Motivations for Electric Propulsion

- Environmental considerations
  - low carbon footprint
  - pollutants (NOx, particulates)
  - noise
- Size scaling
  - small vehicles, urban mobility
- Distributed propulsion, airframe integration
  - efficiency, flight controls
- Life and maintenance
- Long duration flights
  - surveillance, communications,…
Nomenclature

- **Electric propulsion**
  - all or part of thrust produced from electrical power
    (e.g., electric motor driving propeller)

- **Hybrid electric propulsion**
  - only part of thrust from electric power
  - example: turbofan combined with propellers driven by battery powered motors

- **Hybrid electric powertrain**
  - multiple sources used to turn same shaft

- **Turboelectric propulsion**
  - turbine engine power either fully or partially diverted to drive elec. gen. for propulsion

Electric Propulsion Components

- **Source**
  - batteries, fuel-cell, solar, electric generator, …

- **Power electronics and transmission**
  - voltage conversion, controls, power distribution, …

- **Motors**
  - conventional, superconducting, …

- **Thruster**
  - propeller, ducted fan, …
Power Sources: Solar

- 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 efficiency
  \[ \eta_{\text{conv}} \text{(electron/photon)} \approx 95\% \]
- For solar rad. spectrum
  - \[ \eta_{\text{conv}} \approx 34\% \]
    single P-N cell (Shockley Queisser limit)
  - \[ \eta_{\text{conv}} \approx 50-85\% \]
    stacked cells

\[ \frac{W_{\text{max}}}{\text{rad}} = \eta_{\text{conv}} \cdot \frac{Q_{\text{Solar}}}{A_{\text{cells}}} \] (V.8)

- limits maximum continuous thrust available for given size vehicle
- Maximum available radiation is flux at high altitude (solar constant) = 1366 W/m²
- For solar aircraft, maximum \( A_{\text{cell}} \) limited by lifting surface area
Power Sources: Solar

- Example 737 size vehicle
  - wing surface area, 102 m²
  - 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 multilayer-PN cell architecture

\[ W_{\text{max}} = 0.5 \times (1366 W/m^2)(102 m^2) = 70 kW \]

- So replacing medium scale commercial aircraft with solar electric power requires at least 1000× increase in propulsive efficiency
  - solar viable for low payload, light (unmanned?) aircraft (at high altitude above cloud coverage?)

Power Sources: Batteries

- Currently, leading battery technology for propulsion (and many other applications) is Li ion (Li+)
- During cell discharge
  - oxidation reaction at neg. electrode, Li+ removed from electrode and migrate across electrolyte to pos. electrode
  - To balance charge, equivalent number of e\textsuperscript{-} travel through the external circuit
  - Simultaneous electrochemical reduction reaction proceeds at positive electrode, e\textsuperscript{-} from external circuit and Li+ from electrolyte reform starting material
- During charging, flow of Li+ (and e\textsuperscript{-}) reversed

\[ \text{www.jmbatterysystems.com/technology/cells/how-cells-work} \]
Power Sources: Batteries

• Figures of merit for batteries
  – specific energy \( (e, \text{MJ/kg}) \)
  \(~0.36-0.9\) \(~45\)
  – energy density \( (\bar{e}, \text{MJ/L}) \)
  \(~0.9-2.2\) \(~34\)
  – specific power \( (\dot{e}, \text{kW/kg}) \)
  \(~0.25-0.34\) \(~45\) (for medium size jet engine)
  – cycle durability (# cycles)
  \(~1000\)

• Compared to chemical/fuel, batteries store much less energy (per mass or volume) and have much lower specific powers
  – even higher generator efficiency vs. engine thermal efficiency will not make up for this

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Power Sources: Batteries

• 737 example
  – 50 MW power requirement at takeoff (TO)
    \[
    \dot{W}_{\text{battery}} = m_{\text{battery}} \dot{e} \geq \dot{W}_{\text{TO}}
    \]
    \[
    m_{\text{battery}} \geq \dot{W}_{\text{TO}} / \dot{e} = 50\text{MW} / (0.33 \text{kW/kg})
    \geq 150,000\text{kg}
    \]
  – maximum gross weight @TO \(~80,000\) kg

• Using current batteries as only energy source limited to low power (thrust) vehicles \(\Rightarrow\) kW class vehicles
  – unmanned (mod. speed) drones, GA aircraft, urban air taxis,…
  – e.g., 10kW \(\Rightarrow\) \(~30\) kg, 15 L \(\sim 1\) ft\(^3\)

neglects mass and volume of insulation, cooling,…
Power Sources: Batteries

- Flight duration limited by energy stored in batteries
- Assuming battery operated at its maximum power capacity for 100% of flight
  \[ \Delta t_{\text{flight}} \sim \frac{e}{\dot{e}} \]
- For Li+
  \[ \Delta t_{\text{flight}} \sim \left(\frac{0.75 \text{ MW/kg}}{0.3 \text{ kW/kg}}\right) \sim 2500 \text{s} \sim 40 \text{min} \]
- Assuming avg. power draw is 25% of max
  \[ \Delta t_{\text{flight}} \sim 2.8 \text{hr} \]
- So battery powered vehicles (without recharge) limited to short to moderate duration flights
  – especially considering need for power to operate other systems and reserves

Power Sources: Turboelectric

- Currently architecture of choice for larger EP aircraft (>100 kW) and moderate/long duration
- Most commonly examined version is essentially turboshift (or turbofan) engine with addition of
  – **elec. generator** connected to (power) turbine
  + **power inverter** (AC to DC – high voltage)
  – also electric transmission bus and motors
  + **power controls and thermal management**

\[ + \text{decouples \ turbine rpm from variable fan/prop rpm} \]
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
  - 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.

Power Sources: Electric Generators

- Largest challenge for generators for turboelectric propulsion is increasing specific power
  - currently 2.2kW/kg, technology to raise to 22kW/kg
- Unlike ground systems, limited cooling (fluid) available
- Also need for increasing demonstrated power levels beyond 5 MW
Power Sources: Electric Generators

- To increase electric generator power and power density
  - need higher generator RPM
    - limited by mechanical stresses
  - higher power conversion efficiency, lower weight
    - limited by silicon power electronics
    - SiC potential for higher $\eta$, voltage and specific power (e.g., 9 kW/kg)
  - increasing power generation/distribution voltage, currently ±270 V (or 540V) – need is for kV’s
    - limited by breakdown voltage at altitude (due to reduced pressure)
    - requires better insulation and cabling designs (new wiring harnesses)

Power Sources: Power Inverters

- Including power inverter (AC to DC conversion) hardware reduces current combined specific power to < 2 kW/kg
  - recent demonstrations of SiC electronics with microchannel coolers that achieve ~50 kW/kg
Electric Motors

- Significant EP advantage: capability of distributed propulsion
  - electric motors have minimal reduction in efficiency (>90-95%) and specific power as scaled down in size
  - also variable rpm to optimize propulsor efficiency (like variable rpm compressor)
- 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)
  - higher specific power challenge for viable moderate scale (e.g., regional) EP aircraft
- efforts in superconducting motors

Thrusters/Propulsers

- Need to maximize propulsive efficiency
- Best choices are
  - propellers
  - ducted fans
- Integration into distributed propulsion/aerodynamic designs
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 CO₂ emissions from larger (e.g., regional) aircraft if overall efficiency improved over current turbofans.
  - Hybrid turboelectric systems have greater potential if better batteries able to cope with much of low power portions of flight envelope.