Technical Challenges and Barriers Affecting Turbo-electric and Hybrid Electric Aircraft Propulsion

Dr. Ajay Misra
Deputy Director, Research and Engineering
NASA Glenn Research Center

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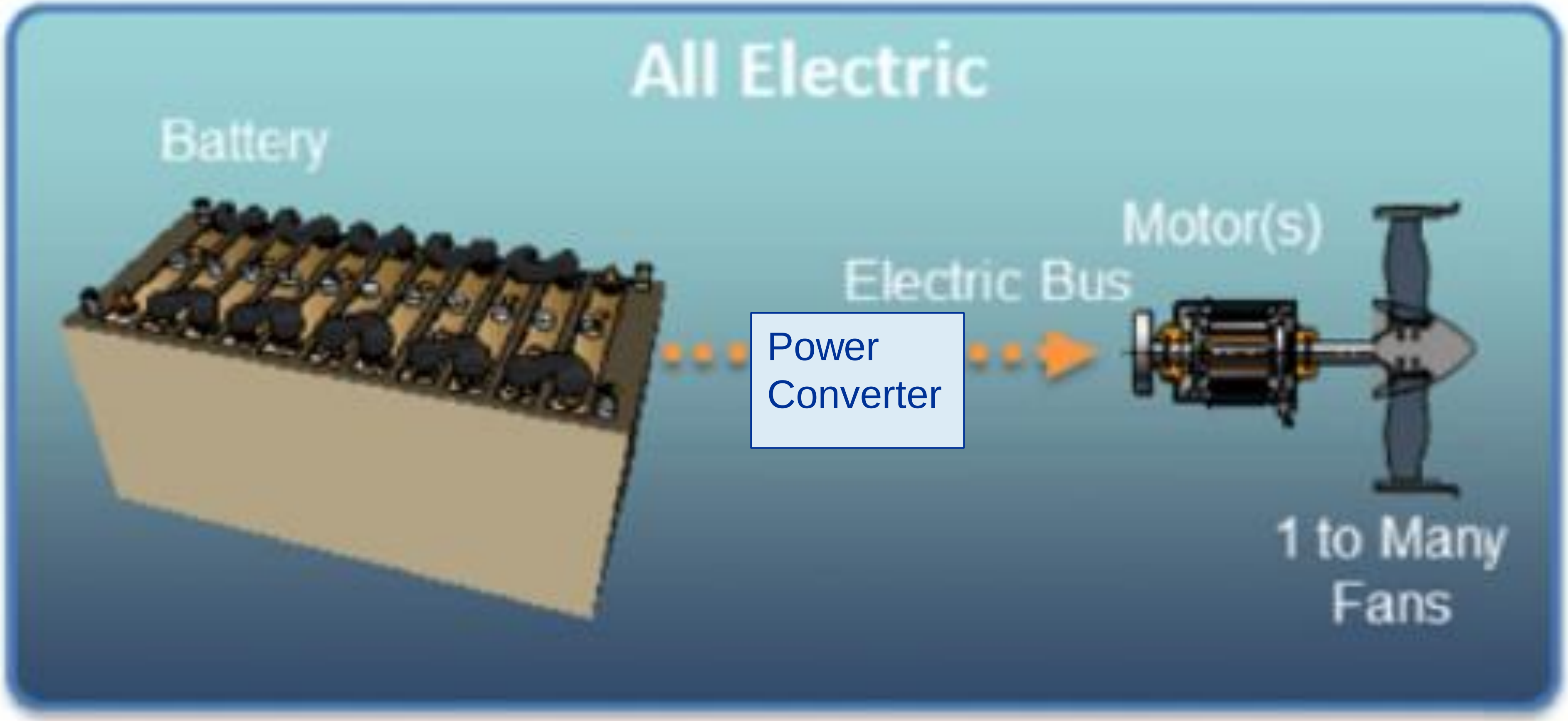
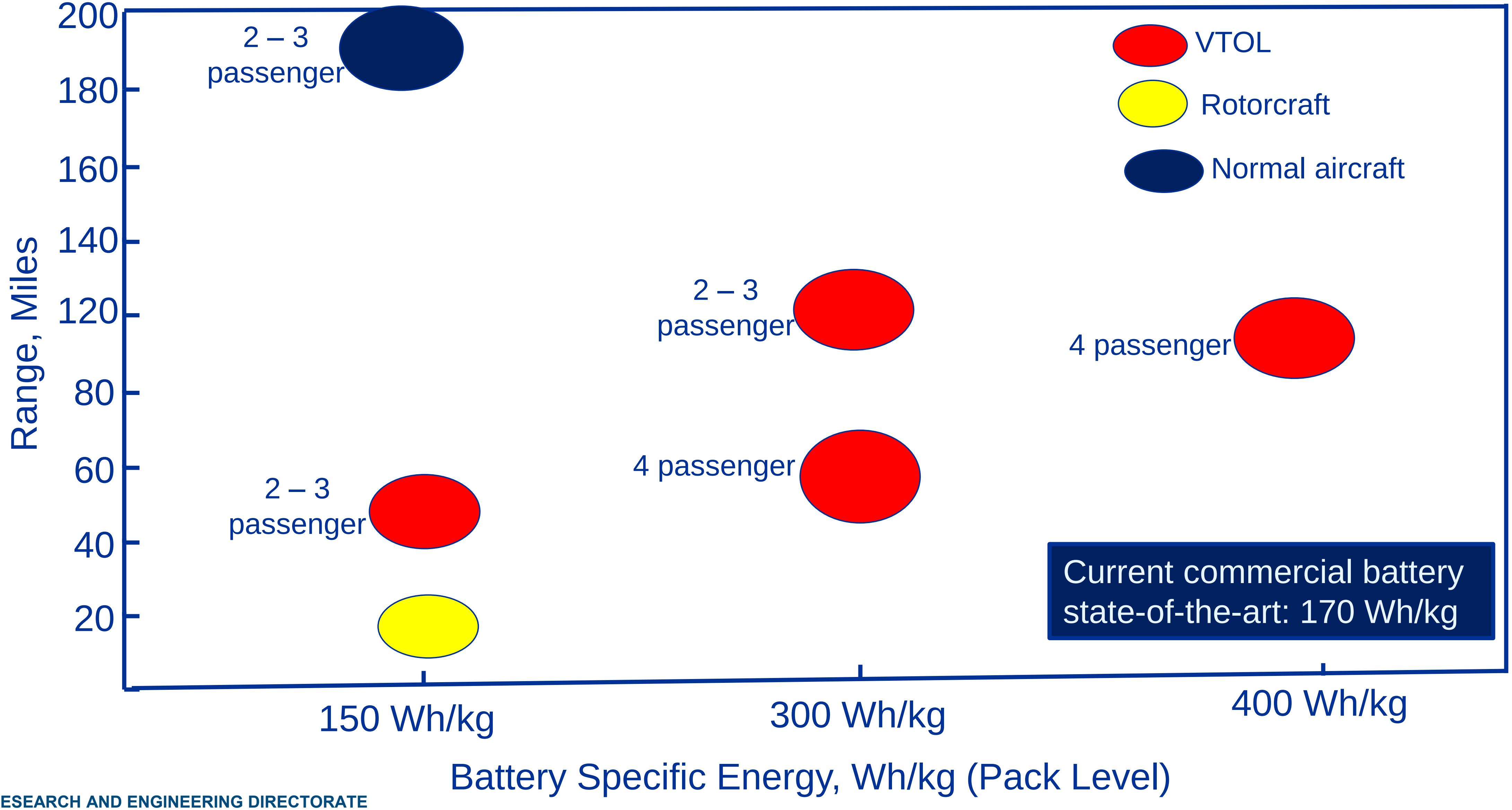
Why Electric

- Improve fuel efficiency
- Lower emissions
- Reduced noise
- Low operating cost
- Efficiency of electrical components significantly higher than IC engines or gas turbine engines

All Electric Aircraft

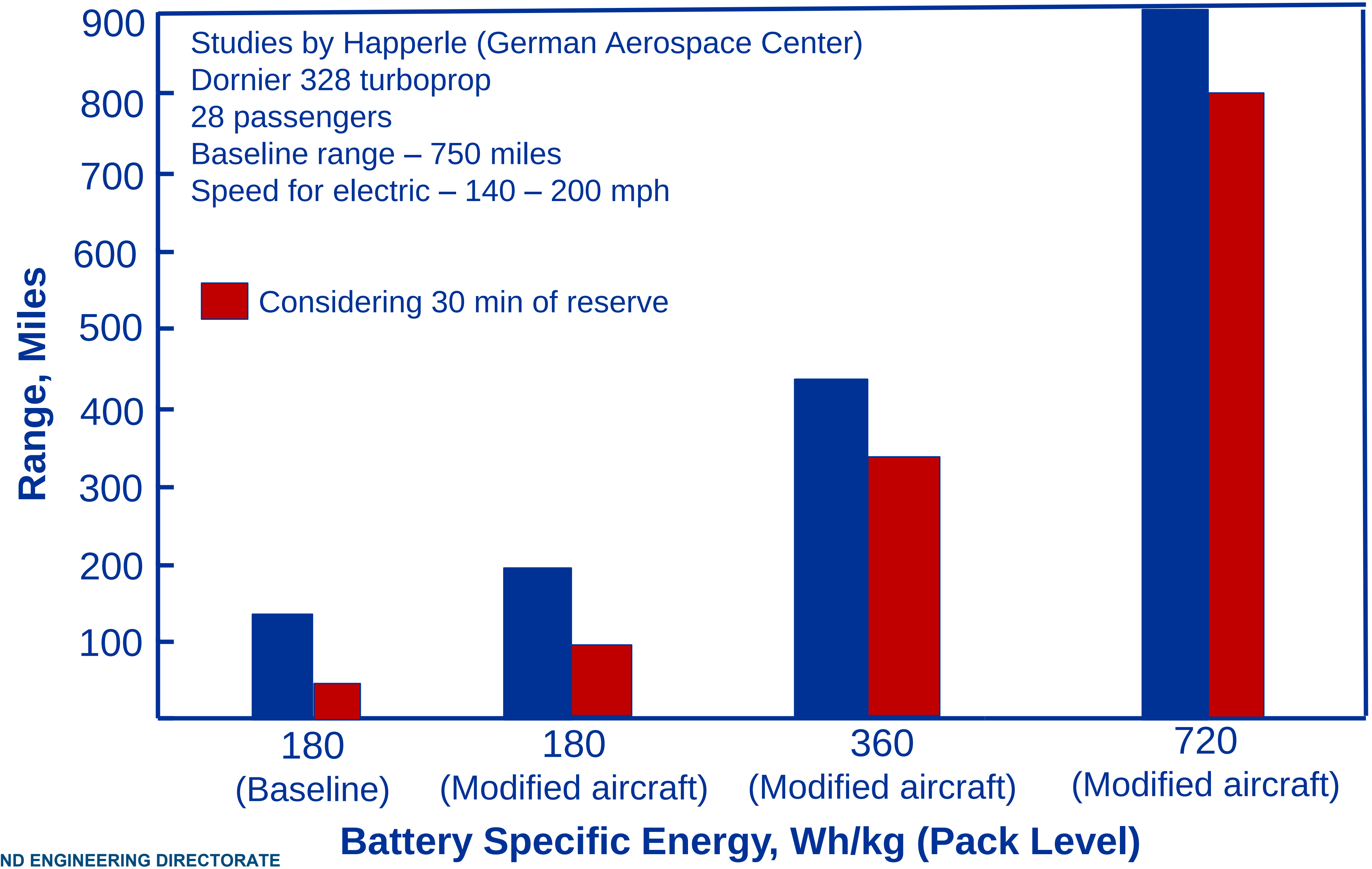


Battery Capability Required for All Electric Urban Mobility Aircraft



Current commercial battery state-of-the-art: 170 Wh/kg

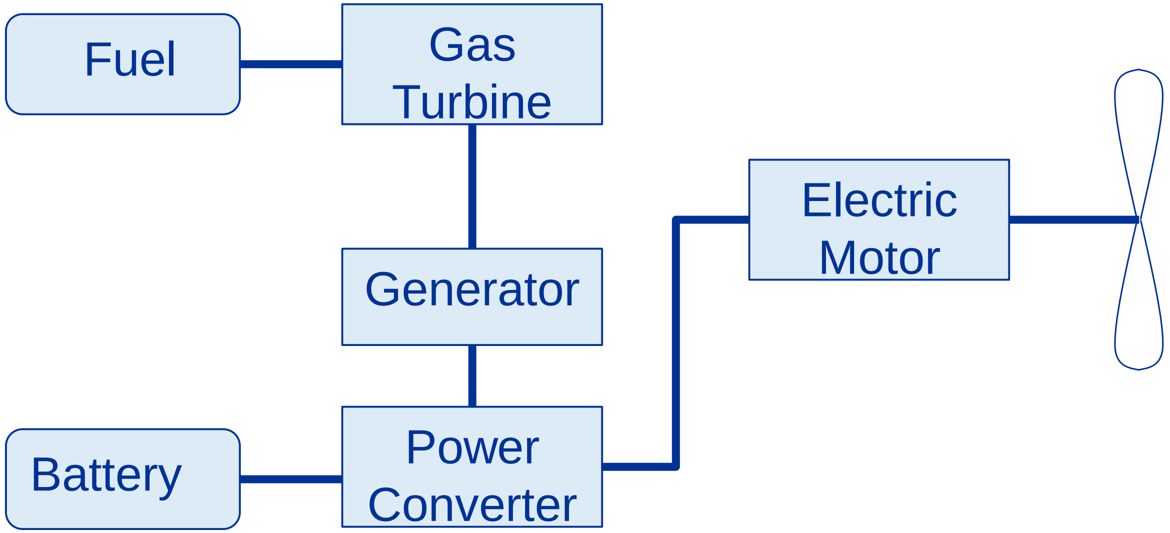
All Electric Commuter Aircraft



Studies by Happerle (German Aerospace Center)
Dornier 328 turboprop
28 passengers
Baseline range – 750 miles
Speed for electric – 140 – 200 mph

🟥 Considering 30 min of reserve

Series Hybrid Electric Aircraft



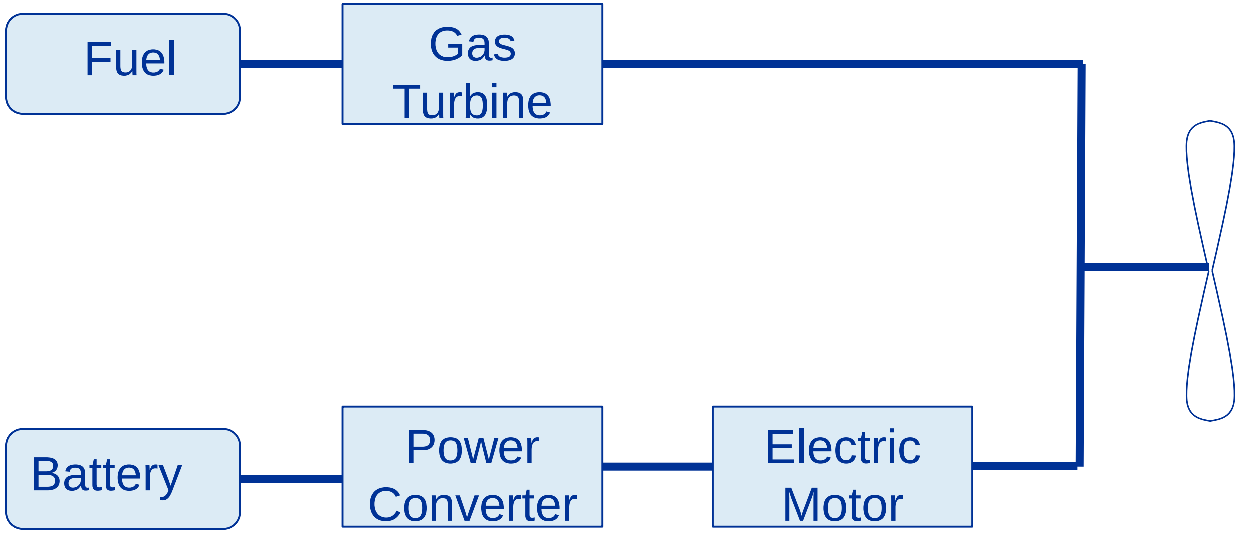
Range Extender

- Gas turbine/IC engine used either to charge batteries or provide auxiliary power to drive the motor
- Battery used during takeoff and part or all of cruise
- Gas turbine/IC engine used primarily during part of cruise
- Gas turbine/IC engine can continuously run at the most efficient point
- Gas turbine is sized much smaller

Challenge:

- Efficiency of small engines relatively low (on the order of 30%) compared to large gas turbine engines

Parallel Hybrid Electric Aircraft



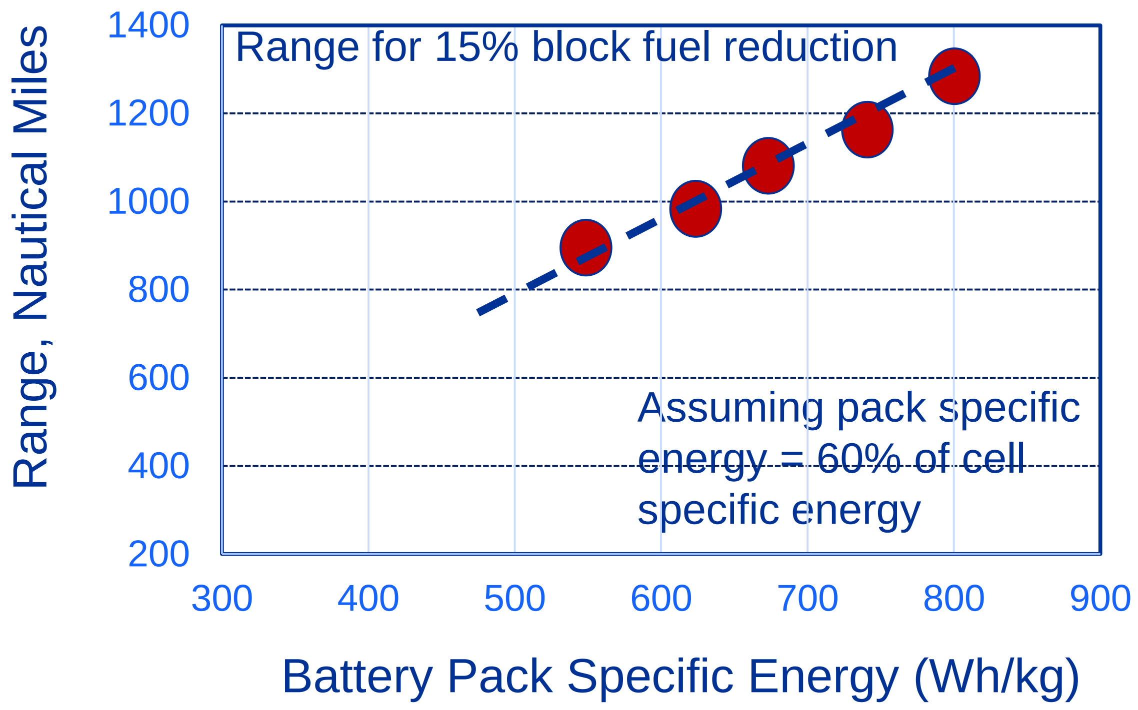
- Degree of hybridization can be adjusted depending on the mission
- One option is for gas turbine to always operate at its peak efficiency point and to use battery when power required is larger than power delivered by the gas turbine (e.g., during takeoff)

Challenge:

- Increased complexity of the mechanical coupling
- Increase in control complexity as power flow has to be regulated and blended from two power sources

Battery Requirement for Commuter and Regional Hybrid Electric Aircraft

Hybrid electric, 70 Passengers (Based on Isikveren et.al., ISABE 2015 Paper)



48 passenger turboprop

- For 600 nm, battery pack with specific energy greater than 500 Wh/kg for total energy to be less than conventional propulsion
- Battery specific energy must be at least 600 Wh/kg for operating fuel/energy cost parity with advanced conventional propulsion

RUAG Dornier – DO228NG (Juretzko)

- 20 passenger hybrid electric aircraft
- 335 – 350 miles range with battery specific energy of 150 Wh/kg

Single Isle 737-Class Aircraft

Boeing SUGAR Volt

- Parallel hybrid, ~150 PAX
- 1-5 MW, 3-5 kW/kg, 93% efficient electric machines
- 60% efficiency improvement over 2005 baseline aircraft if a renewable grid is assumed

Battery requirement: 750 Wh/kg

Pompet et.al. (Germany):

- Single aisle 180 passengers, 3300 n miles base line
- 13 % block fuel reduction for 1500 Wh/kg battery pack
- 6% block fuel reduction for 1000 Wh/kg battery pack
- May not be any benefit for battery pack with less than 1000 Wh/kg specific energy

Lent (UTRC):

- Single aisle 737 class, geared turbofan
- Electric motor used during takeoff along with gas turbine engine
- Addition of turbogeneartor during takeoff more effective
- Batteries greater than 1000 Wh/kg required to be competitive with turbogenerator

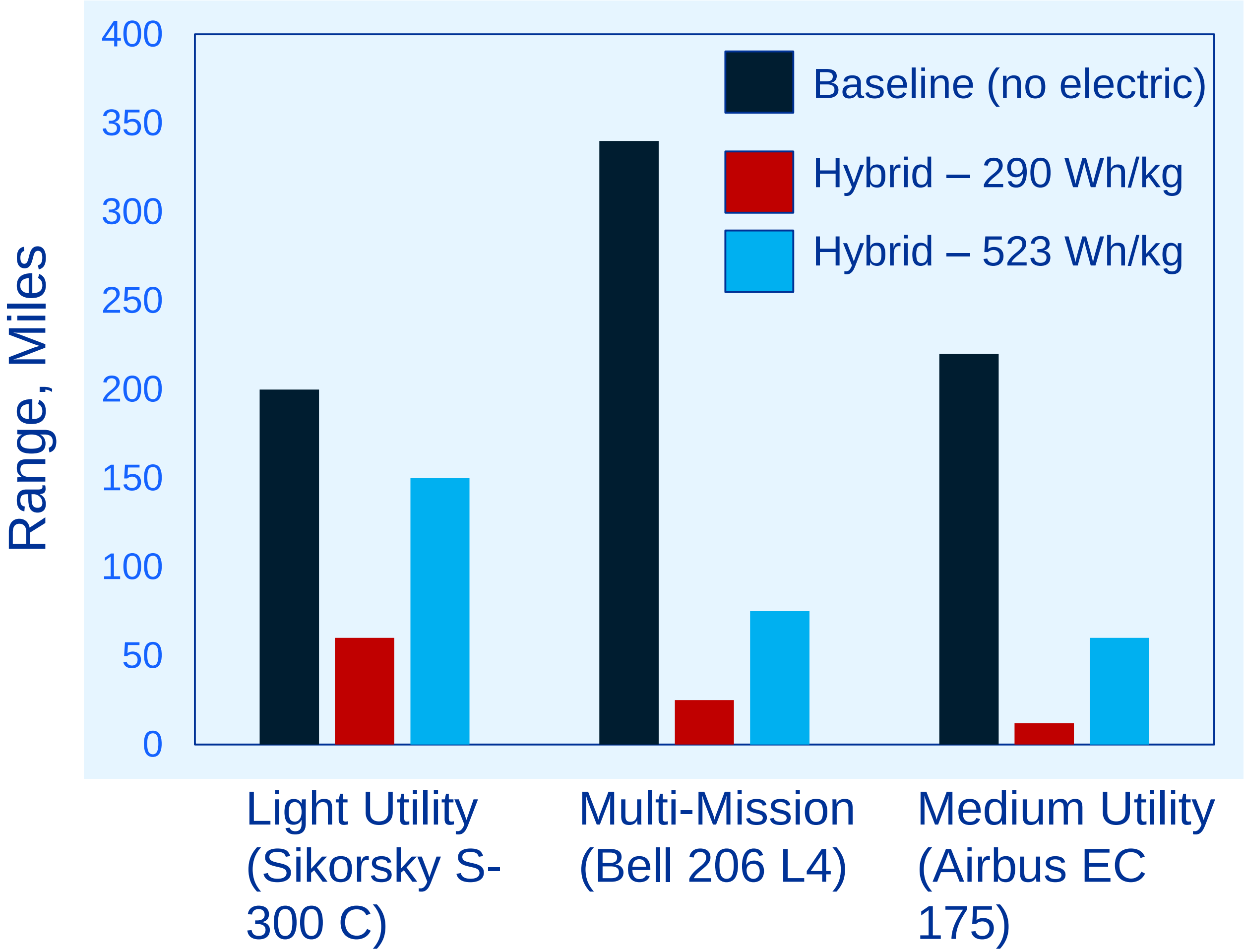
Single-aisle 737 class hybrid electric aircraft will require 1000 Wh/kg or higher battery specific energy

Hybrid Electric Helicopters

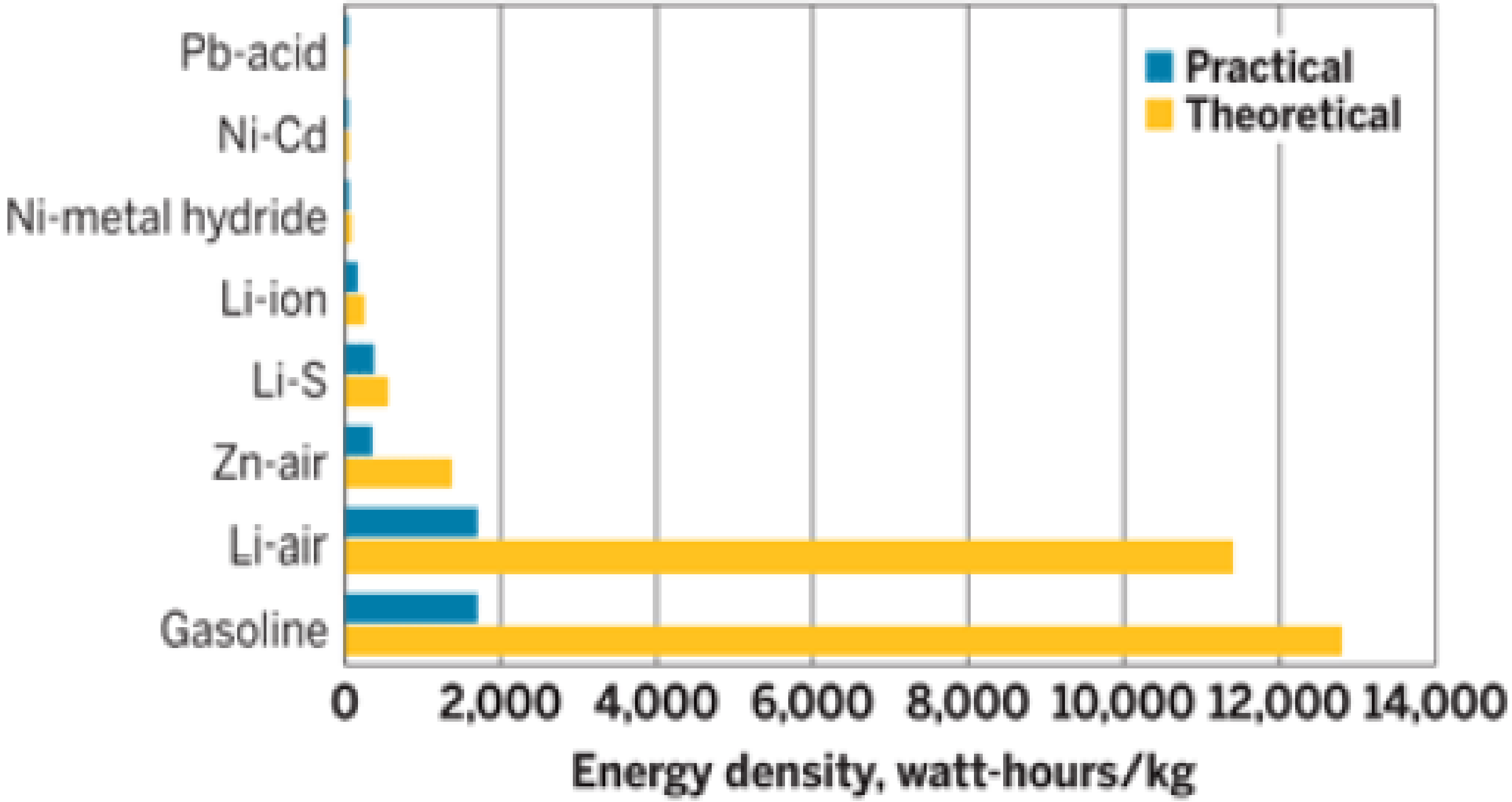
Light Utility

Multi Mission

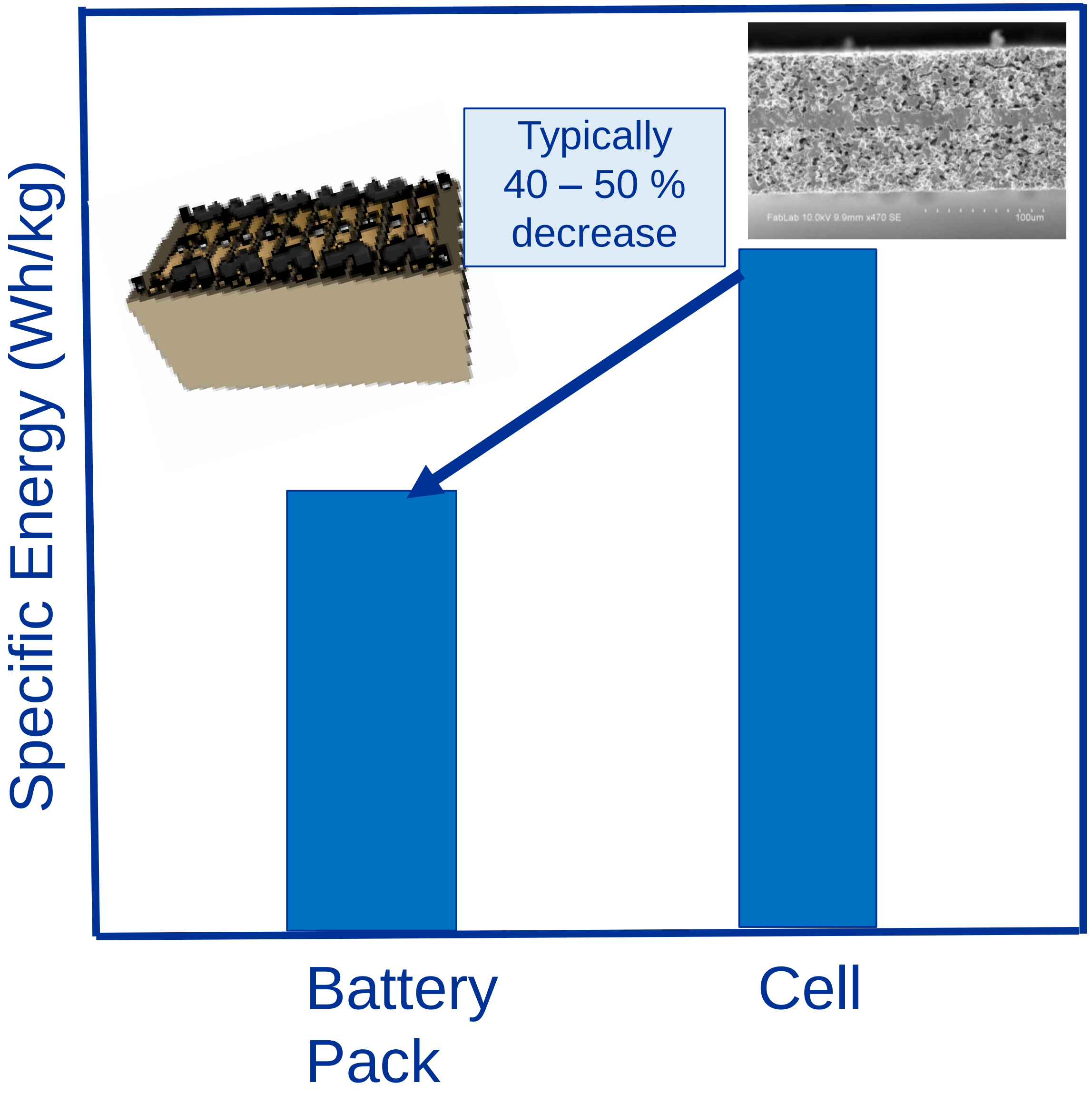
Medium Utility



Battery Chemistry Possibilities



Reduction in Cell-to-Pack Battery Specific Energy

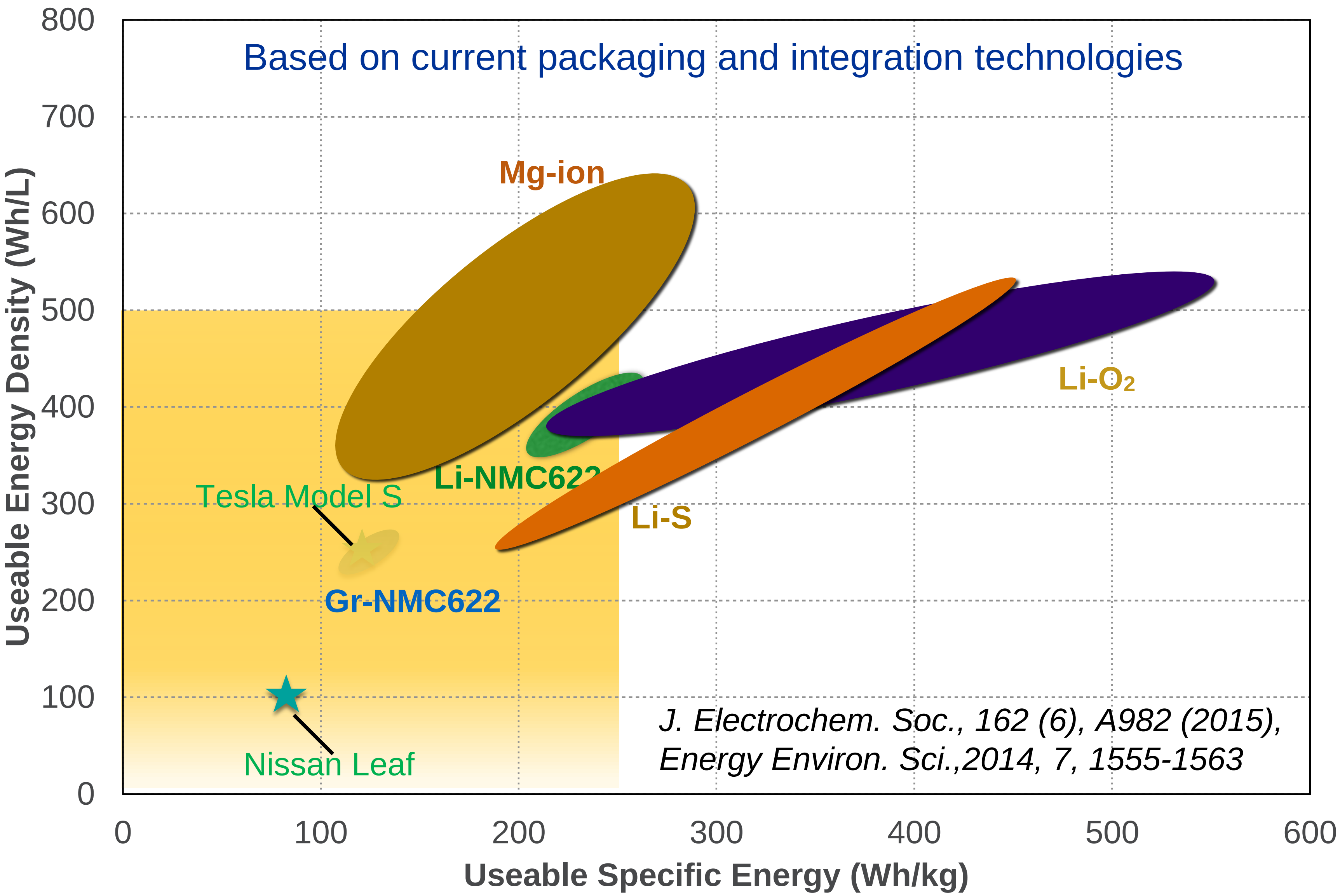


Typically 40 – 50 % decrease

Reduction in Specific Energy From Cell to Pack:

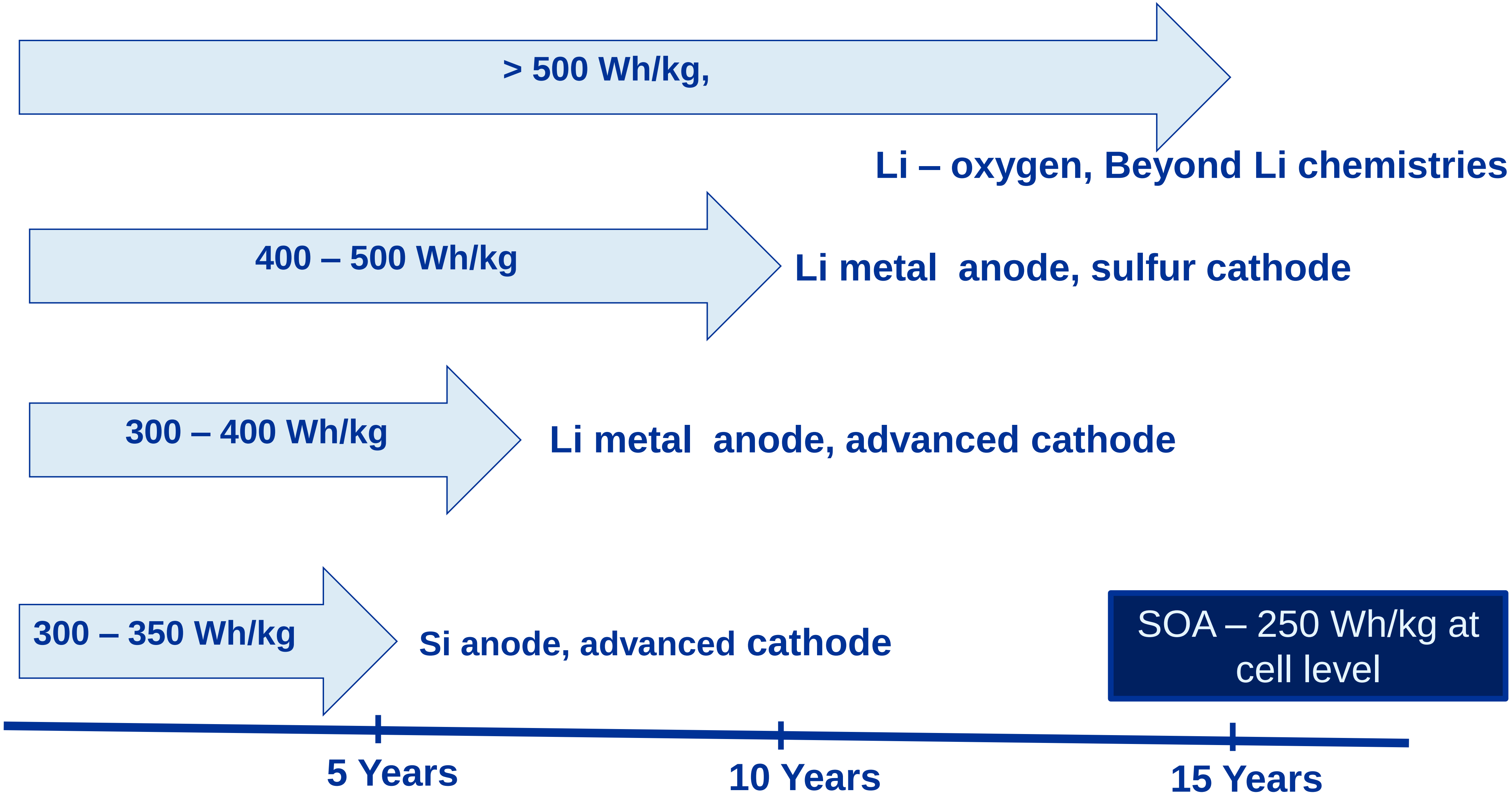
- Thermal management
- Battery management system
- Safety features
- Packing

Limits on Useable Specific Energy



J. Electrochem. Soc., 162 (6), A982 (2015),
Energy Environ. Sci.,2014, 7, 1555-1563

Notional Progression of Battery Capability



> 500 Wh/kg,

Li – oxygen, Beyond Li chemistries

400 – 500 Wh/kg

Li metal anode, sulfur cathode

300 – 400 Wh/kg

Li metal anode, advanced cathode

300 – 350 Wh/kg

Si anode, advanced cathode

SOA – 250 Wh/kg at cell level

5 Years

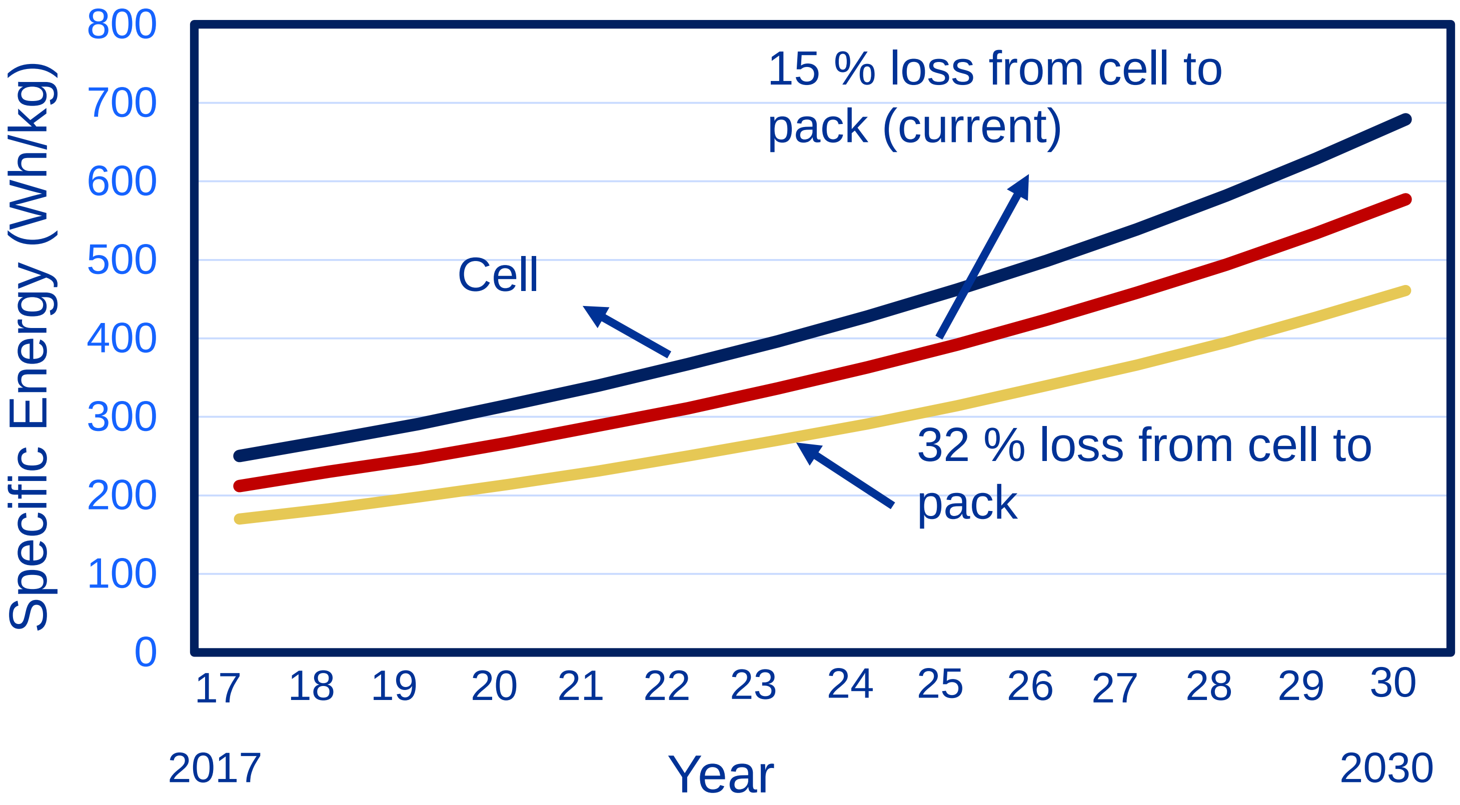
10 Years

15 Years

Projected Advances in Battery Technology

Rate of increase in specific energy is typically on the order of 5 – 8% per year
Specific energy loss from cell to pack is typically 50 to 60%

Assuming 8% increase per year at cell level

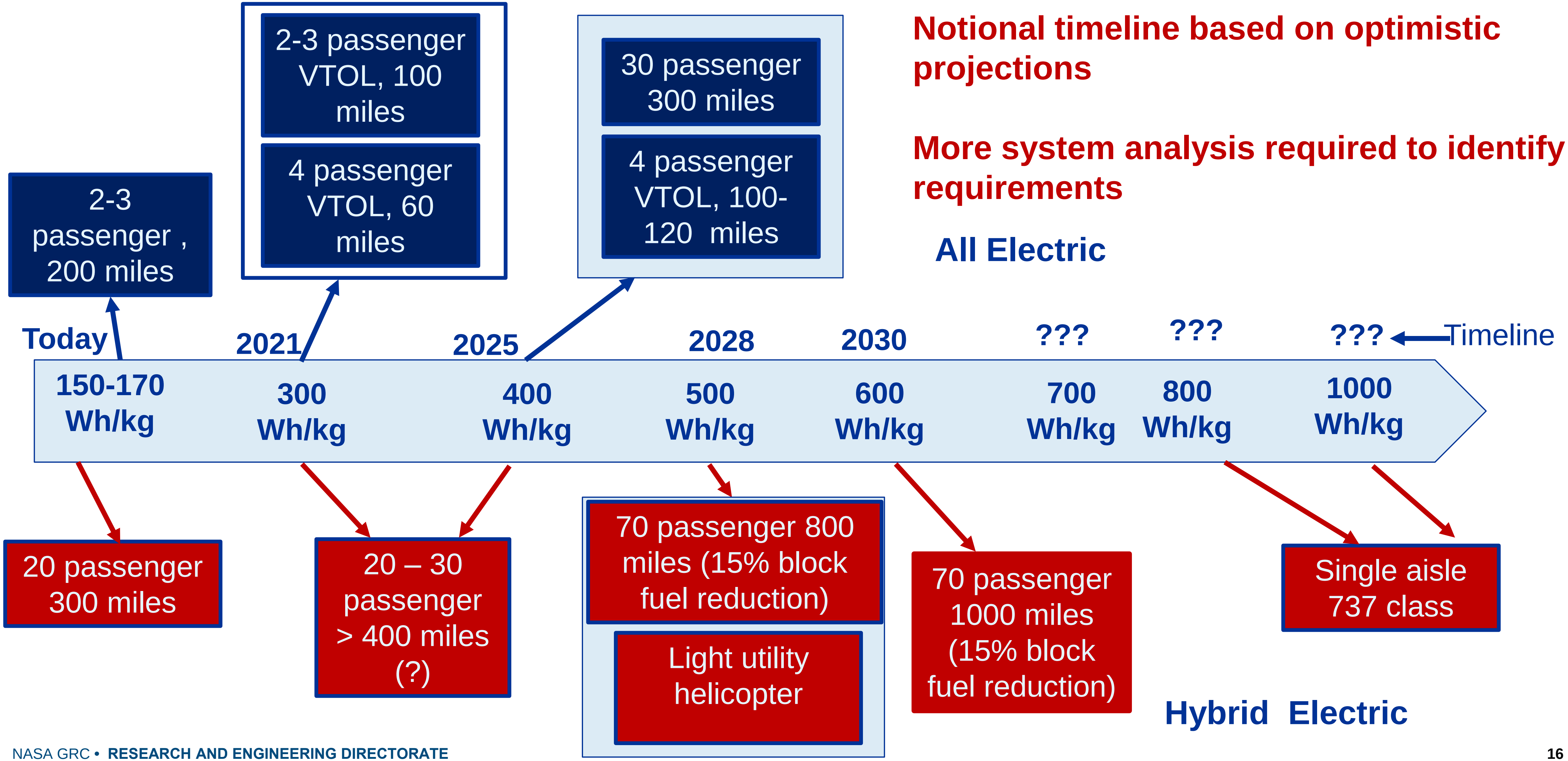


Innovation required in:
- New chemistries and materials for cells
- Pack design and integration

Dependency of Evolution of Electrified Aircraft on Battery Advances

Notional timeline based on optimistic projections

More system analysis required to identify requirements



All Electric

2-3 passenger , 200 miles

2-3 passenger VTOL, 100 miles

4 passenger VTOL, 60 miles

30 passenger 300 miles

4 passenger VTOL, 100-120 miles

Today **2021** **2025** **2028** **2030** **???** **???** **???** ← Timeline

150-170 Wh/kg **300 Wh/kg** **400 Wh/kg** **500 Wh/kg** **600 Wh/kg** **700 Wh/kg** **800 Wh/kg** **1000 Wh/kg**

20 passenger 300 miles

20 – 30 passenger > 400 miles (?)

70 passenger 800 miles (15% block fuel reduction)

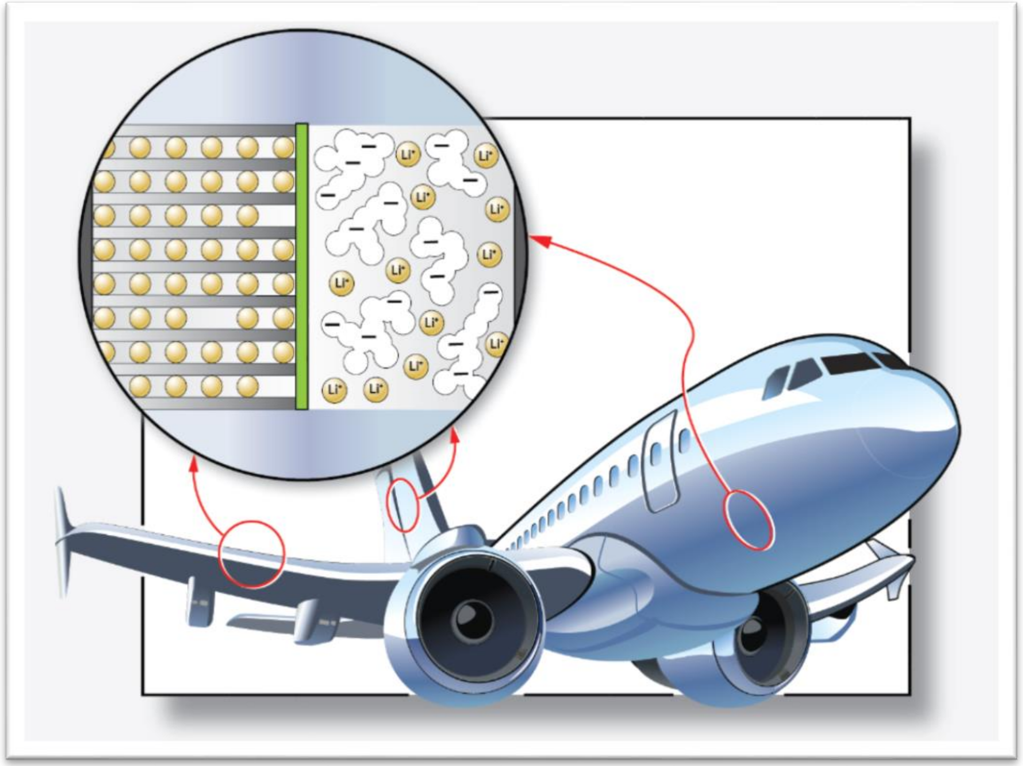
Light utility helicopter

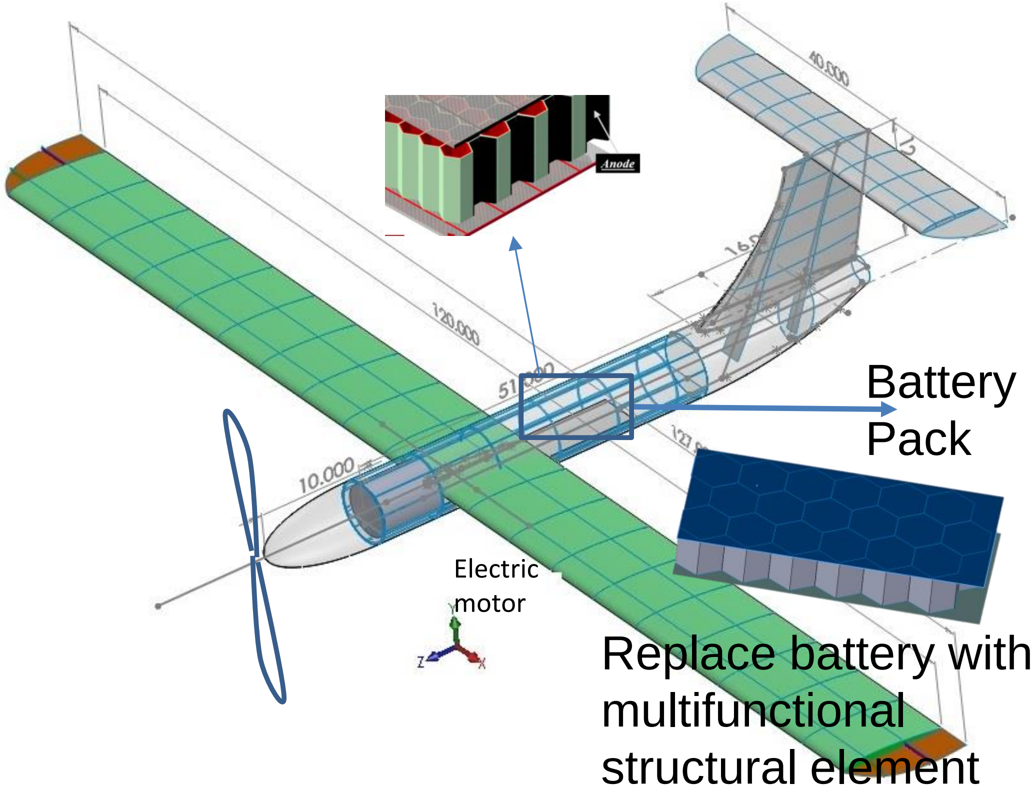
70 passenger 1000 miles (15% block fuel reduction)

Single aisle 737 class

Hybrid Electric

Multifunctional Structures With Energy Storage Capability



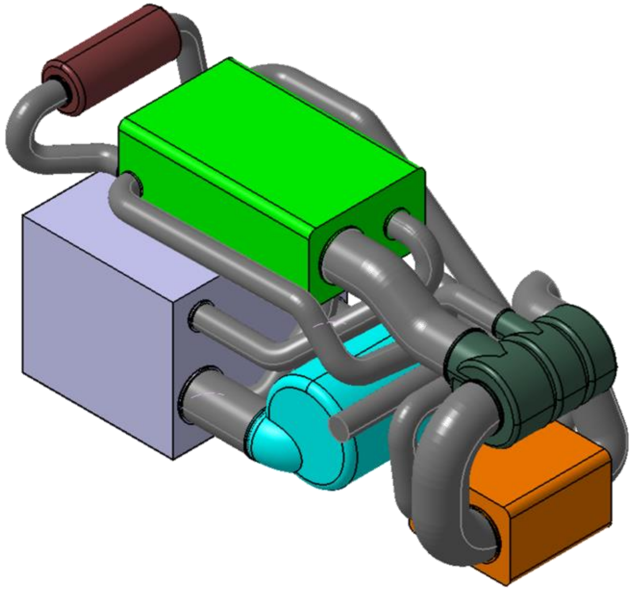


Battery Pack

Replace battery with multifunctional structural element

Batteries with some load bearing capability or structure with energy storage capability ????

Application of Fuel Cells



X-57 FUELEAP System Using Solid Oxide Fuel Cell: Power output: 120kW (161hp) max continuous, 158kW (209hp) peak

- Specific power: 314 W/kg (0.19 hp/lb)
- Efficiency: 62% (10k ft, std day)

>Gross weight: 3,000 lbs
>Wing loading: 19 lbs/sq ft
>Takeoff power: 2x97hp
>Stall speed (landing): 58 nmi/hr
>Cruise speed: 135 nmi/hr
>Cruise power: 2x70hp
>Cruise efficiency: 2.2 km/kWh
(equivalent to 40 nmi/gal AuGas)

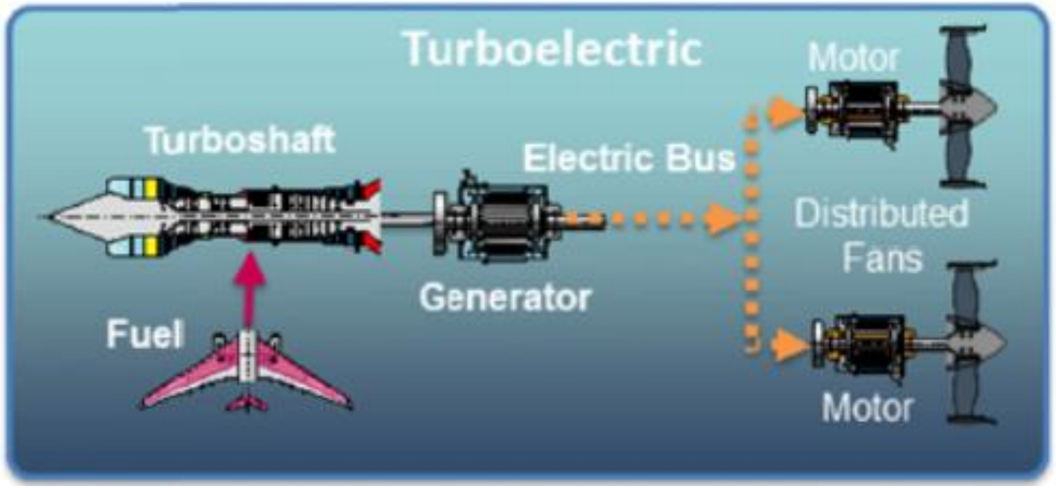
Solid oxide fuel cells

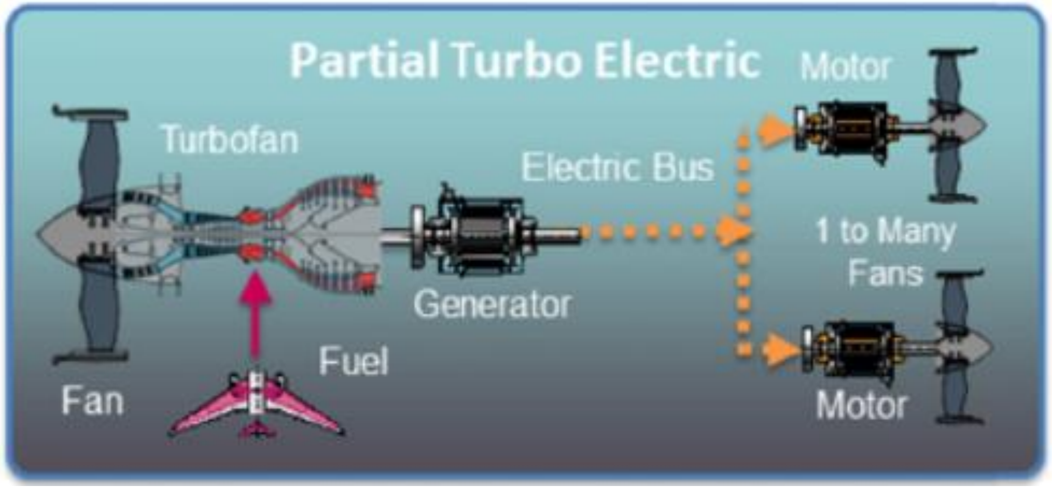
- High efficiency
- Low power density at system level
- Potential range extender for small hybrid electric aircraft
- Durability, thermal cycling

PEM fuel cell:

- Needs hydrogen

Turboelectric Aircraft





Benefits of Turboelectric Propulsion:

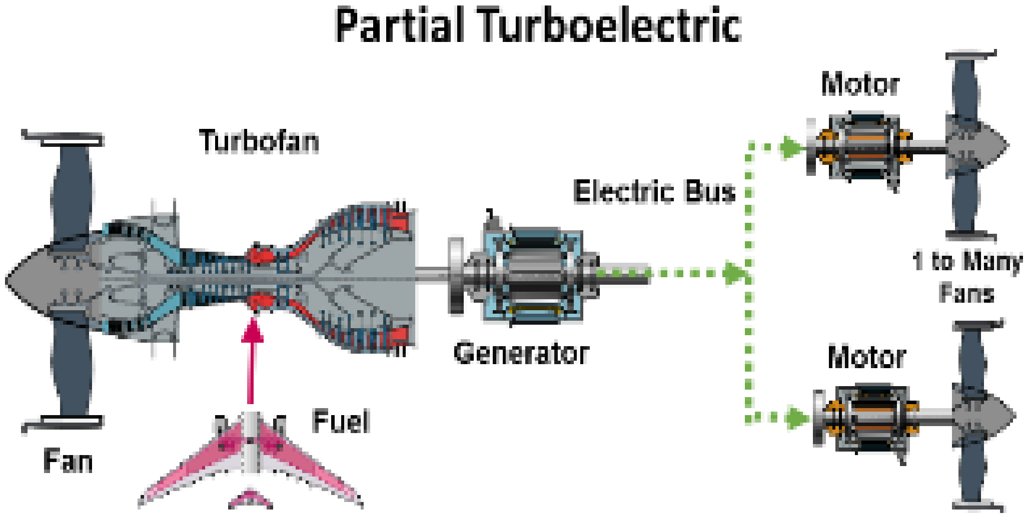
- Enables new aircraft configurations
- Decoupling of speeds of turbine and fan
- Multiple fans can be driven by one gas turbine, providing high propulsive efficiency due to higher bypass ratio (BPR)
- Can enable boundary layer ingestion capability

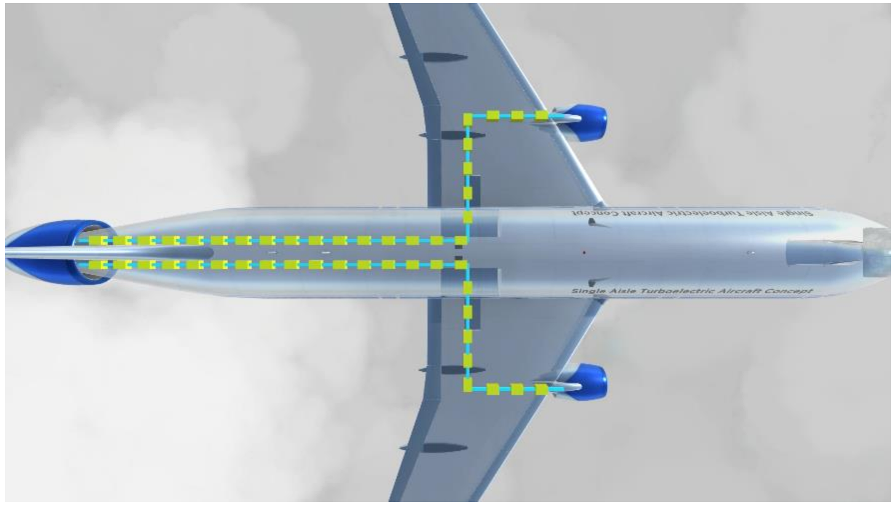
Boundary Layer Ingestion Testing at NASA GRC

Challenge:

- Development of distortion tolerant fan

Advanced Single Aisle Turboelectric Concept





Single-aisle Turboelectric Aircraft with Aft Boundary Layer Ingestion (STARC – ABL)

- Conventional single aisle tube-and-wing configuration
- Twin underwing mounted turbine engines with attached generators on fan shaft
- Ducted, electrically driven, boundary layer ingesting tailcone propulsor
- Projected 7 – 12 % fuel burn savings for 1300 nm mission

Distributed Electric Propulsion

X – 57: Distributed Electric Propulsion Demonstrator

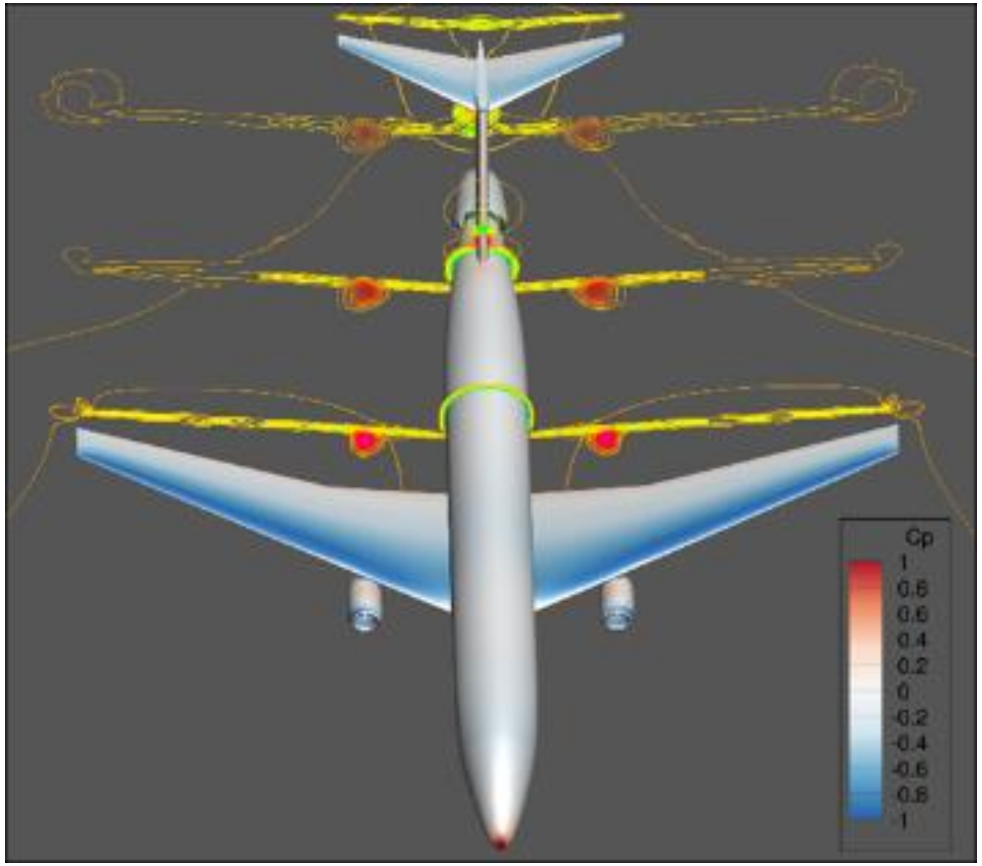
- Dozen, small electric motors that accelerate airflow over the wing – provides more lift at low speed – enables takeoff in normal runway

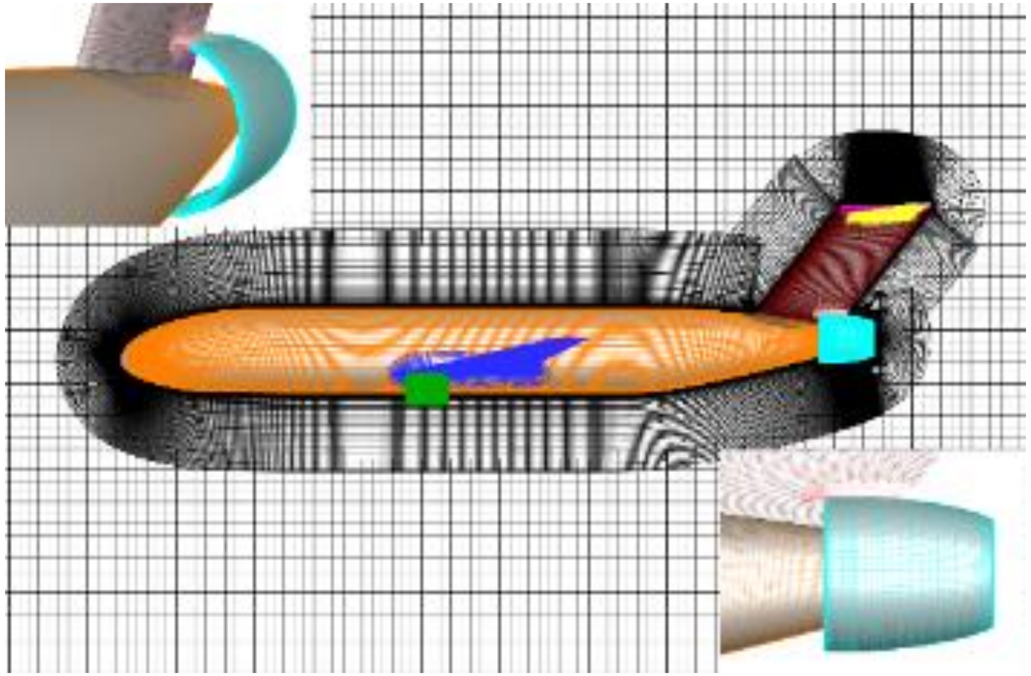
- Cruise – two electrically driven propellers mounted on tip of each wing

9-Passenger Concept

- 9 passenger plane, battery powered with turbine range extender
- Much more efficient, cost effective and quiet than comparable aircraft
- Increase use of small and medium US airports and decrease emissions

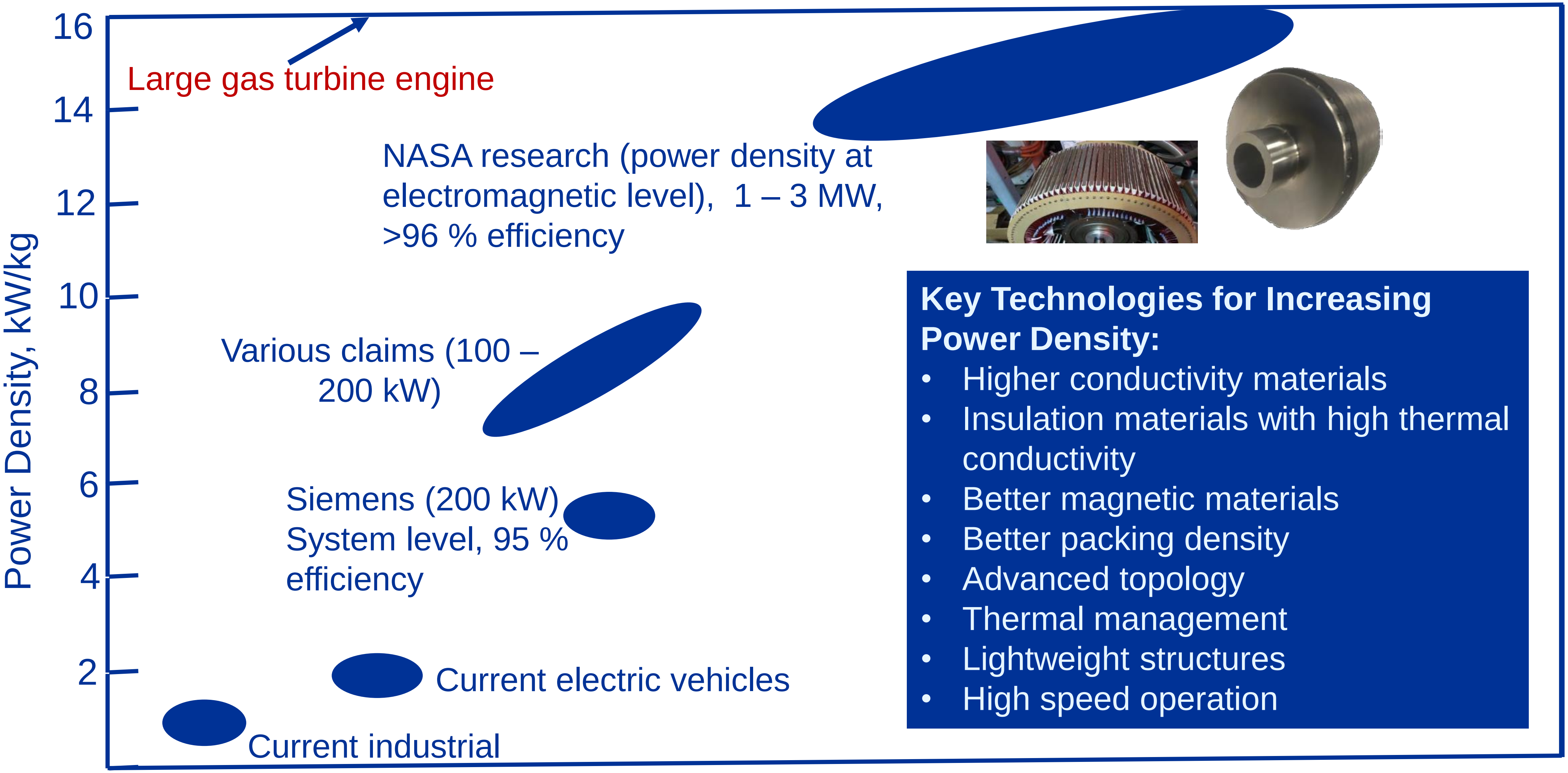
Propulsion-Aircraft Integration for Electrified Aircraft





Need analytical tools to assess benefits of propulsion airframe integration on electrified propulsion aircraft configurations

High Power Density Electric Motors



Key Technologies for Increasing Power Density:

- Higher conductivity materials
- Insulation materials with high thermal conductivity
- Better magnetic materials
- Better packing density
- Advanced topology
- Thermal management
- Lightweight structures
- High speed operation

High Power Density Power Converters

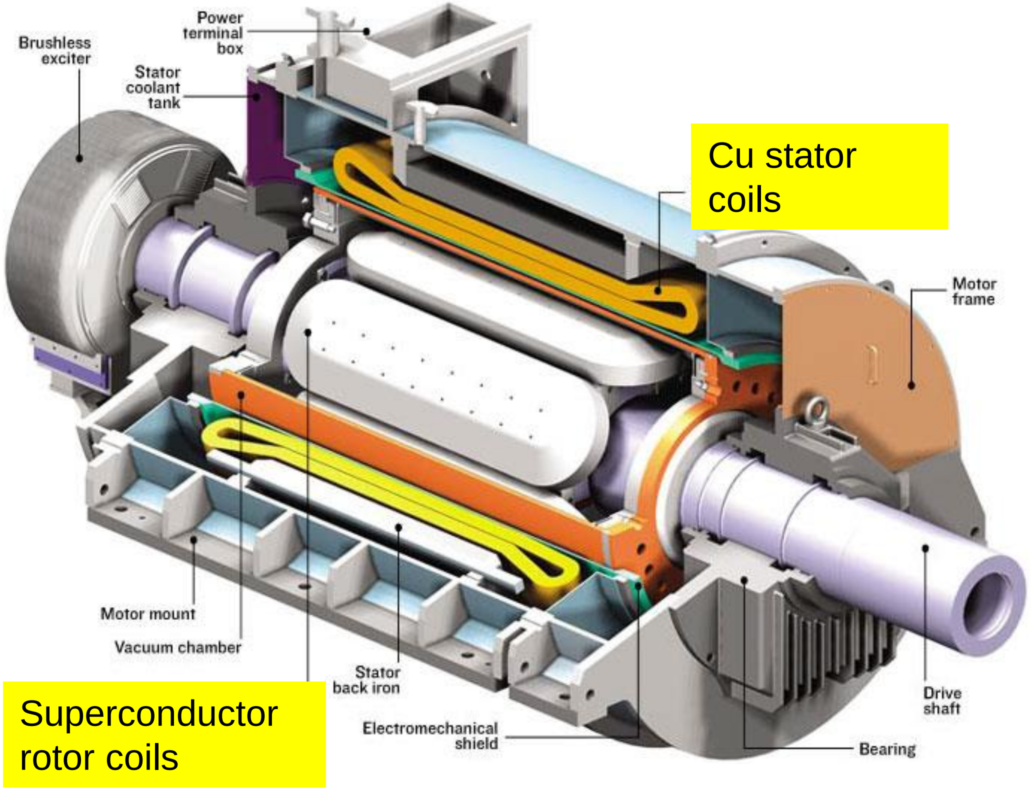
- High power density power converters needed
- Need 2-3X increase in power density of MW scale converters
- Goal:
  - 19 kW/kg plus 99 % efficiency with non-cryogenic cooling
  - 26 kW/kg plus >99 % efficiency with cryogenic cooling
- Approach – Wide bandgap semiconductors (SiC and GaN)

Advanced magnetic materials to handle the higher switching speeds afforded by new SiC and GaN semiconductors.

Large Turboelectric Aircraft With Superconducting Motors

Large Aircraft with Superconducting Motor

Current research: Development of fully superconducting, MW scale motor



High ac losses major challenge for superconducting stator

Power densities greater than 20 kW/kg achievable

Thermal Management Challenges

- For a 5 -10 MW system, 100s of kW heat generated

- Heat from multiple sources – power electronics, motors, batteries

- Integration of heat rejection from multiple sources

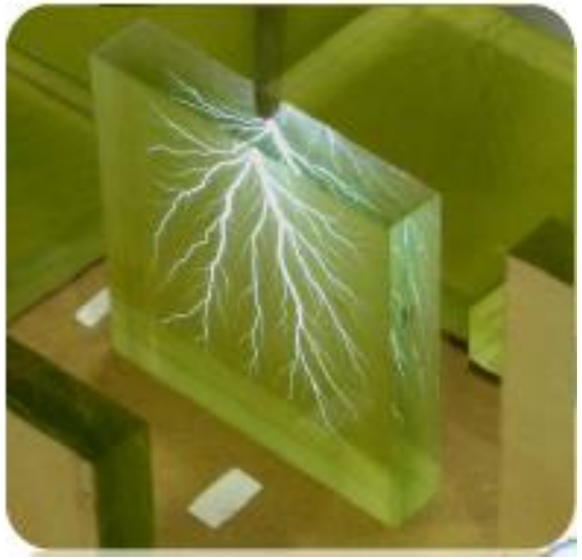
- Low grade heat difficult to handle

- Increasing use of composites lowers the heat rejection capability of the system

- Lightweight and compact thermal management system required
- Integrated thermal management approach at the aircraft level required

Power Transmission

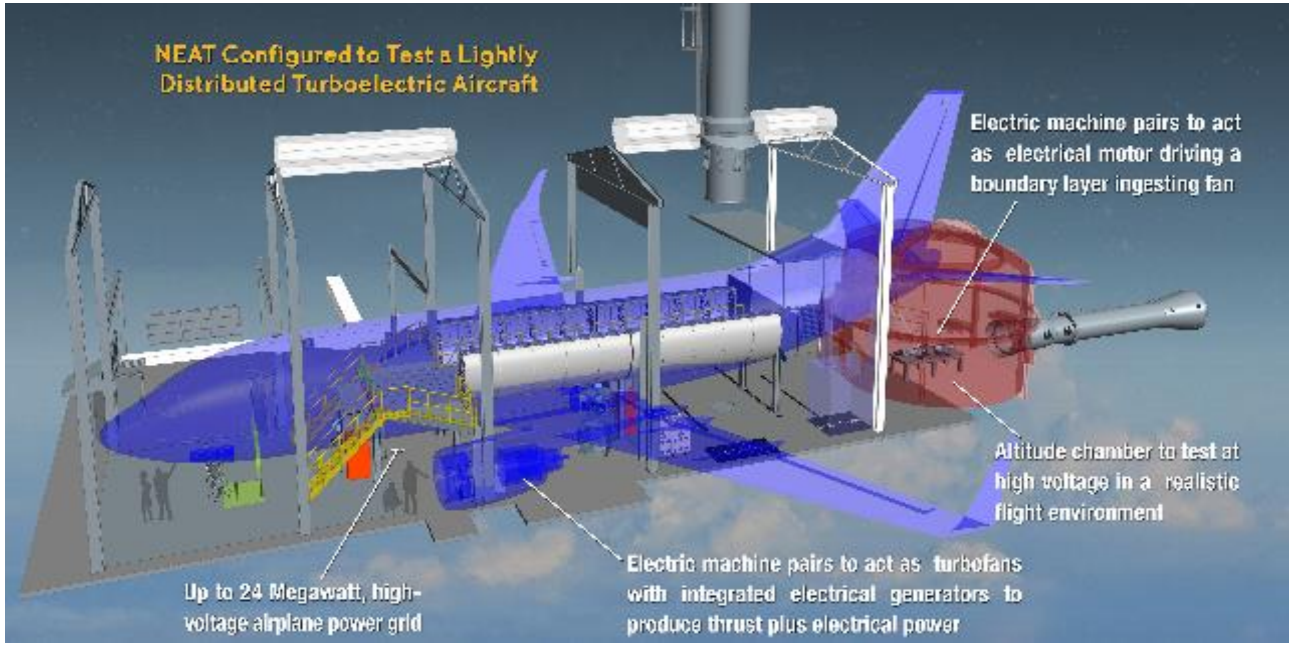
- Transmission of MWs of power will require large diameter Cu with severe weight penalty
- High voltages (on the order of 2000 V or more) will be required for the current generation of power cables (Cu, Al)
  - Advanced insulation materials required
  - Thermal management of the power cable system
- New materials with higher electrical conductivity than Cu required
  - Carbon nanotubes show promise
  - Superconducting materials possibility – will require cryogenic cooling of transmission cables



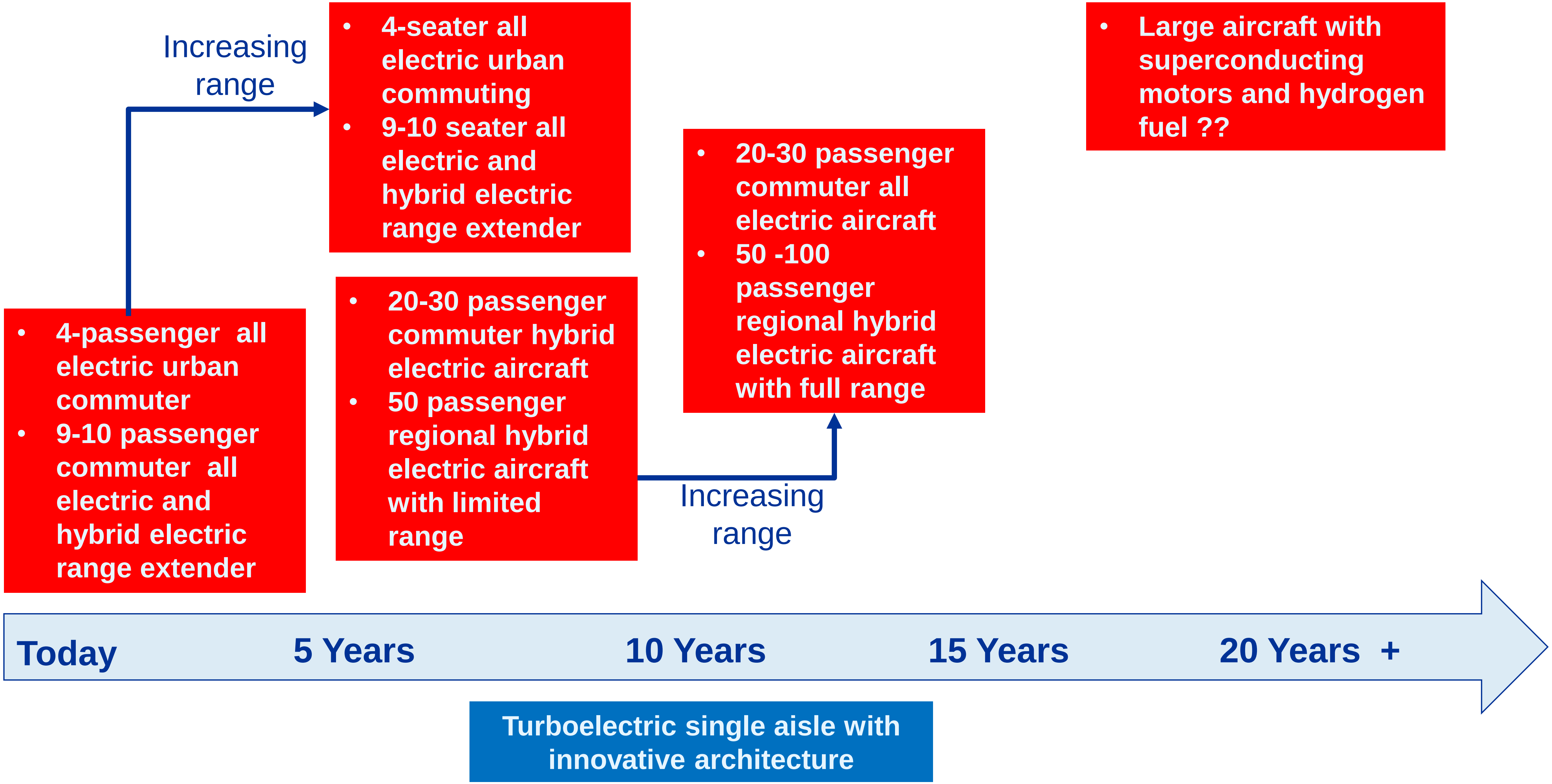
Development of Integrated System

- Integration of multiple components and optimization of performance of integrated system a challenge
  - Optimum power extraction from turbine
  - Coupling of generator, motor, and fan
  - Optimized energy management
- Control system with energy coming from multiple sources
- Integrated testing required to address system and sub-system level integration challenges

NASA Electric Aircraft Testbed (NEAT) for testing multi MW level power system



Notional Progression of Electrified Aircraft



- 4-passenger all electric urban commuter
- 9-10 passenger commuter all electric and hybrid electric range extender

Increasing range

- 4-seater all electric urban commuting
- 9-10 seater all electric and hybrid electric range extender

- 20-30 passenger commuter hybrid electric aircraft
- 50 passenger regional hybrid electric aircraft with limited range

Increasing range

- 20-30 passenger commuter all electric aircraft
- 50 -100 passenger regional hybrid electric aircraft with full range

- Large aircraft with superconducting motors and hydrogen fuel ??

Today 5 Years 10 Years 15 Years 20 Years +

Turboelectric single aisle with innovative architecture

Concluding Thoughts

- Electrified Aircraft is a reality – NOT "IF", IT IS "WHEN"

- Progression of all electric and hybrid electric aircraft is a strong function of advances in battery technology

- Turboelectric aircraft with innovative propulsion architecture and integrated airframe-propulsion system is an attractive option for large single aisle aircraft

- Advances in many component technologies required
  - 3 to 5 times increase in power density of electric motors
  - 3X increase in power density of power converters
  - 3 - 5X decrease in weight of power cables for MW level power transmission

- Integration of technologies and demonstration of integrated technologies at sub-system and system level are required