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Electric Propulsion (EP) for Aircraft

NASA, Aviastar.org

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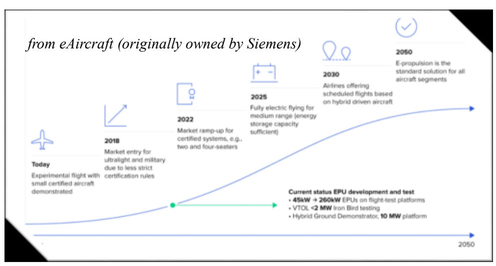
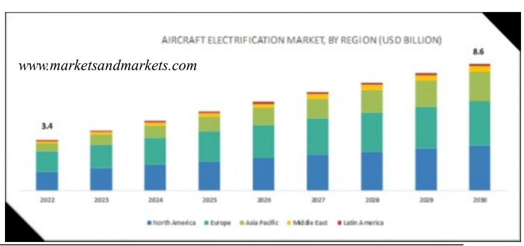
EP for Aircraft

- While modern interest in EP aircraft dates to 1970's, significant effort devoted to developing aircraft EP systems in last 10-15 years
- Some studies suggest significant market penetration of (manned) EP aircraft between 2030 and 2050





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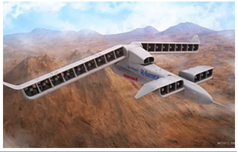
Motivations for EP

- Environmental considerations
  - lower carbon footprint
  - reduced pollutants (NO_x, particulates)
  - noise
- Longer life, lower maintenance costs
- Scaling to smaller vehicles
  - regional transportation, urban mobility
- Distributed propulsion, airframe integration
  - alternative to control surfaces
  - boundary layer ingestion and increased aircraft L/D
- Long duration flights, e.g. HALE
  - surveillance, communications,…

Aurura Flight Sciences



BAE

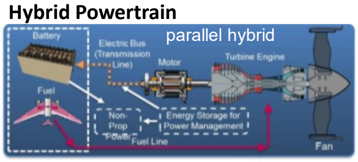
Lecture Goals

- Introduce EP nomenclature and architectures
- Define some metrics for evaluating EP systems
- Describe various EP system components
  - how they operate
  - current performance metrics and their implications for EP aircraft
  - advances in EP technology

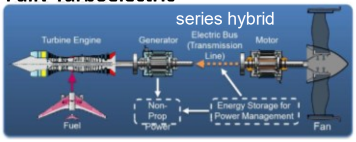
EP Nomenclature for Aircraft

- **All-electric propulsion**
  - 100% of energy and thrust from elec. (e.g., batteries, supplying electric motor driving propeller)
- **Hybrid electric propulsion**
  - part of energy sourced and/or thrust produced from electric
    - e.g., turbofan (fuel energy and non-elec. thrust generation) combined with propellers driven by battery powered motors
  - **hybrid electric powertrain**
    - electrical and non-elec. sources used to turn same shaft
  - **turboelectric propulsion**
    - turbine engine power either fully or partially diverted to drive elec. gen. for propulsion (no batteries)
  - **series vs. parallel** hybrid
    - all power delivered to propulsor elec. vs mechanical delivery from fuel

Hybrid Powertrain



Fully Turboelectric



Huff et al., NASA

Electric Propulsion Components

Electricity Source → Power Electronics/ Transmission → Motor → Propulsor/ Thruster

- **Source**
  - solar cells, batteries, fuel-cell, electric generator driven by heat engine, …
- **Power electronics and transmission**
  - voltage increase and conversion (e.g., rectifier AC→DC; inverter DC→AC), power controls, power bus (distribution), …
- **Motors**
  - AC synchronous, brushless DC, switched-reluctance, superconducting, …; and motor controllers
- **Propulser/Thruster**
  - propeller, ducted fan, …

EP Performance Considerations

- Some considerations for evaluating propulsion components and systems
  - mass
    - contribute to aircraft's TOGW (take-off gross weight)
  - volume or area
    - impacts aircraft size
  - maximum power and turndown ratio
    - determines deliverable thrust
  - energy storage
    - controls aircraft range

EP Performance Metrics

- Can combine these to produce various performance metrics

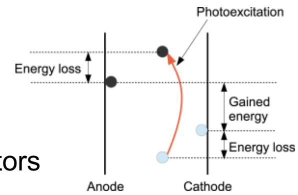
(V.8)

specific energy (e) ≡ energy storage/mass
energy density $(\bar{e})$ ≡ energy storage/volume
specific power $(\dot{e})$ ≡ maximum power/mass
specific mass (α) ≡ mass/area

- For comparison, some metrics for typical jet engine propulsion systems
  - $e_{\text{jet fuel}}$ ~ 43 MJ/kg
  - $\dot{e}_{\text{turbofan}}$ ~ 10-30 kW/kg

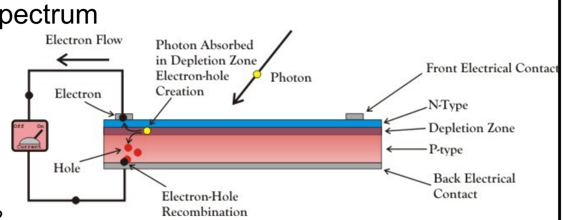
Solar Photovoltaics

- Convert solar radiation to electricity with photovoltaic (PV) cell
  - direct conversion of EM radiation photon→ free electron (current)
- Solar PV typically employ semi-conductors
  - maximum (Carnot) conversion effic. η_{conv} (electron/photon) ~ 95%



Alharbi and Kais, Renewable & Sustainable Energy Rev. ***43****, 2015*

- For solar radiation spectrum
  - η_{conv} ~ 34% single P-N cell*
  - η_{conv} ~ 50-85% stacked cells
- Min. specific mass
  - a ~ 0.2-0.4 kg/m²



**Shockley Queisser limit*

Maximum Power Availability

- Power available for thrust production limited by available solar radiation that can be collected/converted to electricity

$$\dot{W}_{\max} = \eta_{conv}\dot{Q}''_{solar}A_{cells} \quad \text{(V.9)}$$

radiation flux (W/m^2) — surface area avail. for solar cells (m^2)

  – maximum available radiation is flux at high altitude (solar constant) = 1366 W/m^2
- So maximum solar cell specific power

$$\dot{e} = \eta_{conv}\,\dot{Q}''_{solar} \,/\, a_{min} \quad \text{(V.10)}$$

$$\sim 0.5(1366\ W/m^2)/0.3\ kg/m^2 \cong 2.3\ kW/kg$$

Commercial Aircraft Scaling

- **Example 737 size vehicle**
  - wing surface area, 102 m^2
  - current CFM-56 engines (2) must supply ~$50MW$ increase in flow KE to meet take-off thrust
- Assuming 100% coverage with PV cells (neglects area between cells, …) and maximum solar flux

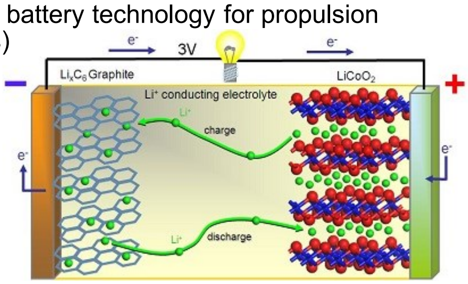
$$\dot{W}_{max} = 0.5\ (1366\ W/m^2)(102\ m^2) = 70\ kW$$

$$m = \dot{W}_{max} / \dot{e} = 70kW/\ 2.3kW/kg = 30\ kg$$

- Replacing medium scale commercial aircraft with solar electric power requires at least 700× increase in propulsive efficiency and/or vehicle lift-to-drag ratio
  - solar as sole power source viable for light (but not necessarily small) aircraft
  - advantage at high altitude (above cloud coverage)

Li Ion Batteries

- **Li ion** (Li^+) currently, leading battery technology for propulsion (and many other applications)
- During cell discharge
  - oxidation reaction at (-) electrode, Li^+ removed and migrates across electrolyte to (+) electrode
  - to balance charge, same number of e^- travel through the external circuit

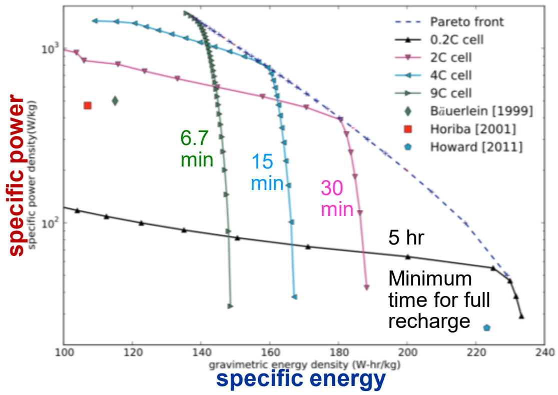


www.jmbatterysystems.com/technology/cells/how-cells-work

  - simultaneous electrochemical reduction reaction proceeds at (+) electrode; e^- from external circuit and Li^+ recombine
- During charging, flow of Li^+ (and e^-) reversed
- Heat dissipated in both modes, requires **thermal management**

Li⁺ Performance Metrics

- Typical performance metrics for Li⁺ batteries
  - data from 2013, so some improvements possible
- Specific power and energy are *inversely related*
- Fast charging advantageous for rapid aircraft turnaround
  - increased revenue but reduced range



adapted from Brelje and Martins, Prog. in Aero. Sciences 104 (2019) and Xue et al., J Elecchem. Soc.160 (2013)

Li⁺ Battery – Jet Fuel Comparison

- Compare metrics to current aircraft propulsion

Metric	Li Ion	Jet-A/Turbofan
e (MJ/kg)	0.35 – 0.9	43*
$\bar{e}$ (MJ/L)	0.9 – 2.2	34*
$\dot{e}$ (kW/kg)	0.1 – 1.0	10-30**

⇧ *comparable to solar at lower altitudes*

- compared to fuel, batteries store ~20-100× less energy (per mass or volume) AND they do not lose mass during flight ⇒ range reduction
- battery specific powers ~10-100× below current propulsion for moderate-sized commercial aircraft
- high generator efficiency and low motor mass compared to engines can't currently offset this

*assumes negligible mass of fuel tank and fuel pump
**commercial turbofans

Commercial Aircraft Scaling

- 737 example
  - 50 MW power requirement at takeoff (TO)

$$\dot{W}_{battery} = m_{battery}\left(\dot{e}\right) \geq \dot{W}_{TO}$$ *midrange for reasonable e*

$$m_{battery} \geq \dot{W}_{TO}/\dot{e} = 50MW/\left(0.5\,kW/kg\right)$$
$$\geq 100{,}000\ kg$$

  - maximum gross weight @TO only ~$80{,}000\ kg$
- Using current batteries as only energy source limits EP to low power (thrust) vehicles $\Rightarrow kW$ class vehicles
  - unmanned (moderate speed) drones, GA aircraft, urban air taxis,…
  - e.g., $10kW \Rightarrow$ ~$20kg$, $15\ L$ (< 1ft^3)

neglects mass and volume of insulation, cooling,…

Flight Duration

- Flight duration limited by energy stored in batteries and power usage

$$\boxed{\Delta t_{flight} \sim e/\dot{e}} \quad \textbf{(V.11)}$$

- Assuming midrange Li$^+$ battery operated at its maximum power capacity for 100% of flight

$$\Delta t_{flight} \sim (0.65\ MJ/kg)/(0.5\ kW/kg) = 1300s \cong 22min$$

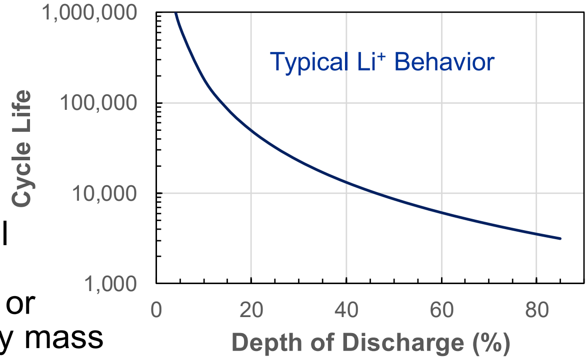
- Assuming avg. power draw is 33% of max

$$\Delta t_{flight} \sim 1\ hr$$

- So battery powered vehicles (without recharge) limited to short to moderate duration flights
  - especially considering need for power to operate other systems and reserves

Battery Lifetime: Cycle Durability

- Lifetime typically limited by number of discharge-charge cycles before significant performance degradation
- Completely discharging battery reduces lifetime
- Need near full discharge to extend range or reduce battery mass
  – so expect ~1000-3000 cycles



e.g, ~180-500 days @ 6 cycles per day

Future Improvements

- Various technologies being developed that may show improvement over Li^+
- Lithium-sulfate batteries (Li-S)
  – commercial systems @ 1.8 *MJ/kg*
  – theoretical capability of 9 *MJ/kg*
- Lithium-air batteries: Li anode, “air” cathode (porous material that draws in oxygen from air
  – demonstrated ~6 *MJ/kg*
  – theoretical limit ~40 *MJ/kg*

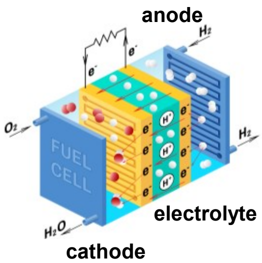
Future Improvements

- Solid-state batteries
  - pure Li metal anode and solid electrolyte (solid-state ceramic)
    - gives high lithium conductivity at room temperature and better stability (so better safety)
  - higher energy density: demonstrated up to 1.8 MJ/kg (NASA SABERS)
  - fast charging/discharging: 0-80% charge in 15 min (at 1.8 MJ/kg) and achieved 800 cycles (Quantum Scape)
- Also zinc-air, aluminum-air, magnesium ions and graphene

Fuel Cells (FC)

from DLR

- Demonstrated in ground and aerospace vehicles
- Electrochemical device like battery
  - but does not require recharging
  - chemical reactants fed to electrodes
  - produce: current, product(s), heat
- H_2 fuel cells
  - produce no CO_2 emissions, just H_2O and heat, which can meet other onboard needs
  - protons migrate through electrolyte to cathode, recombine with O and circuit e^-



adapted from Airbus

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H_2 Fuel Cell Performance

- SOFC (solid oxide) technology
  - operate at high T (400-700 °C), slow startup (preheating)
- PEMFC (polymer electrolyte membrane)
  - low T operation (50-80 °C), fast startup
  - catalyst separates H into protons and e^-
- Performance

Metric	Li Ion	SOFC	PEM
$\dot{e}$ (kW/kg)	0.1 – 1	0.5 – 2.5	1.5 – 2.5

- H_2 storage
  - while H_2 has high e (>120 MJ/kg), it has low $\bar{e}$ (<1 MJ/L as gas, ~ 8 MJ/L as liquid) ⇒ large volume requirement
  - requires cryogenics for liquid storage, high pressure for gaseous storage
  - safety concerns

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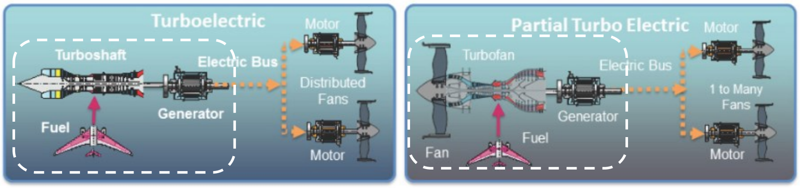
Turboelectric Systems

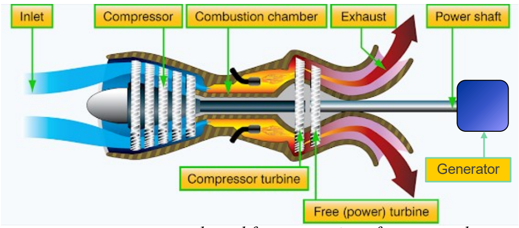
- Currently architecture of choice for larger EP aircraft (>100 kW) and moderate/long duration flights
- Most commonly examined version is turboshaft engine (fully turboelectric) or turbofan engine (partial TE) with power extracted to produce electricity using an **electric generator**



Commercial Aircraft Prop. and Energy Systems Research: Reducing Global Carbon Emissions Ch. 4, Electric Propulsion, NAP, 2016

Power Turbine

- Power is extracted from the engine by adding an additional turbine ≡ **power turbine**
  - also called free turbine
    - drives a shaft uncoupled from LP, HP spools turning compressors (and fan)



adapted from www.aircraftsystemstech.com

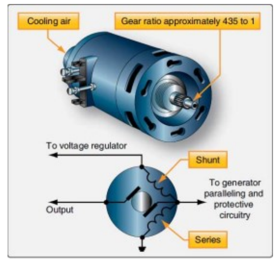
  - power turbine rpm optimized for thermal power extraction (shaft power) and electric generator operation, while main turbine rpm optimized for engine operation
  - lower weight/size power turbine than if used to direct-drive turbofan

Electric Generators

- Electrical machines use principle of induction between stationary magnetic field (stator) and rotating electromagnet (rotor)
  - generators use mechanical torque to turn rotor and induce current (can be in rotating or stationary coils)
  - motors use current to generate torque to turn rotor
- Voltage level produced by generator based on rpm and main magnetic field strength
- Require cooling (thermal management) to dissipate waste heat from impedance losses
- Generators can produce AC or DC outputs

Current Aircraft Electric Generators

- Used on modern aircraft to provide auxiliary power and more recently as starter generators
  - turns engine over until self-sustained operation
  - then extra windings allow it to switch to electric power generation
  - connected to engine shaft through mechanical gear box (always engaged)
- Currently meeting more electric requirements on modern aircraft
  - Boeing 787: each engine (GEnx, Trent 1000) has two 250 kVA (kW) variable frequency generators = total of 1 MW electric power generation
  - F-35: PW F135 has two 80 kW gen's.

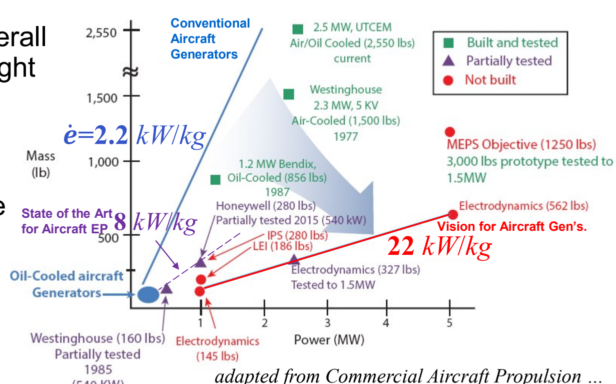


http://www.flight-mechanic.com

Boeing.com

Electric Generator Specific Power

- Major challenge for turboelectric propulsion is increasing generator specific power well above batteries ($\sim 0.1\text{–}1\ kW/kg$)
  - to lower overall system weight
- Unlike ground systems, limited cooling (fluid) available
- Also need for increasing power levels beyond 5 MW



adapted from Commercial Aircraft Propulsion … Chapter: 4 Electric Propulsion, NAP, 2016

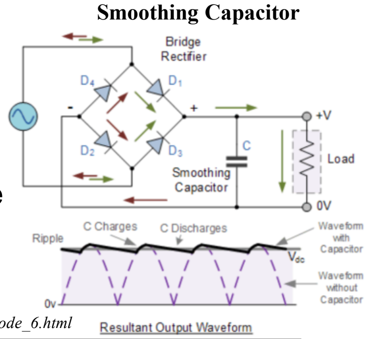
Electric Generator Improvements

- To increase electric generator power and power density
  - need higher generator RPM
    - limited by mechanical stresses
  - superconducting materials can reduce electrical losses (resistance in windings)
    - will require cryo-coolers to lower material temperatures where superconducting behavior occurs
  - increasing power generation/distribution voltage
    - currently ~540-600 V *demonstrated in Airbus E-Fan X*
    - interest in achieving ~ 2-3kV
      - reduces cables mass, can be dominant in overall system specific power
    - limited by breakdown voltage at altitude (due to reduced pressure)
    - requires better insulation and cabling designs (new wiring harnesses)

AC-DC Conversion: Rectifiers

- Some advantages if electrical power distributed to motors as DC
  - higher transmission efficiency
  - reduced EM interference
    - cross-talk can occur to wire bundles carrying data/control signals
  - allows for variable motor speed and decoupled from turbine/generator rpm
- **Rectifiers**
  - if using AC generator can use rectifier to convert to DC
  - e.g., diode rectifier for each phase

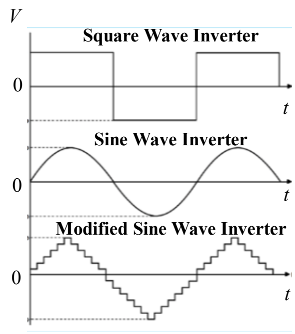
Full Wave Rectifier with Smoothing Capacitor



/www.electronics-tutorials.ws/diode/diode_6.html

DC-AC Conversion: Inverters

- For DC transmission systems using AC variable speed motors, need to convert DC to AC
- **Inverters**
  - use fast switches and delay circuits to reverse current flow and emulate AC supply
  - aircraft propulsors generally need high (rotational) speed motors, above 1 kHz
  - combined with high power and high efficiency needs of EP recent efforts have focused on SiC MOSFET electronics
    - high temperature (power/voltage) capability
    - device with microchannel coolers capable of ~50 kW/kg



Electric Motors

- High conversion efficiency from electrical power to shaft power
  - ~90-98% efficiency
- Significant EP advantage: capability of distributed propulsion
  - unlike turbine engines, electric motors have minimal reduction in efficiency and specific power as scaled down in size
- Variable rpm able to optimize propulsor efficiency as function of flight conditions, control requirements
- One moving part ⇒ long lifetime, low maintenance
- Like generators, challenge is to increase motor specific power
  - 5 kW/kg (260 kW) electric motor from Siemens (e-aircraft prop. sold to Rolls)
  - potential for 1 MW scale machines to achieve 8-16 kW/kg
  - on-going efforts in superconducting motors

Siemens

Propulsors/Thrusters

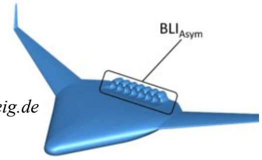
- Goals
  - maximize propulsive efficiency
  - integrate into distributed propulsion for control and aerodynamic efficiency
  - can be used to aid motor cooling
- Common choices
  - propellers
  - **ducted fans**
    - typically smaller for same thrust
    - reduced noise
  - variable speed motor to optimize efficiency at required thrust and flight condition

Distributed and Embedded Propulsion

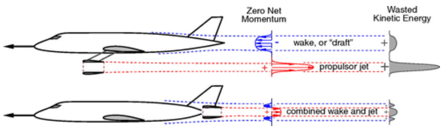
- Compared to turbofans, increases effective bypass ratio
  - so for fixed thrust, lowers required fan pressure ratio and results in increase in propulsive efficiency ($u_e \rightarrow u$)
- If embedded in wing, increases dynamic pressure (higher u) and augments lift production
  - allows smaller wing area for same lift
- Wing acts as downstream stator reducing swirl and increasing fan efficiency

Boundary Layer Ingestion (BLI)

- Instead of placing propulsors in freestream, intentionally have them ingest boundary layer fluid
- Lowering input air velocity results in lower KE for exit gas for same thrust
  - higher propulsive efficiency
- Re-energizes wake and reduces airframe-induced drag



www.tu-braunschweig.de



arc.aiaa.org/doi/10.2514/1.J055755

Variable Speed Optimization

- Having a variable speed motor means ducted fan (or propeller) can be operated at optimum speed (rpm)
  - for given operating conditions
    - altitude and flight velocity and thus (corrected) mass flow rate
  - and required thrust
    - thus fan pressure ratio
- Note fan nozzle likely choked at high Pr or high flight velocity

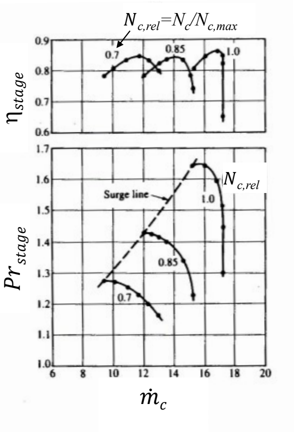


FIGURE 7.14
Hill and Peterson

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EP Summary

- Current battery technology (high weight, low power) limits battery-powered EP to small, short duration vehicles
- With improvements (e.g., higher specific power) in generators & motors and novel vehicle designs
  - turboelectric systems can have impact on reducing CO_2 emissions from larger (e.g., regional) aircraft if overall efficiency improved over current turbofans
  - hybrid turboelectric systems (battery + turbine engine) may have potential for further CO_2 emission reductions (primarily battery for low power portions of flight envelope)