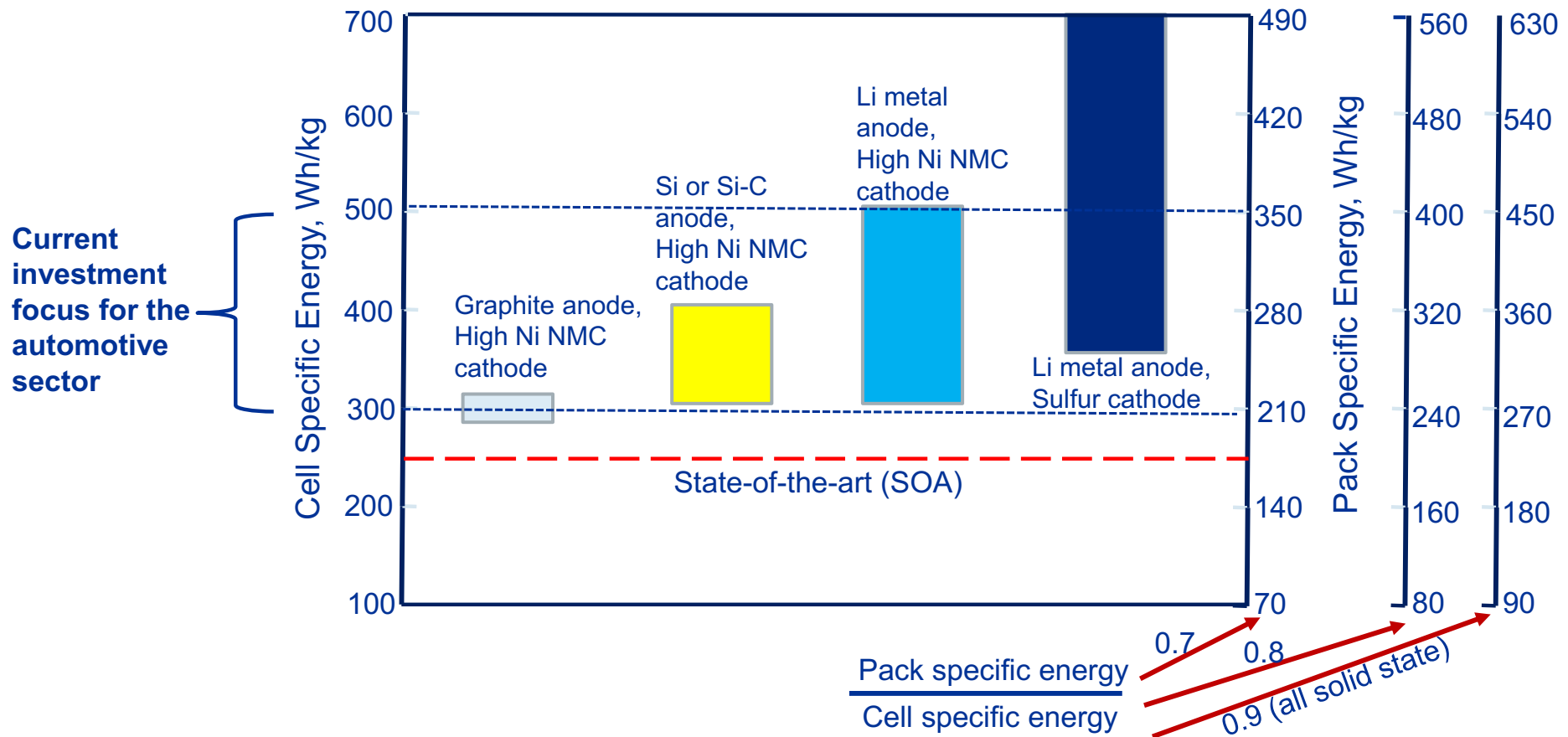
- Battery requirement is a function of degree of hybridization
- Potential hybrid electric short flight (300 – 400 miles) opportunities for large regional and 150 Passenger single aisle with 400 – 500 Wh/kg pack specific energy
- For hybrid electric large aircraft with battery used during takeoff only:
 - 300 Wh/kg pack specific energy for 30-50 passenger aircraft
 - >400 Wh/kg pack specific energy for single-aisle 150 passenger aircraft

Evolution of Electrified Aircraft Market with Improvements in Battery Technology



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

Progression of Specific Energy of Advanced Li Batteries



Comparison of C-Rating and Power Density of Electric Vehicles and Electric Aircraft



	Electric Vehicles	Electric Aircraft
C-rating (burst)	3to 4 for a few seconds	2 to 5 or higher during takeoff and climb and vertical lift/hover, could last for several minutes for many missions
C-rating (steady cruise)	0.5 or lower	Could be 1 and higher depending on mission and speed
Specific power	0.4 – 0.5 kW/kg	1- 2 kW/kg for many missions



Notional Timeline for Evolution of Battery Technology

Timeframe	Pack Specific Energy (Wh/kg)	Likely Chemistry
Present	150 - 170	
2022 - 23	215	Current anode, Adv. NMC cathode, maybe single crystal NMC , liquid electrolyte
2025	250 - 300	Si or Si/C anode, Adv. NMC cathode (including single crystal), liquid electrolyte
2030	300 - 350	Li metal, advanced cathode, liquid electrolyte, first generation of solid state battery
2035	350 - 400	Li metal, all solid state
????	> 400 Wh/kg	Likely Li metal, all solid state
?????	> 500 Wh/kg	New materials, chemistries, concepts

Assumptions: Current pace of development, commercial ready for large pack sizes, adequate cycle life



NASA – DOE Workshop

December 2019, Hosted by Argonne National Laboratory

NASA-DOE Workshop on Batteries for Electric Aviation - December 2019



- Based on the success of the first workshop hosted by GRC in 2017
- Organized by NASA and DOE Vehicles Technology Office, hosted by Argonne National Laboratory
- Attended by ~100 participants (NASA, DOE, national laboratories, aircraft and engine companies, automobile companies, battery manufacturers, academia)
- Highlighted differences between automobile and aircraft applications
- Identified opportunities for leveraging technologies being developed by DOE, national labs, and industry
- Identified technologies and research/testing effort that will be needed for electric aviation beyond the current investment by DOE and industry

Strategy for Addressing Electric Aviation Battery Challenges



- Current investment by DOE and industry will lead to batteries with 300 – 350 Wh/kg pack specific energy
 - Can enable all-electric eVTOL, commuter aircraft and hybrid-electric 50 passenger regional aircraft
- For some missions, batteries with optimized specific energy and power density need to be developed
- Achieving pack specific energy of 400 – 500 Wh/kg will require augmented effort beyond the current level of investment, particularly development and maturation of of all solid state and Li-S batteries including manufacturing technologies for fabricating large size solid state battery stacks
- Achieving pack specific energy greater than 500 Wh/kg will require new paradigms

Differences Between Automobile and Aircraft



	Electric Vehicle	Electric Aviation
Mission profiles	Well established using decades of analysis by DOE and USABC and translated from system to material scale	Needs to be codified and different battery chemistries need to be evaluated under these conditions
Discharge rates	Short pulses (2-10s) at moderate rates until 80% DOD	2-3x higher (could be higher) rate than EVs sustained for 90s at high DOD for eVTOL's
Operating temperature	Need to operate at low temperatures, below 0C	Higher temperature desirable for eVTOL, allowing exploration of high temperature batteries (e.g., solid polymer, ceramic-polymer electrolytes)
Cycle and Calendar life	1000 cycles with a calendar life of 8 years	Calendar life requirements are only 1-2 years but requires 1000-4000 cycles. Limited calendar life may allow use of systems such as Si anodes
Battery swapping	Attempted in the small scale, but limited by infrastructure cost and lack of standardization	Opportunity 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 to cell to module	Opportunities for improving packaging and integrating batteries into vehicle components may offer new opportunities.
Energy density enhancements	235 Wh/kg _{pack} in near-term. Further increase to 300 Wh/kg _{pack} likely to extend range. Focus will be cost reduction after that.	Near term concepts can leverage current battery R&D pipeline. However, 737-class aircraft require >700 Wh/kg _{pack} , requiring new approaches

Battery Needs for Electric Aviation (Beyond Current DOE and Industry Investment)



Technology Needs	
System Level Modeling	Identify reference mission for each aircraft class and conduct system analysis to pinpoint opportunities as a function of battery capabilities
	Link aircraft propulsion models to battery performance and life models to better define interaction of batteries under aviation conditions
Next Gen Li – Performance and Safety	Evaluate high discharge operation of Li-ion cells, especially focused on eVTOL applications and develop possible solutions (e.g., new chemistries with high specific energy and power density capability or new thermal management solutions)
	Evaluate performance of next generation Li-ion (silicon, high Ni NMC) under aviation conditions and examine/model failure modes and safety aspects
Packaging and Integration	Develop efficient designs to package cells to modules and packs taking advantage of emerging approaches such as 3-D printing, bipolar designs and multifunctionality
	Augment R&D on all solid state batteries to examine new designs, manufacturing approaches, high temperature operations, etc.
Beyond Next Gen Li	Develop chemistries with 3-5X higher specific energy, including evaluating the possibility of enabling high energy primary batteries, sulfur-based chemistries, and hydrogen carriers with the aim of providing solutions for large regional and 737-class aircraft



Concluding Thoughts on Battery Technology

- Pack specific energy of 300 Wh/kg is achievable within reasonable timeframe
- Pack specific energy of 400 Wh/kg will probably require maturation of all solid state technology or Li-S with liquid electrolyte
- No clear path for achieving pack specific energy greater than 500 Wh/kg; will require new paradigms
- Performance, safety, and life of developmental batteries under aircraft operating conditions need to be evaluated, particularly under high C-rating operation
- Opportunities for better packaging and integration with aircraft

Questions?



- Submit questions to grc2.cnf.io



EPFD Feeds into Subsonic Flight Demonstrator

EPFD Project

