ARPA-E ELECTRIC MOTORS FOR AVIATION WORKSHOP

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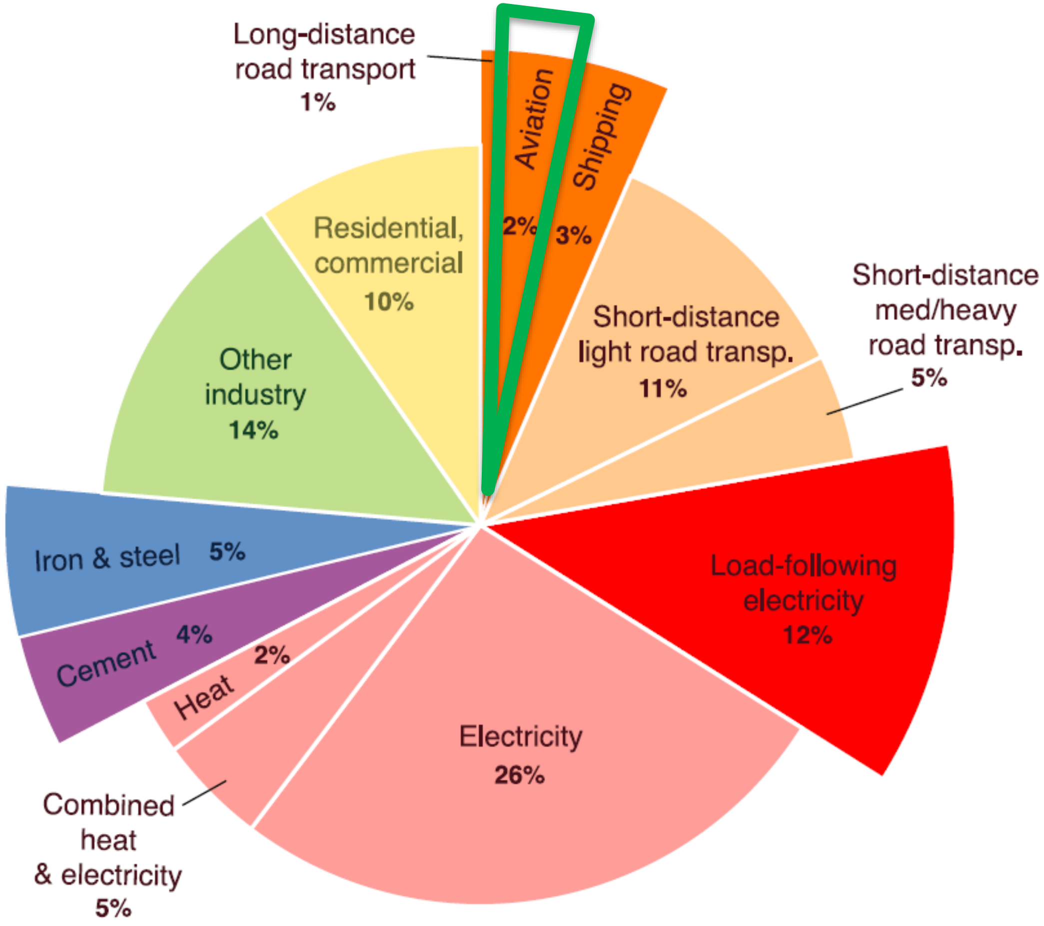
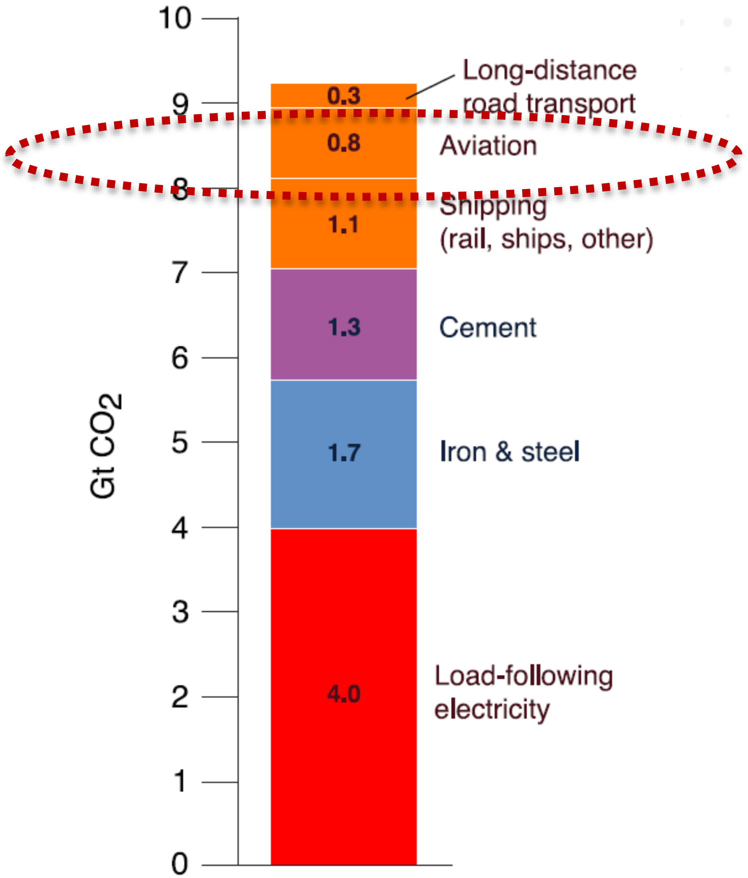
Aviation: Difficult-to-eliminate CO_2 emissions



A **Global fossil fuel & industry emissions, 2014 (33.9 Gt CO_2)**



B **Difficult-to-eliminate emissions, 2014 (9.2 Gt CO_2)**

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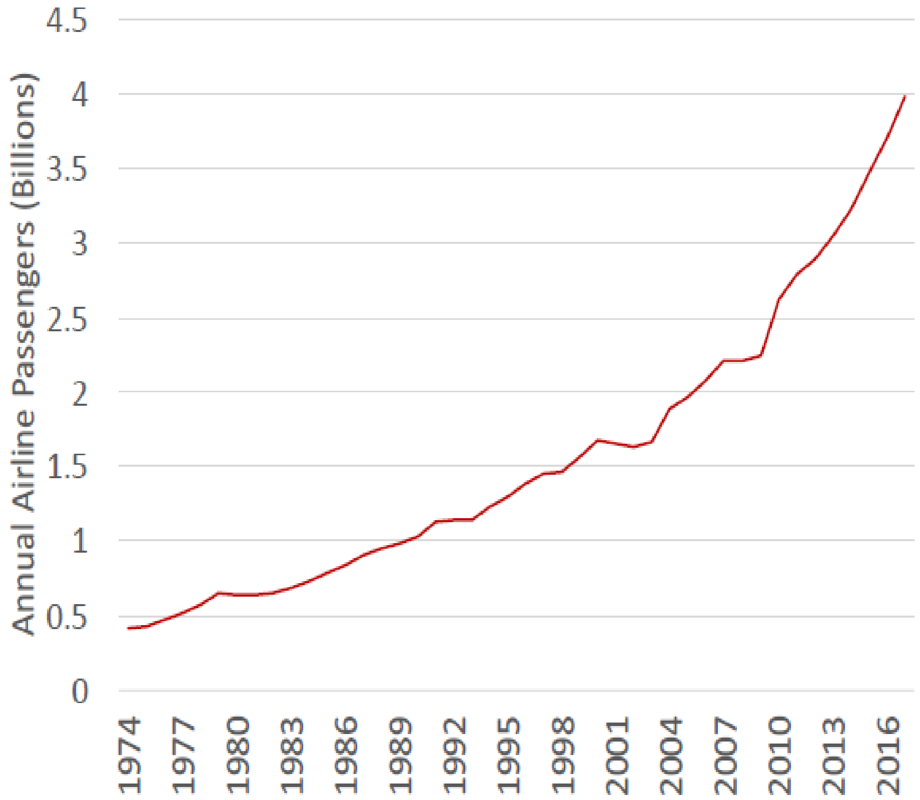
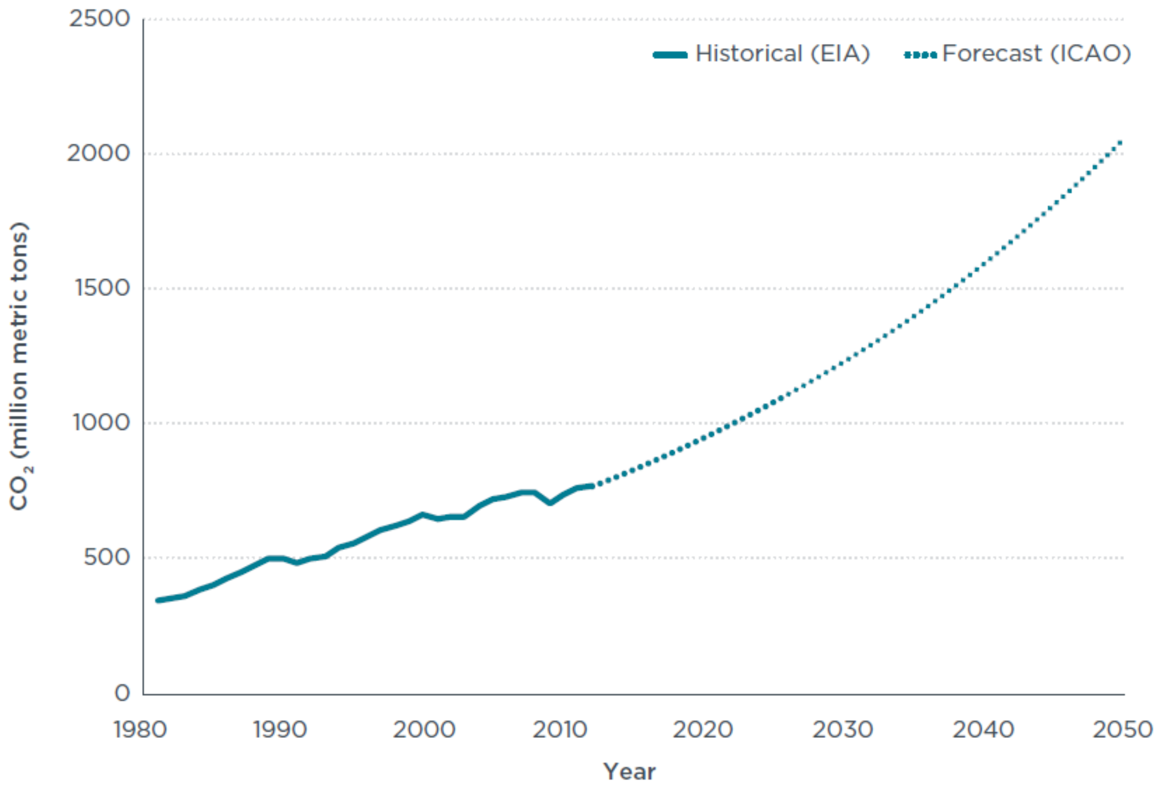
Aviation: Traffic to triple by 2050

Annual airline passengers



Aviation GHG emissions

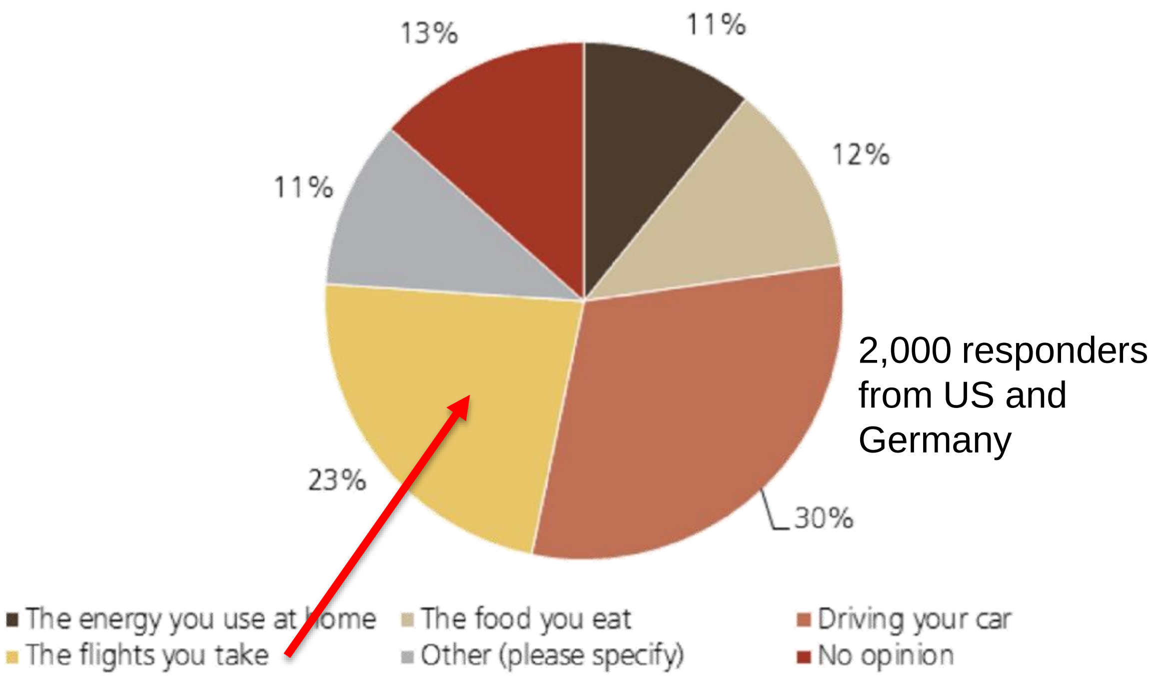


- **CO_2 emissions** from international aviation, as well as global fleet, **will triple at the horizon by 2050**
- Anticipated that aviation industry will miss ICAO's 2020 and 2030 fuel-efficiency goals for new aircraft by more than a decade (due to focus on re-motorization instead of clean-sheet design)

https://data.worldbank.org/indicator/is.air.psgr

Aviation: Public perception shifts negatively toward flying

23% of respondents cited flying as the activity with the most negative impact on the environment (6% in the US, 39% in Germany)



2,000 responders from US and Germany

Source: UBS Evidence Lab

Norway banned regional fossil fuel flight by 2040

Ryanair one of Europe's top polluters, EU data suggests

2 April 2019 | BBC NEWS | Share

'Flygskam' is the Swedish travel trend that could shake the global airline industry

Published: June 21, 2019 3:06 p.m. ET

MarketWatch

**Swedish for "flight shame"*

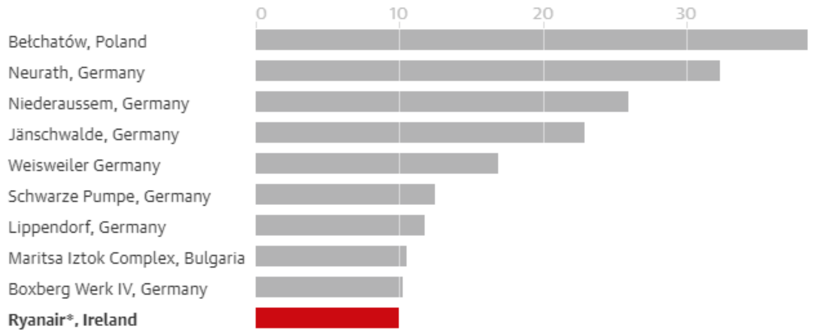
Buzzword was born out of concerns about carbon emissions

'Ryanair is the new coal': airline enters EU's top 10 emitters list

theguardian

Irish firm joins nine coal plants on list, with carbon emissions up nearly 50% in last five years

Megatonnes of CO2 equivalent is the scale

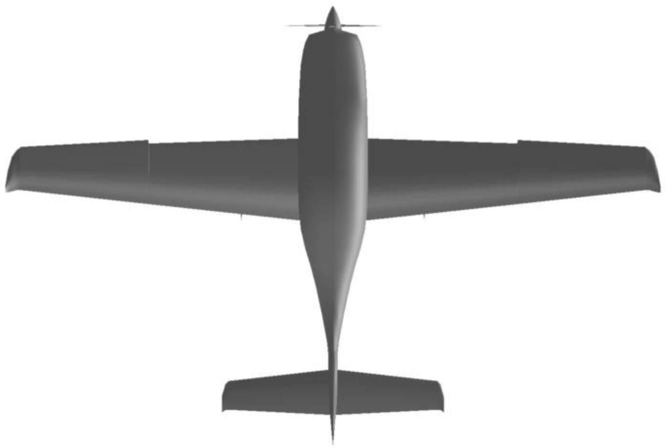


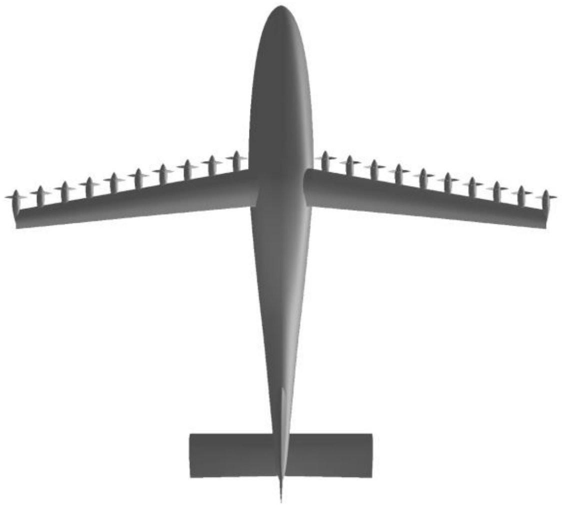
Guardian graphic | Source: European Commission. *all their air flights in the EEA

Aviation: Electric aviation enables new, efficient aircraft design

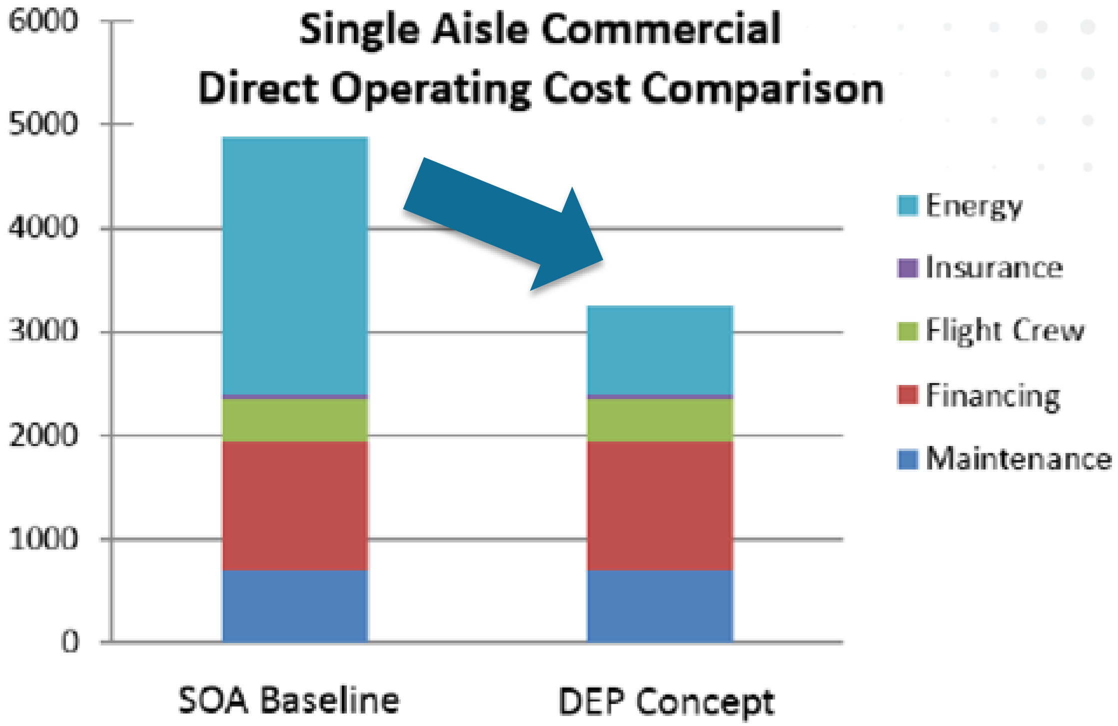
- **Electric propulsion offers fundamentally different characteristics** with several notable benefits:
  - **> 2x efficiency of SOA engines** (especially for smaller engines), simplicity
  - Increased safety through redundancy, extremely quiet, no power lapse with altitude or hot day
- Electric propulsion **scale-free nature enables distributed propulsion**
- Distributed propulsion: distributing the airflows and forces about the aircraft **improves the aerodynamics, propulsive efficiency**, structural efficiency, etc.

Aviation: Some concept designs of electric aviation





A.M.Stoll, et al., “**Drag Reduction Through Distributed Electric Propulsion**”, 2014
K. Moore, A. Ning, “Distributed Electric Propulsion Effects on Traditional Aircraft Through Multidisciplinary Optimization” 2018



Source: Mark Moore, Distributed Electric Propulsion (DEP) Aircraft, 2012, NASA Langley Research Center

Aviation: Civil aviation segments, where should we focus?

Beechcraft 1900
Range: 1,900 km
MTOW: 7.766 kg
Take-off thrust: 9.8 kN

Commuter: < 20 passengers

Boeing B737-MAX 8
Range: 6,570 km
MTOW: 82,191 kg
Take-off thrust: 130.4 kN

Single-aisle (narrow-body): 100 – 200 passengers

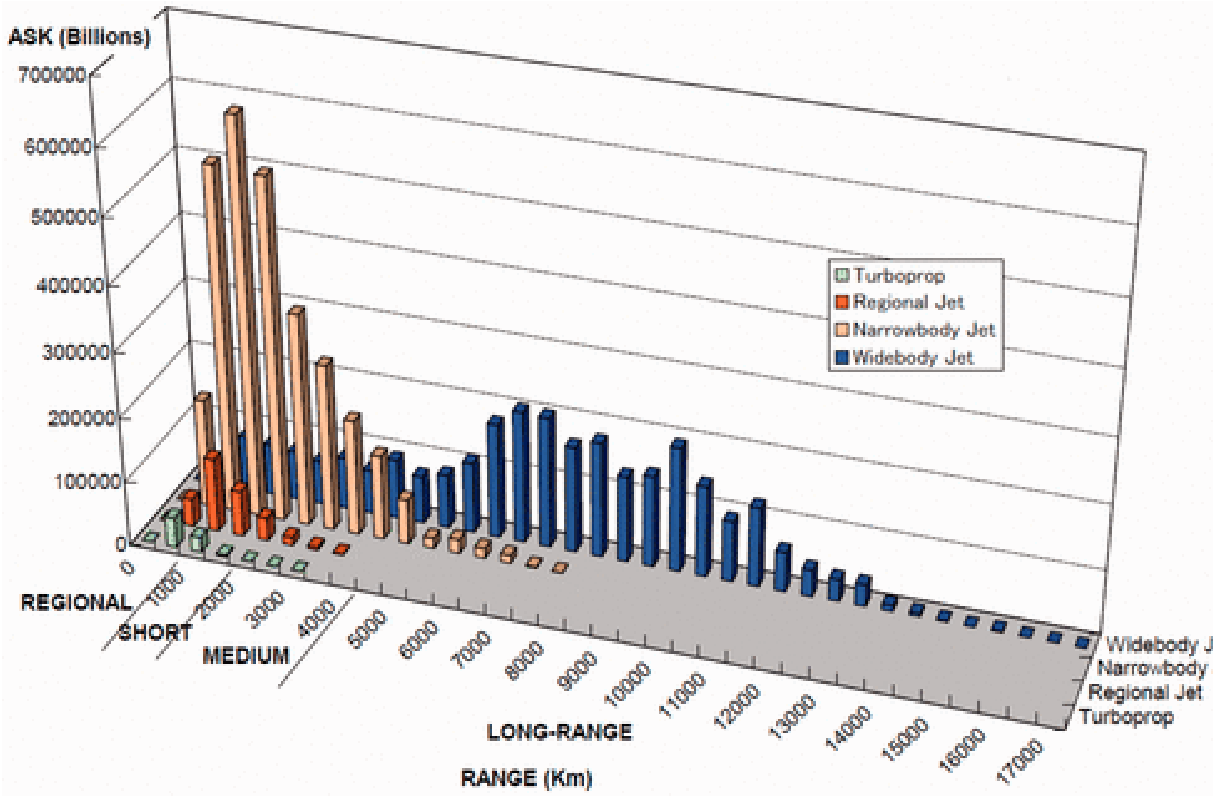
MRJ 70
Range: 1,880 km
MTOW: 40,200 kg
Take-off thrust: 67 kN

Regional: 30-100 passengers

Boeing 777
Range: 15,840 km
MTOW: 300,000 kg
Take-off thrust: 440 kN

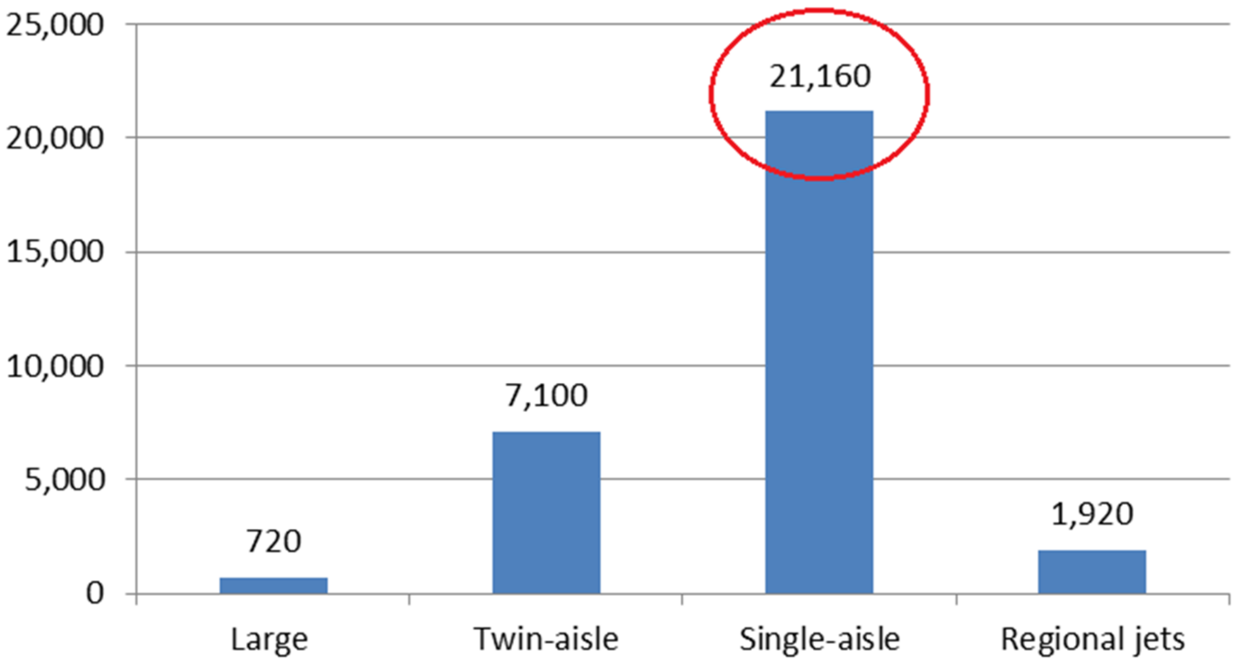
Main focus on narrow-body aircraft
Example: Boeing 737

Aviation: Drivers for electric aviation



Asian demand will be the largest at 6,710 planes, followed by Europe (5,380), North America (5,180), and Latin America (1,800)

Commercial Aircraft Demand (2009-2029), units*



* The corresponding dollar market value is as follows: Large ($220 billion); Twin-aisle ($1.63 trillion); Single-aisle ($1.68 trillion); and Regional jets ($60 billion).

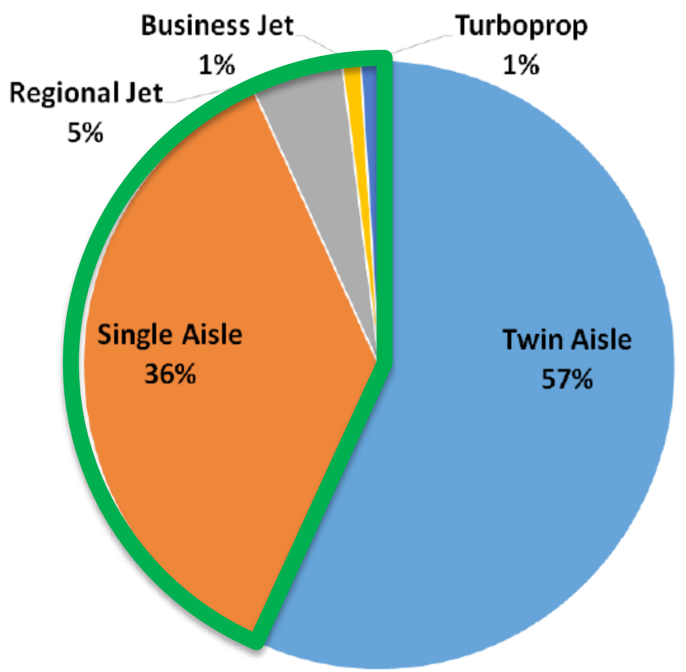
Source: Boeing

Most ordered narrow-body aircraft

Aviation: Addressing ARPA-E mission areas

- **Reduced emissions** ✓
- **Increased efficiency** ✓
- **Reduce imports** ✓
- **Technological competitiveness**
  - Enhances domestic aerospace industry
  - Ensures export of US technology and enables regional mobility around the globe

Global civil aviation fuel consumption



Any savings on fuel consumption can have massive impact on U.S. energy and emissions

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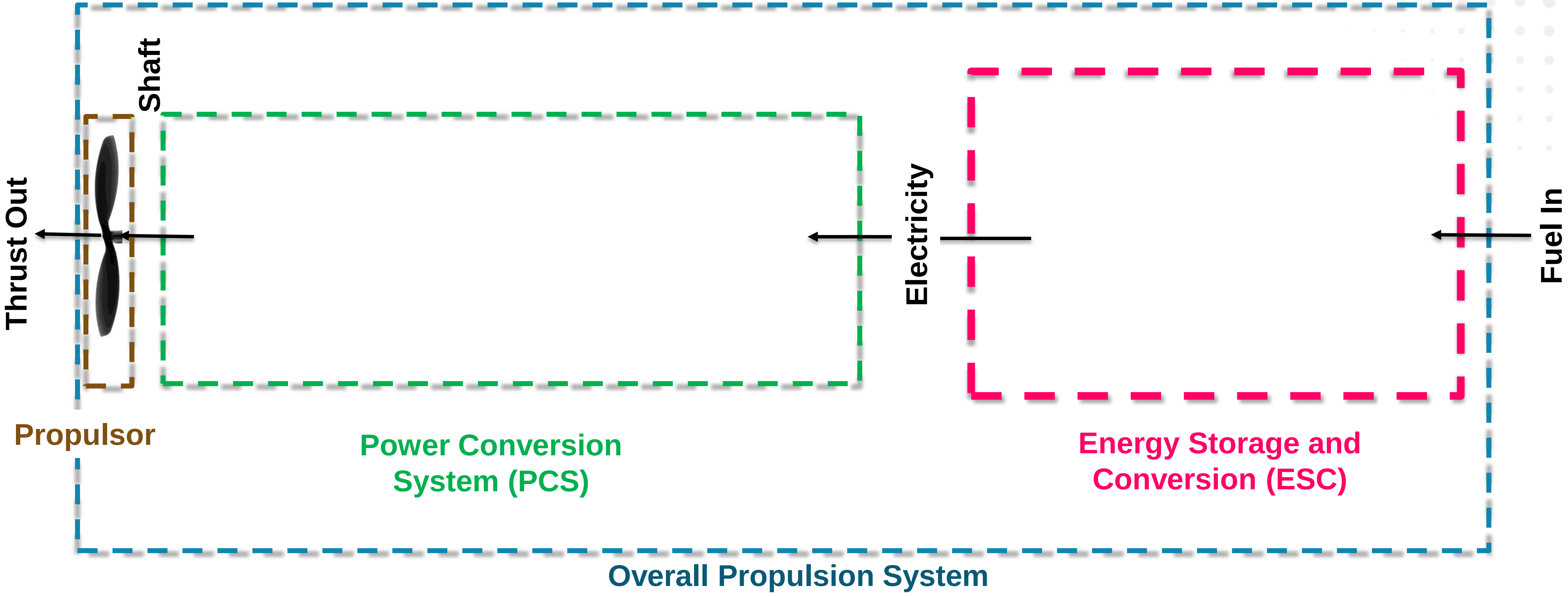
FIGURE 1.1 Global civil aviation fuel consumption. SOURCE: Data from B. Yutko and J. Hansman, 2011, *Approaches to Representing Aircraft Fuel Efficiency Performance for the Purpose of a Commercial Aircraft Certification Standard*, MIT International Center for Air Transportation, Cambridge, Mass.

Aviation: System block diagram



Aviation: Electric aviation needs (stakeholder input)

- **Energy storage to provide target flying range and payload (show stopper)**
- **Light, efficient and high power density electric motors (enabler)**
- **Power electronics to convert, switch and condition the needed power at high voltage (enabler)**
- **Safe and light high voltage distribution to deliver high power (enabler)**

SCENARIO STUDIES – B737-MAX8 ELECTRIFICATION

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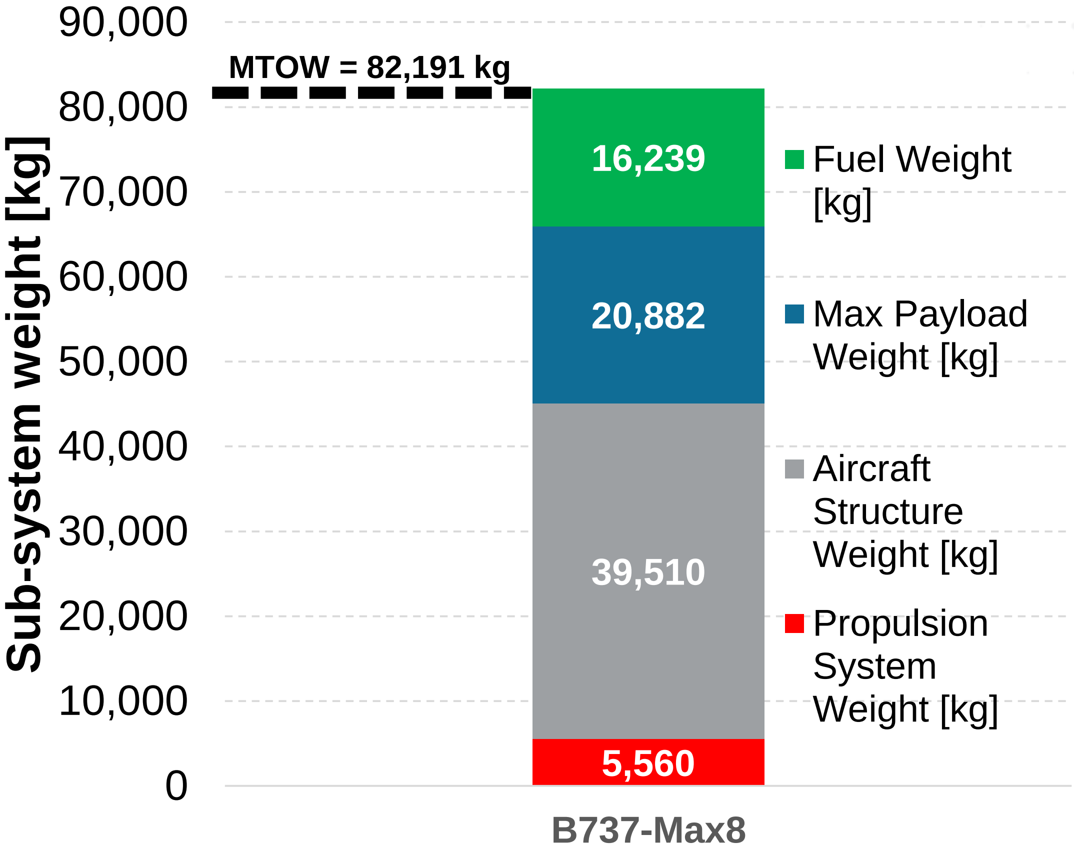
Aviation: Narrow-body aircraft & mission specifications

For this analysis, **aircraft is assumed to take-off at its maximum take-off weight** (MTOW); **with its maximum payload** (Pl_{max} = 20,882 kg); **at given cruise speed**

Boeing B737-MAX 8
Single-aisle (narrow body): 100 – 200 passengers

Cruise speed: **839 km/h**
MTOW: **82,191 kg**
Cruise thrust power: **8.7 MW (calculated)**
Range: 6,570 km
Propulsive System: 2 x CFM LEAP 1B
Take-off thrust: 2 x 130.4 kN



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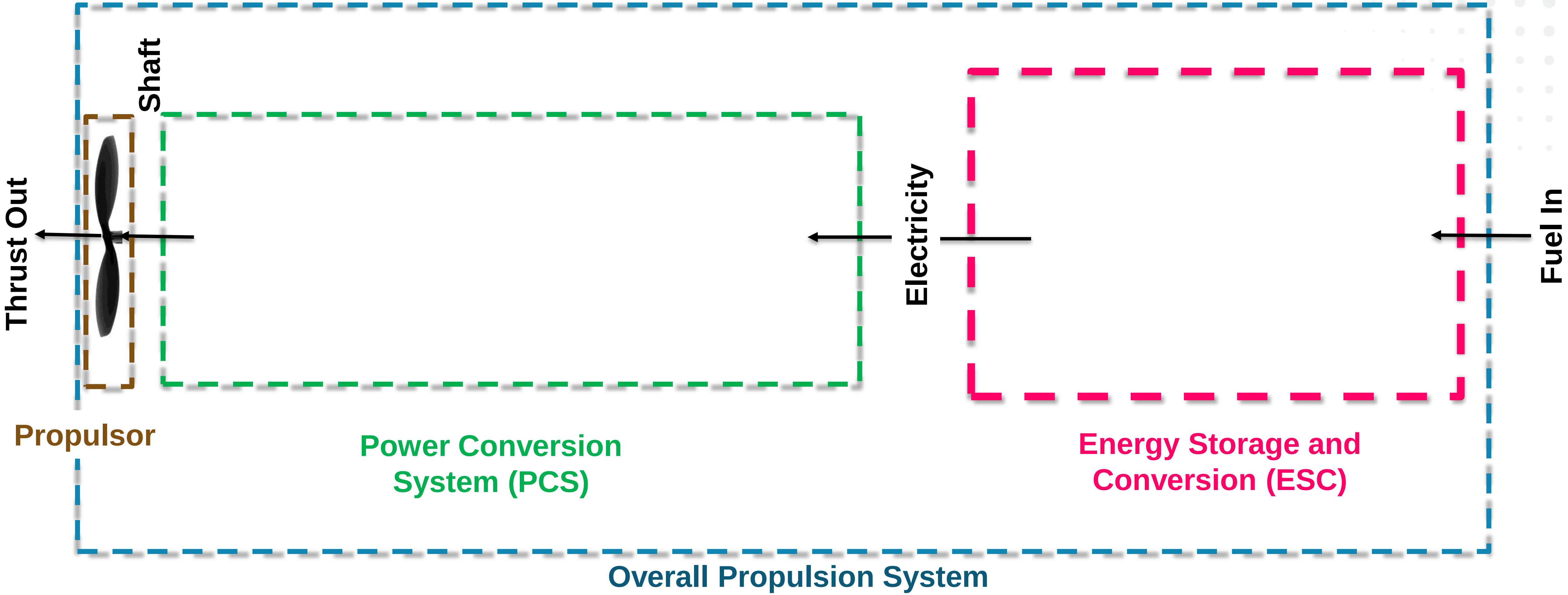
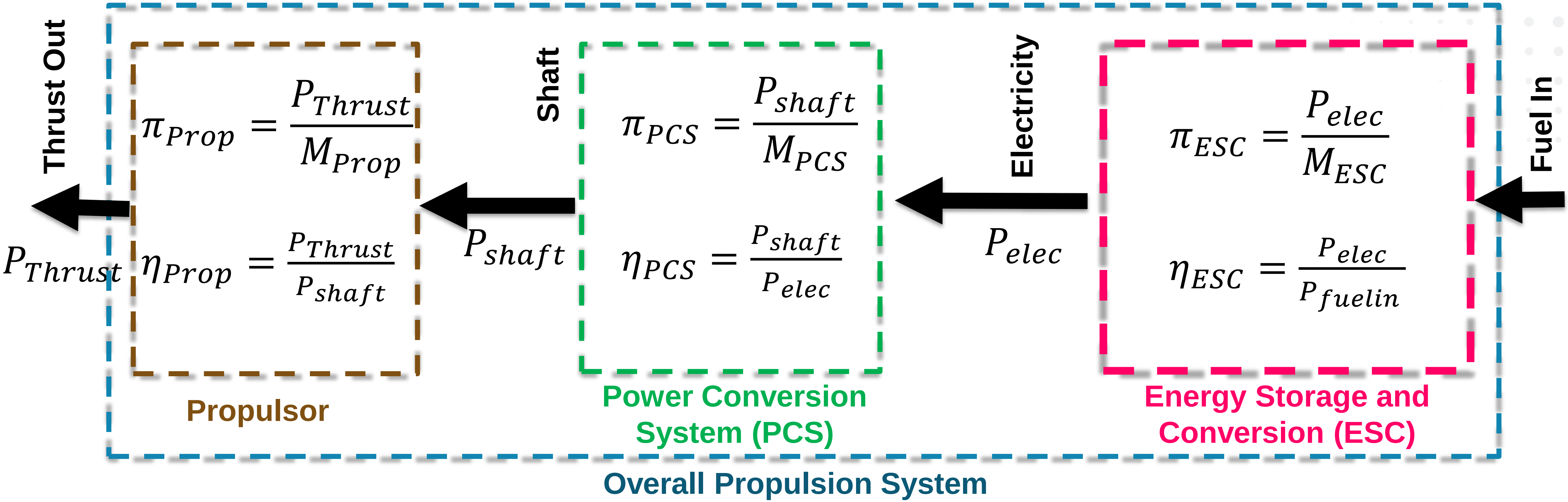
Aviation: System block diagram

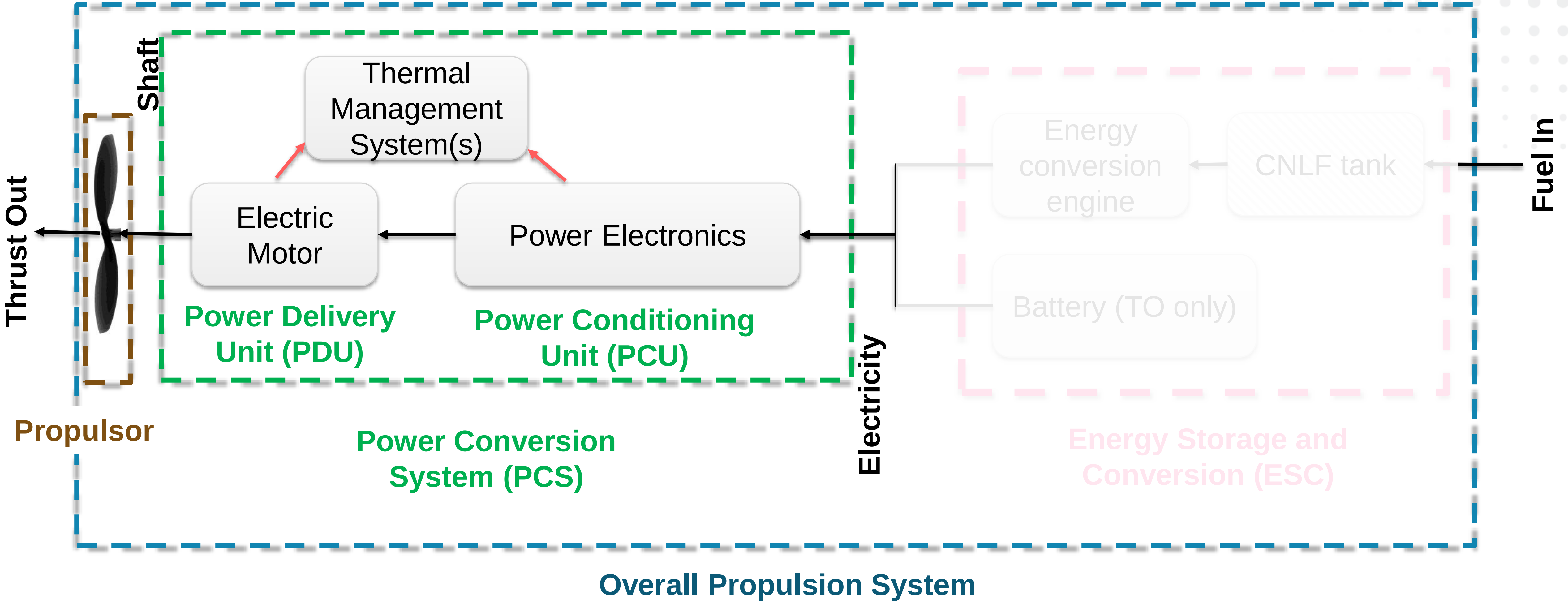


Aviation: Overall propulsion system specific power

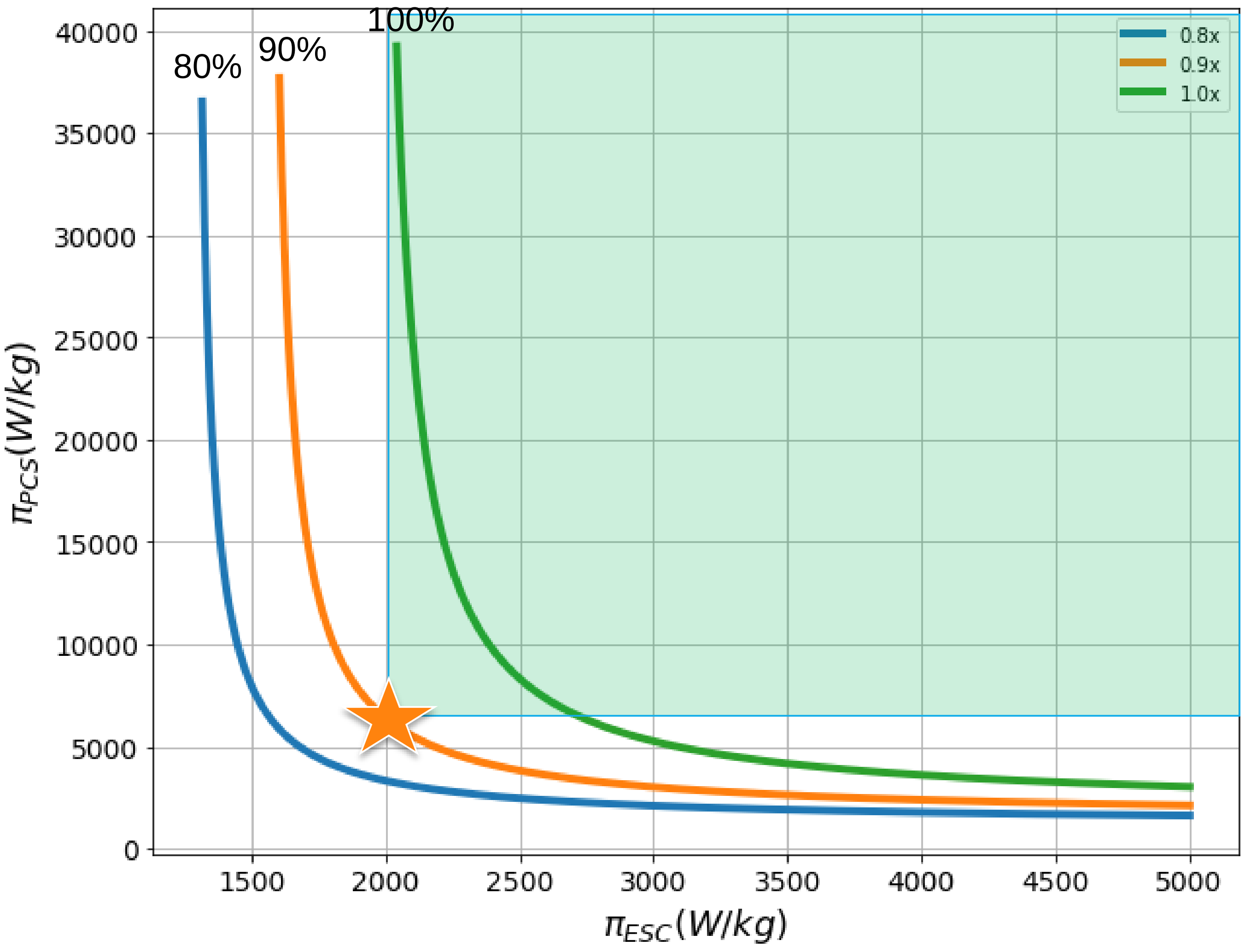


$$\pi_{overall} = \frac{\eta_{overall}}{\frac{\eta_{overall}}{\pi_{Prop}} + \frac{\eta_{PCS}\eta_{ESC}}{\pi_{PCS}} + \frac{\eta_{ESC}}{\pi_{ESC}}}$$

Aviation: System block diagram



Aviation: Component-level specific power targets



$$\pi_{PCS} = \frac{\eta_{PCS}\eta_{ESC}}{\eta_{overall}\left(\frac{1}{\pi_{overall}} - \frac{1}{\pi_{Prop}}\right) - \frac{\eta_{ESC}}{\pi_{ESC}}}$$

INPUTS

- $\eta_{overall}$ = 60%
- $\pi_{overall}$ = 1,250 W/kg (100% range)
- $\pi_{overall}$ = 1,045 W/kg (90% range)
- $\pi_{overall}$ = 895 W/kg (80% range)
- η_{Prop} = 90%,
- π_{prop}= 5,000 W/kg
- η_{ESC} = 70%
- η_{PCS} = 95%

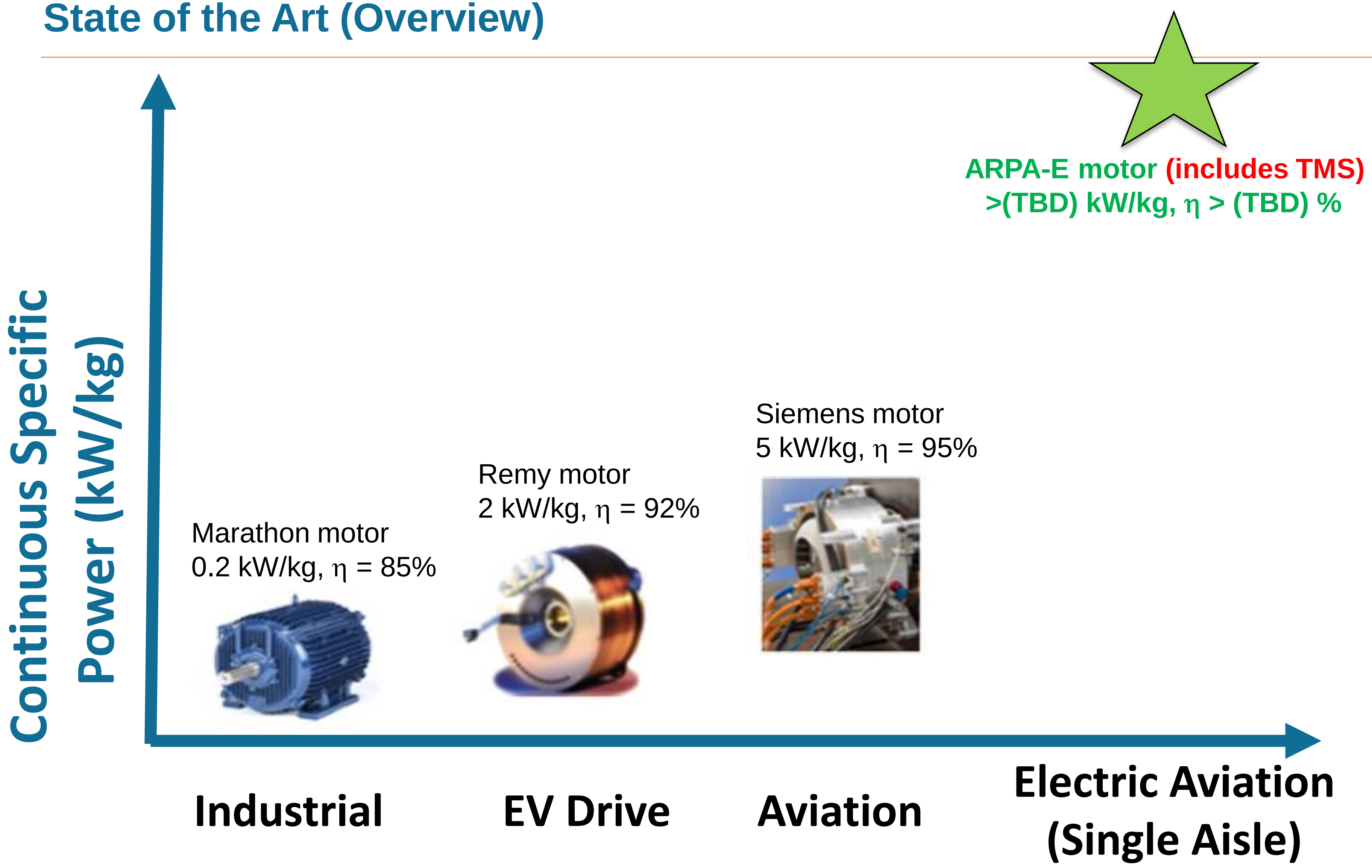
Range = 0.9x

For π_{ESC} ≥ 2,000 W/kg

Need π_{PCS} ≥ 6,400 W/kg

Aviation: Electric Motors – Still a long way to go…

State of the Art (Overview)

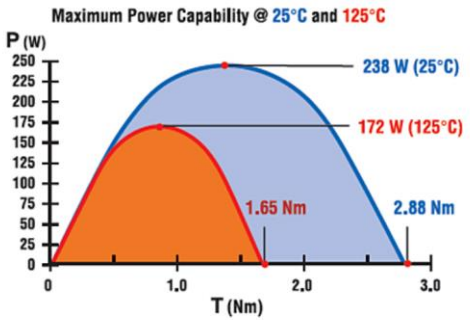


Industry feedback:

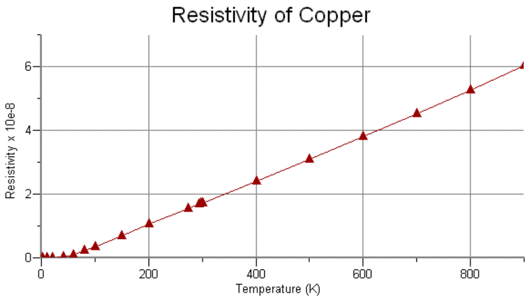
- Specific Power, good metrics for powertrain comparisons. Example: Aviation & EV powertrain
- Cruise Efficiency, important metrics for aviation and wind generators
- Specific Torque, another metrics to compare motors and thermal capabilities.
- Volumetric density, also a good metrics for aviation application for drag and noise constraints

Aviation: Importance of thermal management of electric motor

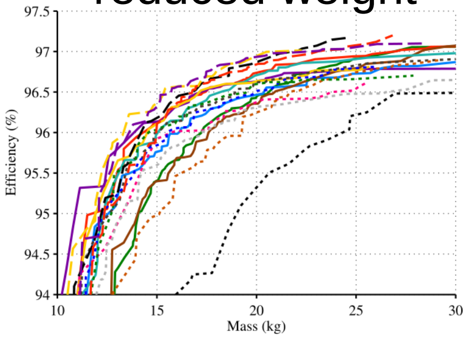
Reduced power & torque at elevated temperatures



Increasing losses with increasing temperature



Reduced efficiency with reduced weight



Air natural convection

Air forced convection

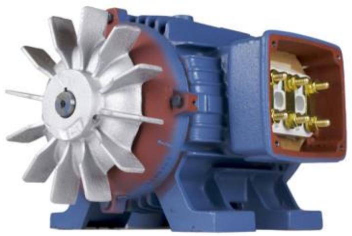
Liquid cooling

Passive two-phase cooling (heat pipe)

Pumped two-phase cooling (likely in the future)

Processors & power electronics cooling over time

Housing fins



Shaft-driven fan

Ethylene glycol (Nissan)

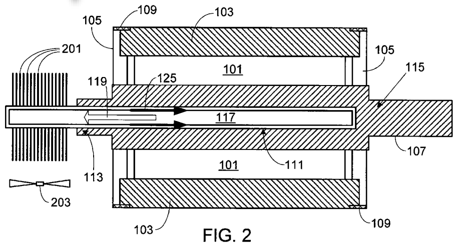


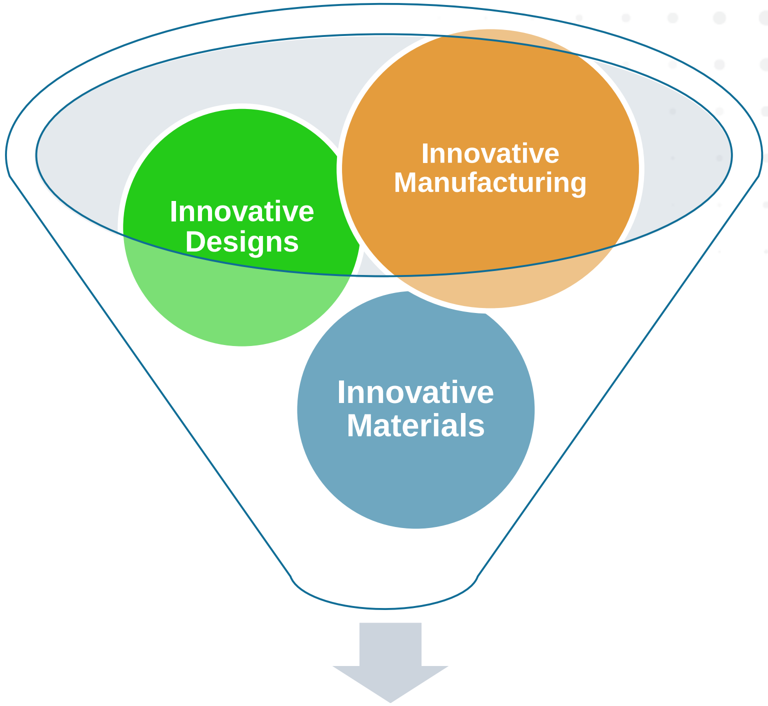
FIG. 2

Rotor-embedded heat pipe (Tesla)

Aviation: Integrated multiphysics co-design (electric/electromagnetic/thermal/mechanical)

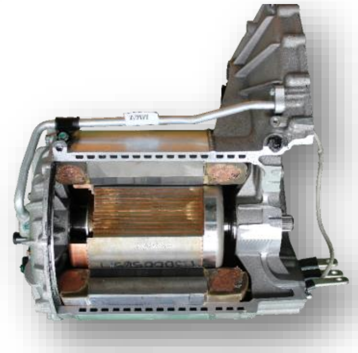
Identification of topologies/architectures, materials, and manufacturing methodologies, embedded cooling with supercritical fluids to achieve the targeted metrics:

- Utilizes low resistance/near source cooling
- High power density
- High efficiency
- Compact
- Reliable
- Meets roadmap to commercialization

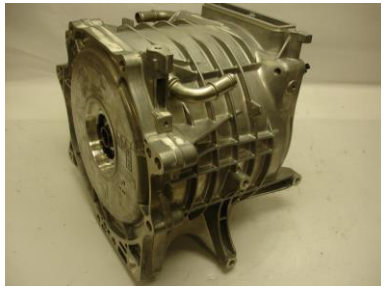


Co-design of electromagnetics, inactive materials, thermal, and power conditioning is a must

Aviation: Light weight motors, what's possible?

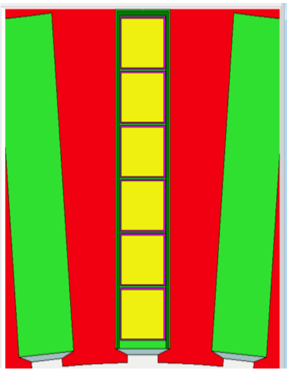


Tesla S60 induction motor

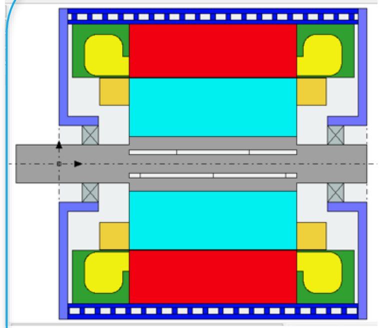


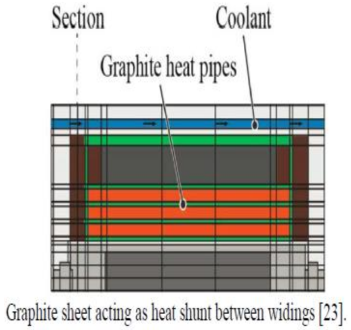
BMW i3

State of art

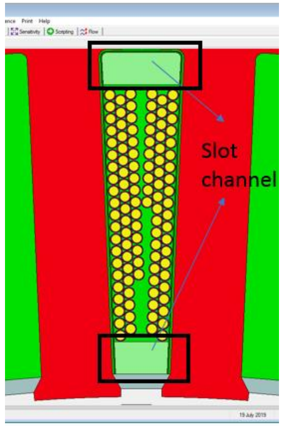


Additive/advanced manufacturing of motor winding and other components

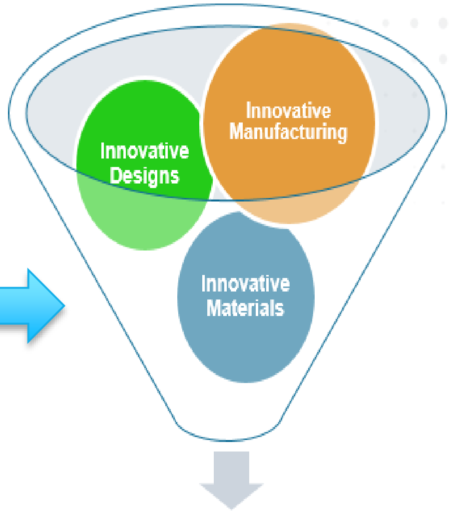




Advances in insulation materials



Embedded cooling and use of highly potent fluids (supercritical etc.)



Co-design process: use of advanced inactive materials and electromagnetic optimization

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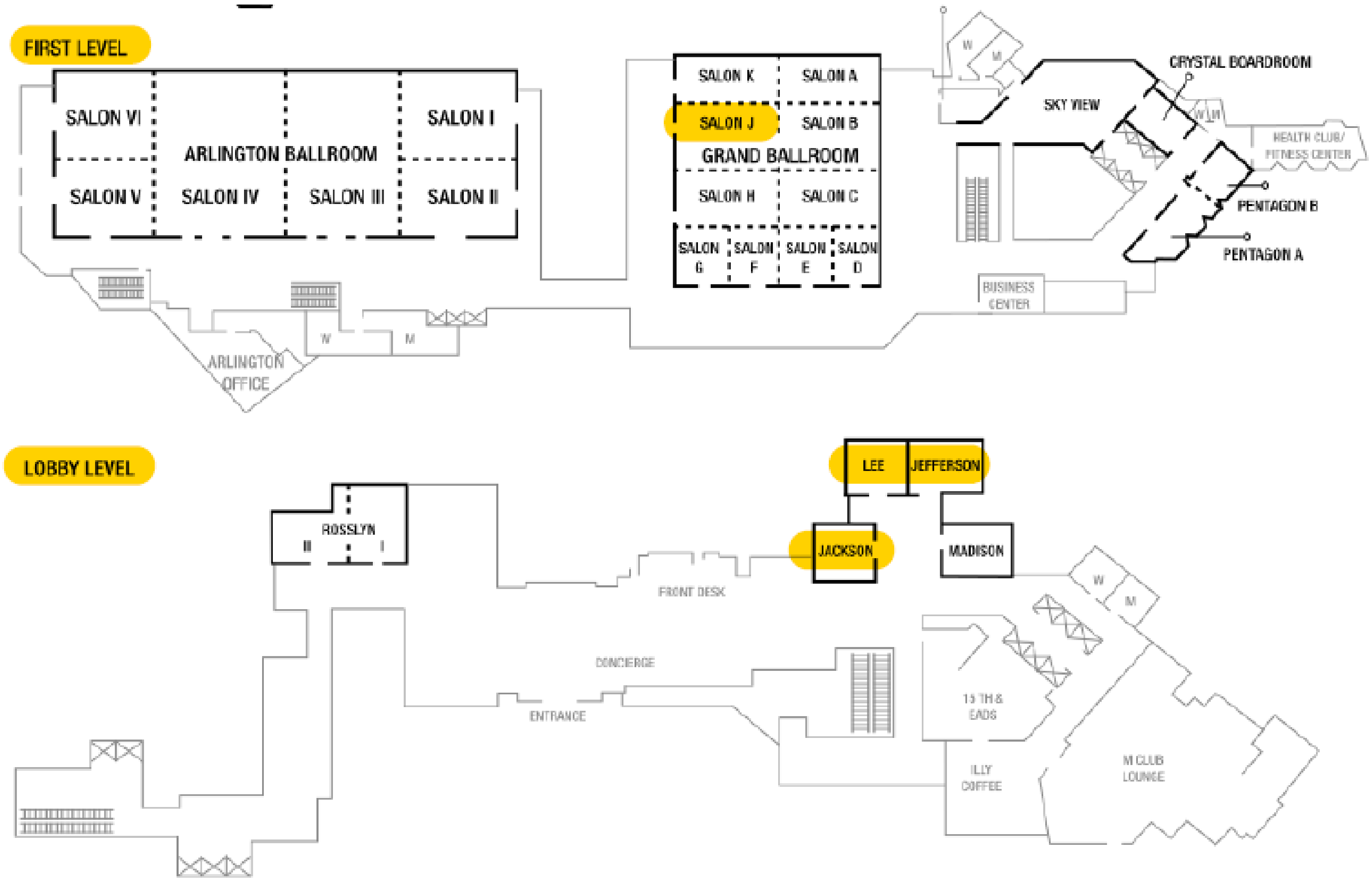
- "Challenges in 3D printing of high conductivity copper" – IPACK2017-74306
- "Cooling of windings in electric machines via 3D printed heat exchanger" – ECCE 2018
- "Advanced cooling concepts for ultra-high-speed machines" – ECCE Asia 2015

BREAKOUT SESSION

Breakout sessions – Morning and Afternoon
Jackson, Lee, and Jefferson Rooms – Lobby Level



Morning breakout session

Jackson, Lee, Jefferson Rooms

Proposed discussion topics:

- Participant introductions
- Seed questions:
    1. How pertinent is the chosen application and our proposed metrics? ARPA-E hard goals?
    2. AC or DC power?
    3. What type of motor: permanent magnet, induction, superconducting, etc.?
    4. Choice of developing integrated system vs motor only?
    5. End of project prototype power scale? 10 kW, 100 kW, ….., 1 MW?
    6. Should the voltage be specified?
    7. Thoughts on cruise requirements vs take-off (3x requirements from cruise)?
    8. Safety, reliability, durability? What's needed for aviation?
    9. Other aspects?
- 15 - 20 minutes before the end of the session: each participant to give a 30 seconds to 1 minute summary

Afternoon breakout session – 1/3

Motor centric (Jackson Room) Grigorii Soloveichik, Zia

Proposed discussion topics:

- Participant introductions
- Seed questions:
  1. What are the key technological paths to very high specific power? Risk and barriers, high-risk/high reward paths?
  2. What are the physical limitations that will prevent achieving high specific power (saturation, etc.)?
  3. Gearbox or gearless options?
  4. How important is the co-design of electromagnetics, power electronics, thermal management?
  5. Should a potential program specify the input voltage (motor specifications)?
  6. What should be the cost metric for a n^{th} of a kind? How do you normalize it (e.g. $/kW, other)?
  7. What should be the program needs for the design, conception and demonstration of new electric motor? (duration, logistics, resources, etc.)
  8. Other aspects?
- 15 - 20 minutes before the end of the session: each participant to give a 30 seconds to 1 minute summary

Afternoon breakout session – 2/3

Integration centric (Jefferson Room) Chris Atkinson, Dipankar

Proposed discussion topics:

- Participant introductions
- Seed questions:
    1. What are the key technological paths to very high specific power? Risk and barriers, high-risk/high reward paths?
    2. Should both volumetric and gravimetric power density be specified?
    3. Final demonstration testing at relevant operating conditions? Options to consider?
    4. Are there other metrics a potential program should consider?
    5. Comments on **electric motors improvements** vs **power electronics improvements**?
    6. How important is the co-design of electromagnetics, power electronics, thermal management?
    7. Should the voltage be specified?
    8. What should be the cost metric for a n^{th} of a kind? How do you normalize it (e.g. $/kW, other)?
    9. What should be the program needs for the design, conception and demonstration of integrated system? (duration, logistics, resources, etc.)
- 15 - 20 minutes before the end of the session: each participant to give a 30 seconds to 1 minute summary

Afternoon breakout session – 3/3

Thermal management centric (Lee Room) Dave Tew, Vivien

<u>Proposed discussion topics:</u>

- Participant introductions
- Seed questions:

  1. Role of thermal management to enable very high specific power? Risk and barriers, high-risk/high reward paths?
  2. What should be the cooling approach? Single phase, two-phase?
  3. How about the use of supercritical fluids?
  4. Specific metrics to judge the merit of the thermal management system? Coefficient of Performance, Thermal Resistance, others?
  5. Can/how the progress in microelectronic cooling be transferred to electric motor?
  6. What should be the program needs for the design, conception and demonstration of new electric motor? (duration, logistics, resources, etc.)
  7. Other aspects?

- 15 - 20 minutes before the end of the session: each participant to give a 30 seconds to 1 minute summary

Recall: NOT of Interest

- This potential program is about integration, not the development of new power electronics alone
- Software development alone
- Paper studies
- Material development alone without integration into targeted system or sub-system