Disruption as an Enabler of Decarbonization: The Prospects of All-Electric Aircraft

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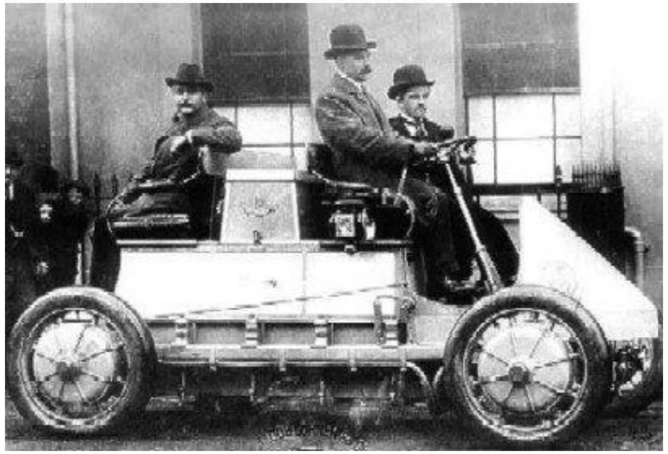
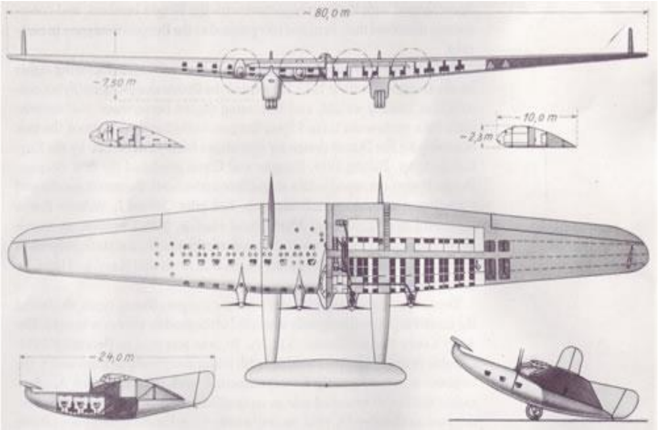
Long Times Scales from Concept/Design to Product



Gasoline-electric Lohner-Porsche, 1900.
http://www.hybrid-vehicle.org/hybrid-vehicle-porsche.html

95 years

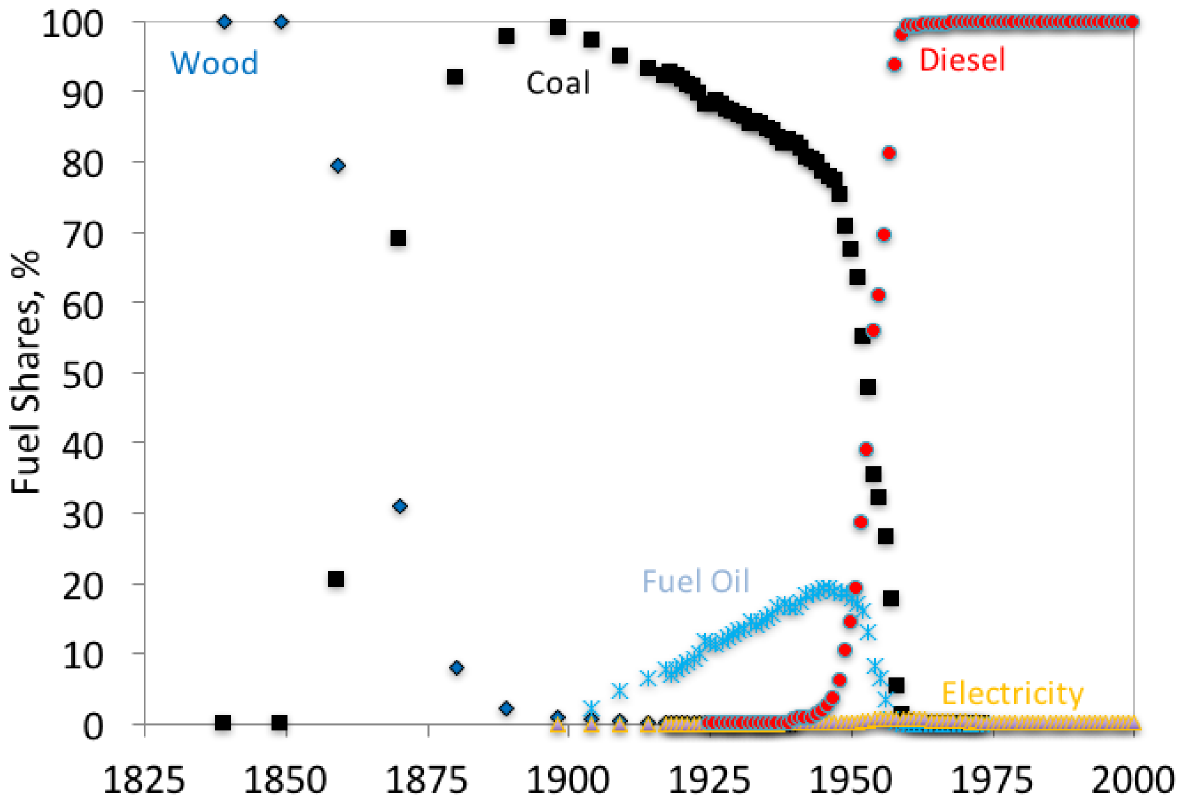


Hugo Junkers' 1924 design for a giant flying wing. The wing was to accommodate 26 cabins for 100 passengers, carry a crew of 10, and have enough fuel for 10 hours of flight.
http://www.century-offlight.net/Aviation%20history/flying%20wings/Early%20Flying%20Wings.htm

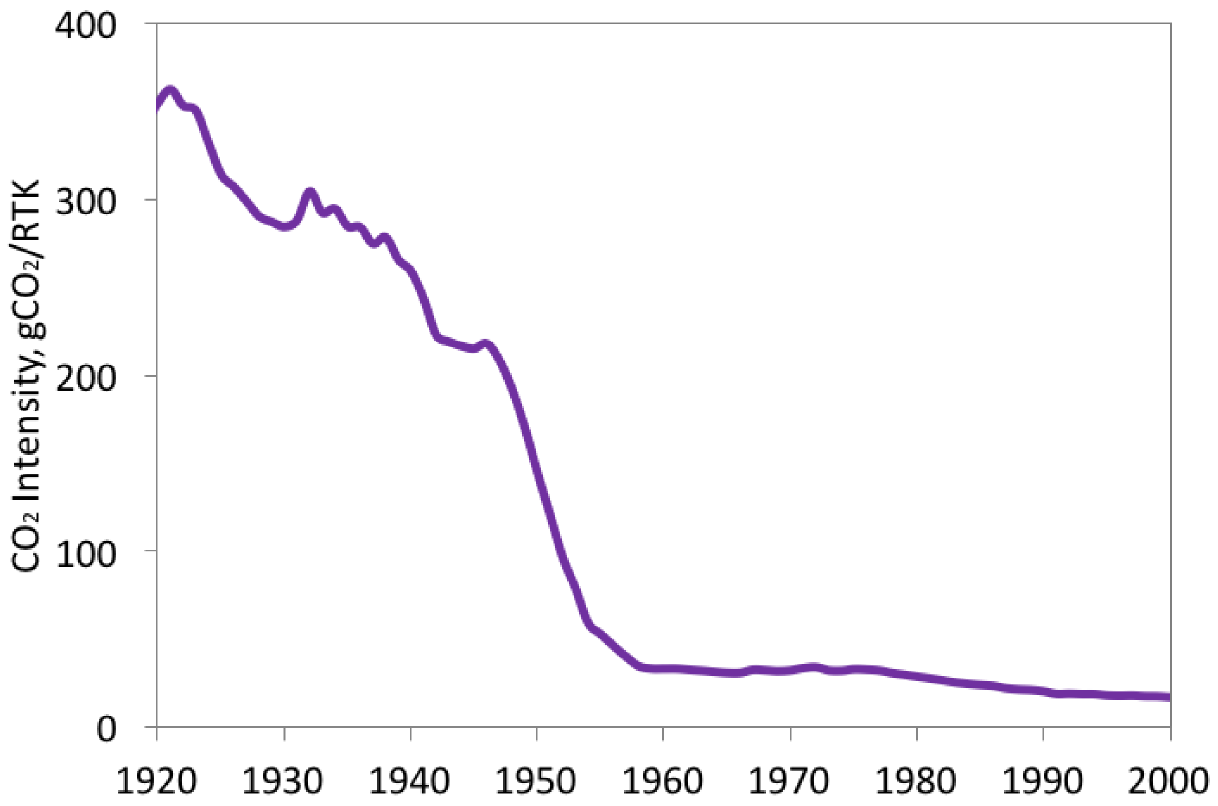
73 years

Yet, Rapid Technological Change is Possible: US Railroads

Fuel Shares: Yard, Passenger, and Freight Sector



CO_2 Intensity: Freight Railroads



Schäfer A., Sweeney J., Draft Paper, 2016

Global Aviation Passenger Demand Growth 5%/yr

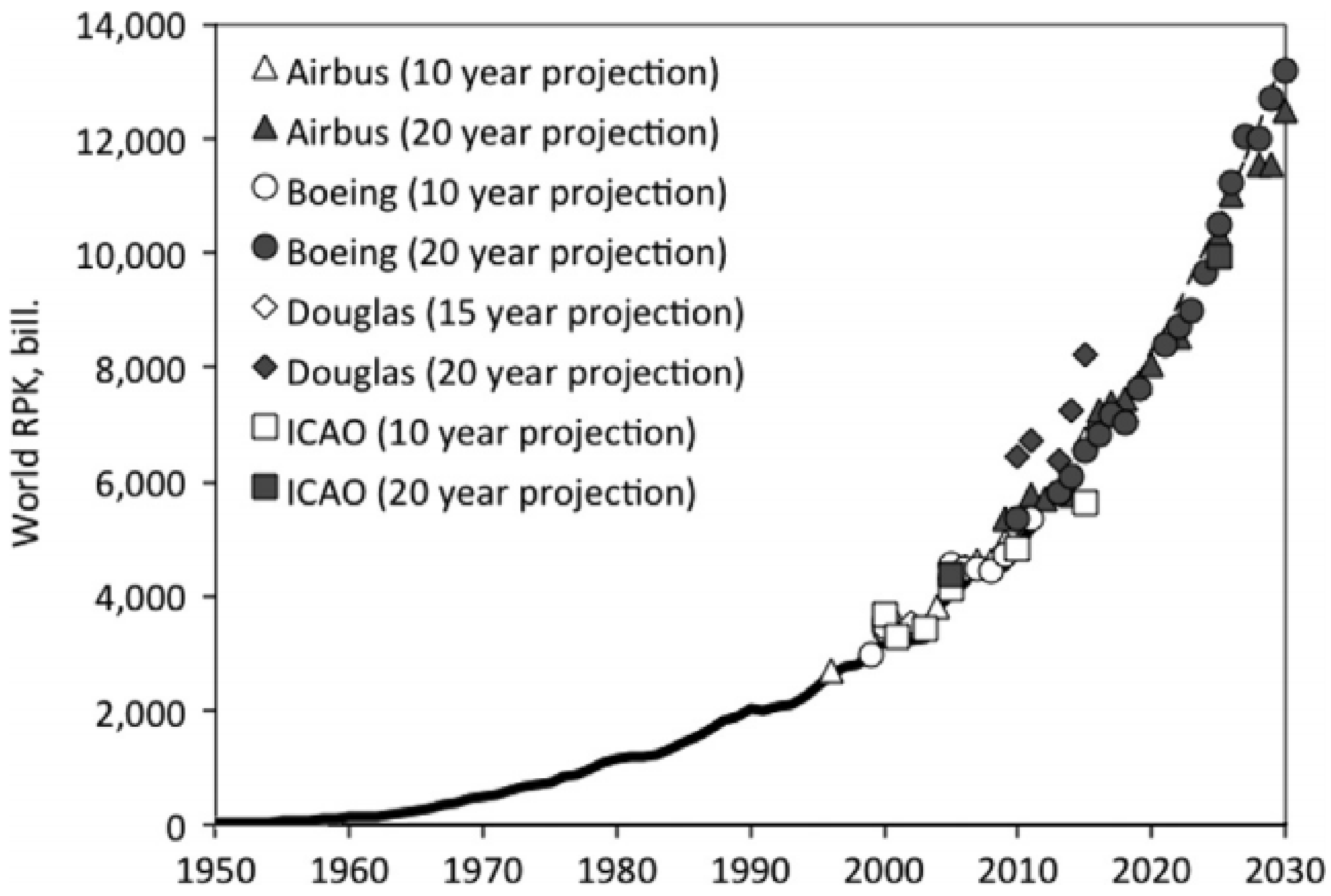
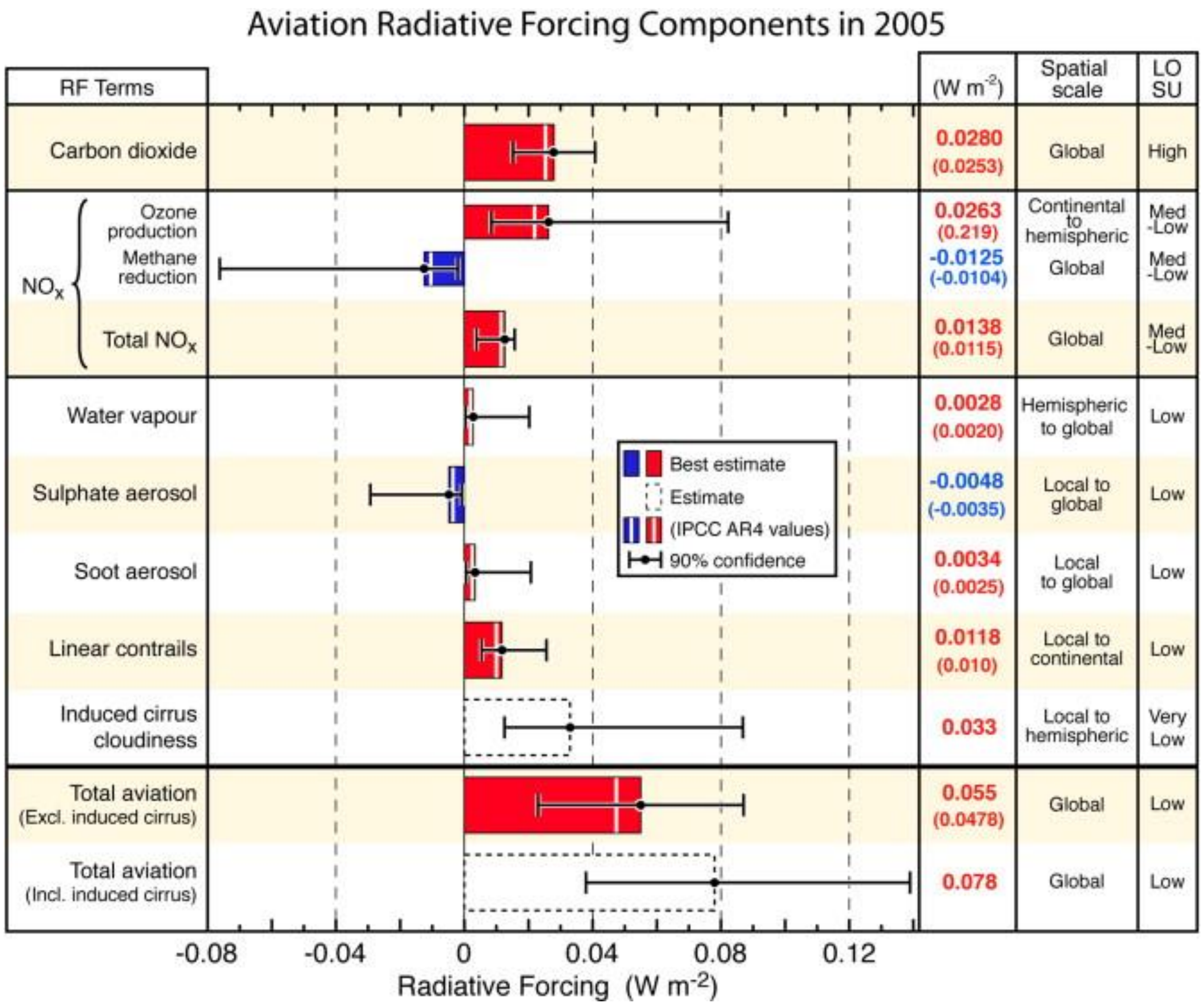


Fig. 1. World passenger revenue passenger-km, historical (1950–2011) and projections (Source: Airbus Industries, various years; Boeing Commercial Airplanes Group, various years; McDonnell Douglas, various years; International Civil Aviation Organization (ICAO), various years).

Schäfer A.W., Waitz I.A., 2014. Air transportation and the environment, Transport Policy 34:1–4.

All-Electric Aircraft can eliminate CO_2 and non-CO_2 Warming

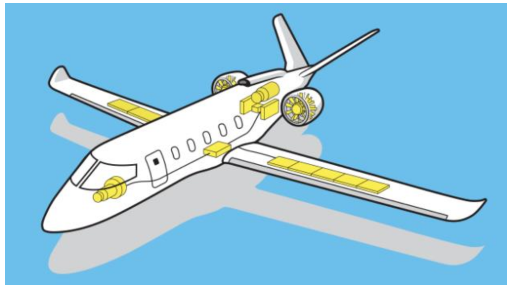


Lee D.S., Fahey D.W., Forster P.M., Newton P.J., Wit R.C.N., Lim L.L., Owen B., Sausen R., 2009. Aviation and Global Climate Change in the 21st Century, Atmospheric Environment 43(22–23):3520-3537.

Two Pathways toward All-Electric Aircraft

All-electric VTOL

Hybrid-electric



Improvements in batteries, power electronics, and electric motors

All-electric

16.05.2019

Lilium reveals new air taxi as it celebrates maiden flight

- Lilium Jet is the world's first all-electric jet-powered five-seater air taxi
- Capable of traveling up to 300km in just 60 minutes, with zero operating emissions
- Lilium will manufacture and operate the Lilium Jet as part of a revolutionary on-demand air taxi service

Munich 16 May 2019: Lilium, the Munich-based startup developing a revolutionary on- demand air taxi service, today revealed its new five-seater air taxi prototype for the first time. The unveiling of the new Lilium Jet came as the all-electric aircraft completed its maiden flight in the skies over Germany earlier this month.

Electric Aircraft Architectures (leading to Distributed Propulsion)

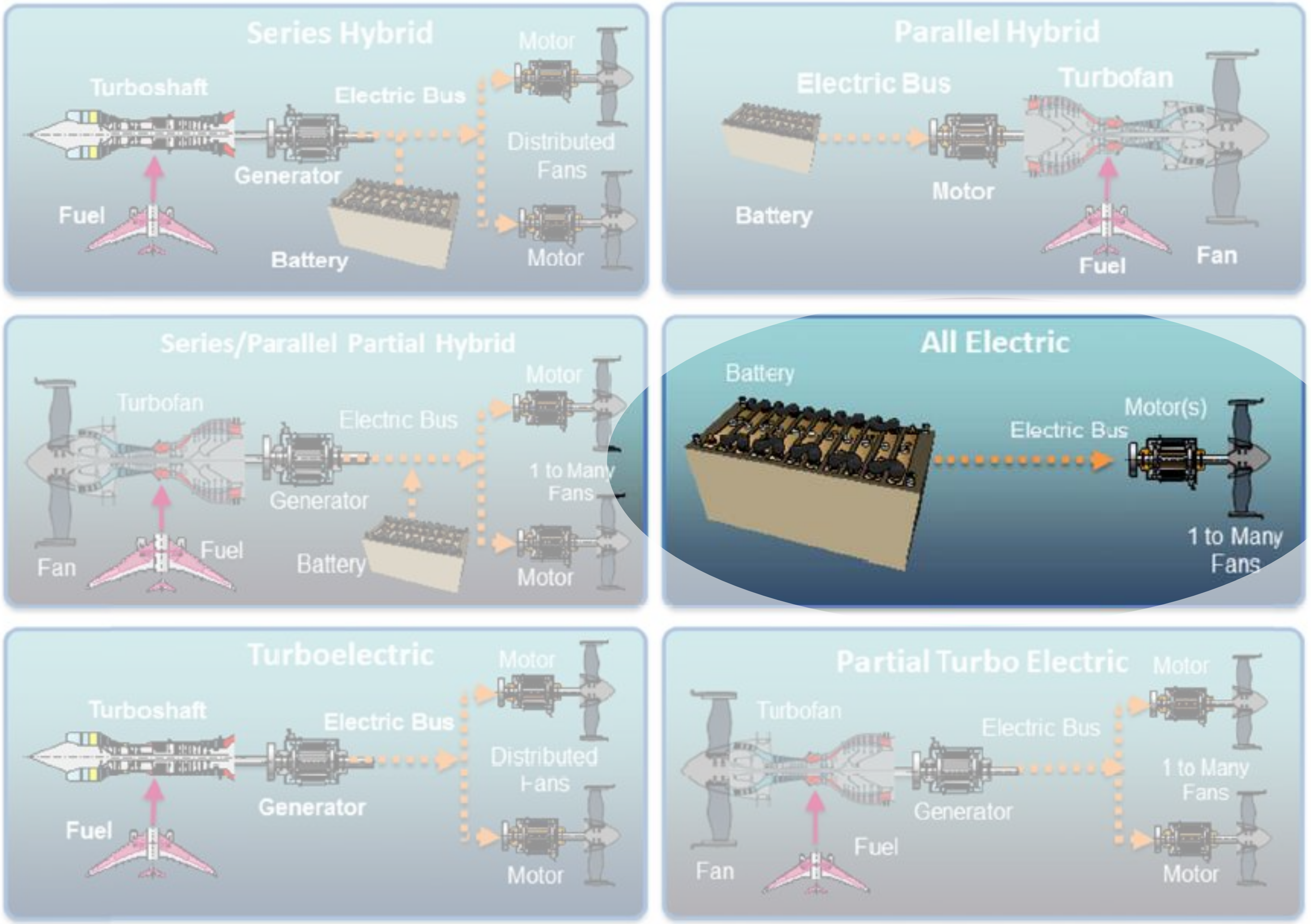
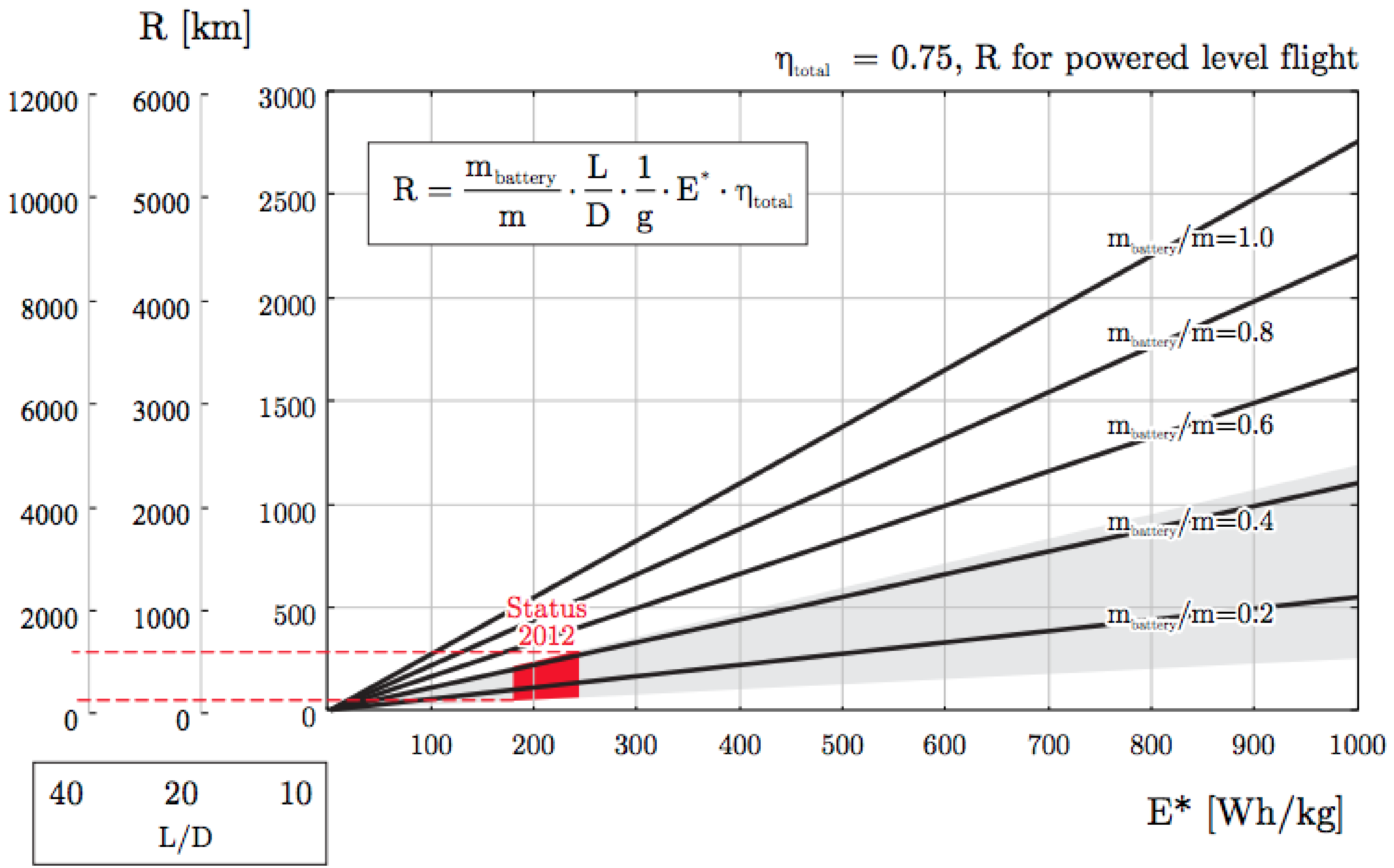


FIGURE 4.1 Electric propulsion architectures. SOURCE: Modified from James L. Felder, NASA Glenn Research Center, "NASA Hybrid Electric Propulsion Systems Structures," presentation to the committee on September 1, 2015.

National Academies of Sciences, Engineering, and Medicine. 2016. Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions. Washington, DC: The National Academies Press. doi:10.17226/23490.

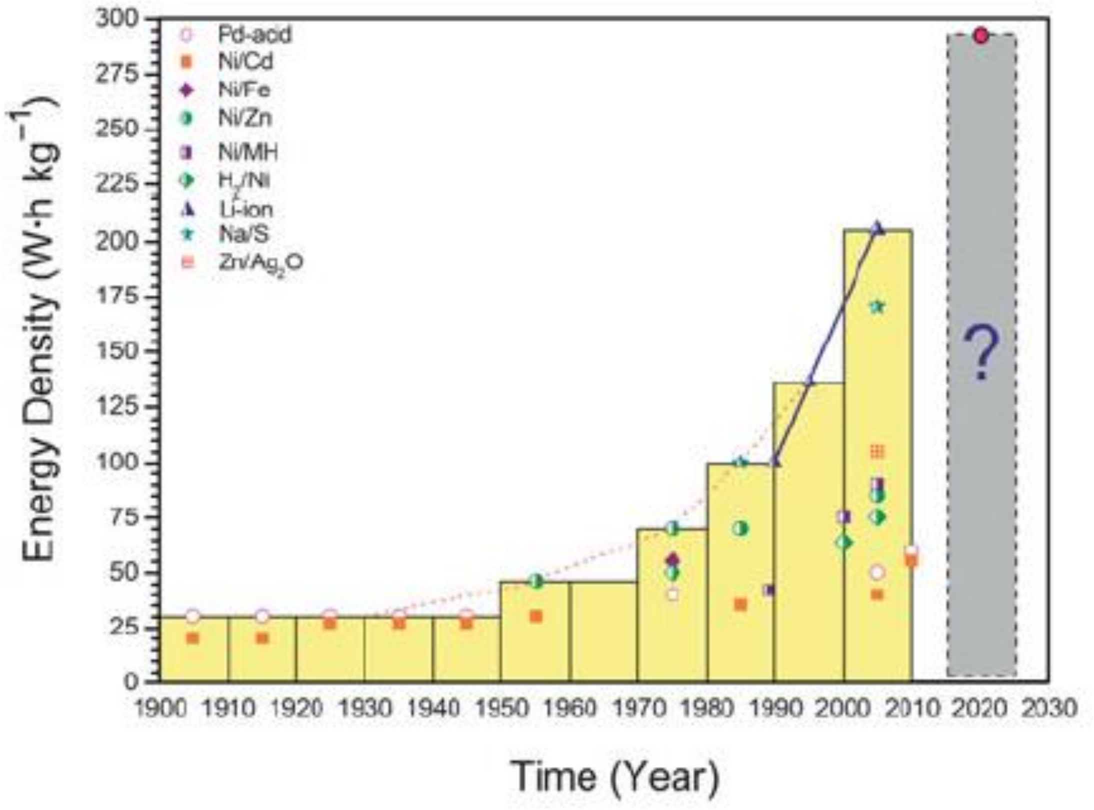
(Breguet) Range Equation: All-Electric Aircraft

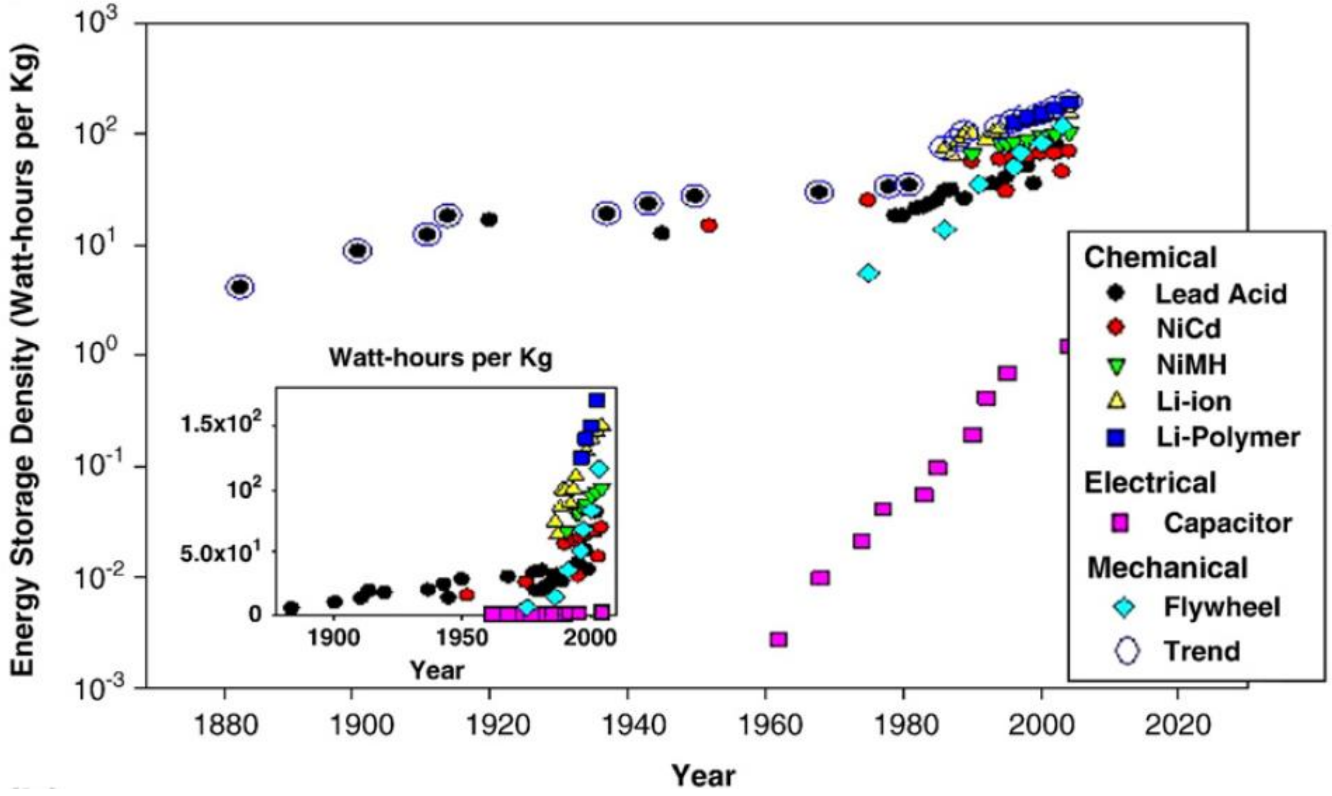


Hepperle M., 2012. Electric Flight – Potential and Limitations. AVT-209 Workshop on Energy Efficient Technologies and Concepts Operation, Lisbon, Portugal, pp. 1–30.

Battery Specific Energy has increased by ~ 3%/yr

(A doubling every 20-25 years)

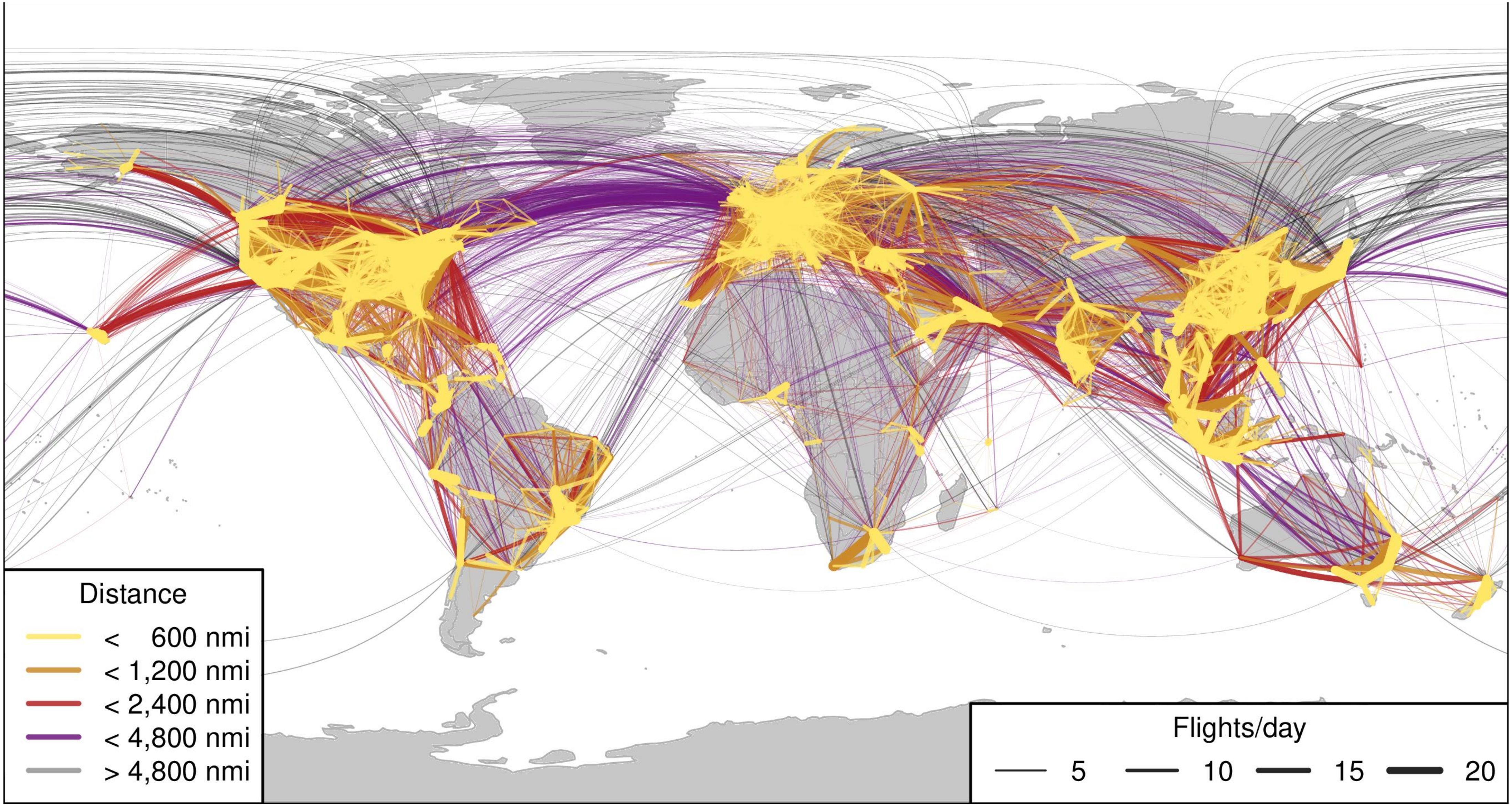




Crabtree G., Kócs E., Trahey L., 2015. The energy-storage frontier: Lithium-ion batteries and beyond. MRS Bulletin 40, 1067-1076.

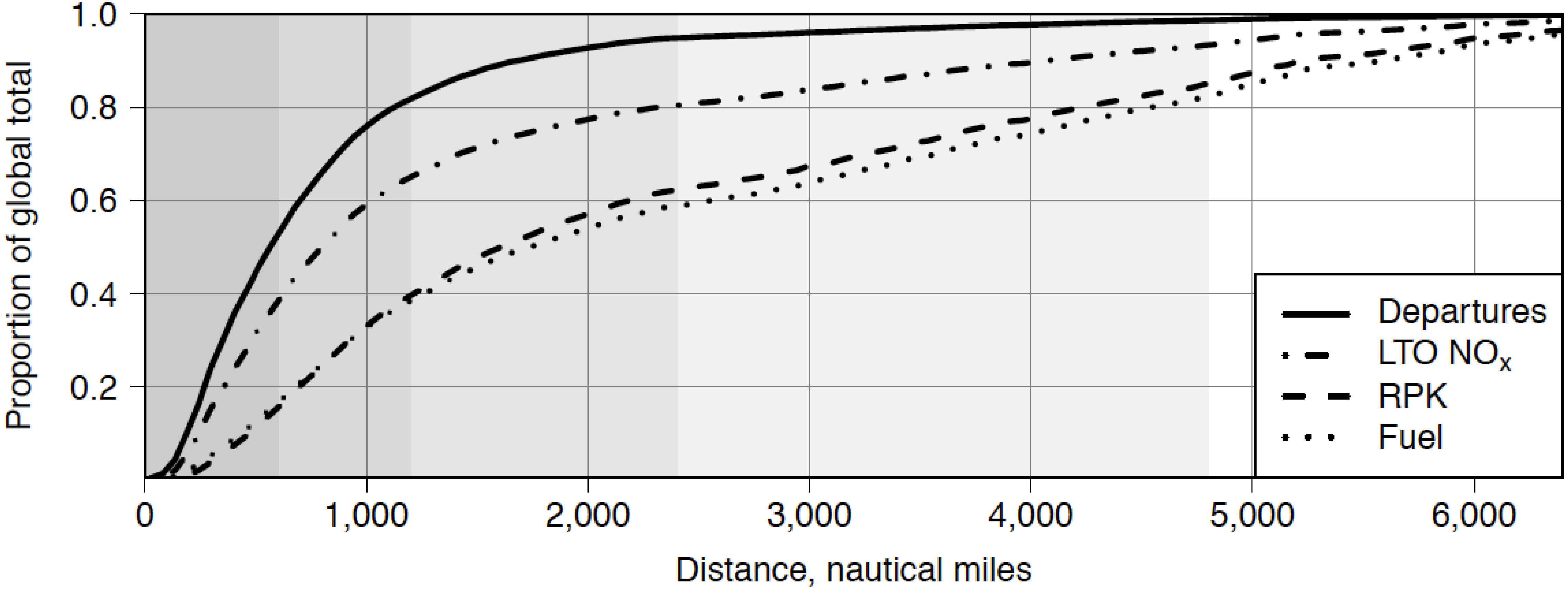
Koh H., Magee C.L., 2008. A functional approach for studying technological progress: Extension to energy technology, Technological Forecasting and Social Change 75(6):735-758

All-Electric Aircraft Market Size by Distance



Schäfer A.W., Barrett S.R.H., Doyme K., Dray L.M.D., Gnadt A.R., Self R., O'Sullivan A., Synodinos A.P., Torija A.J., 2019. "Technological, Economic and Environmental Prospects of All-Electric Aircraft", Nature Energy 4:160-166.

Key Air Transportation Characteristics



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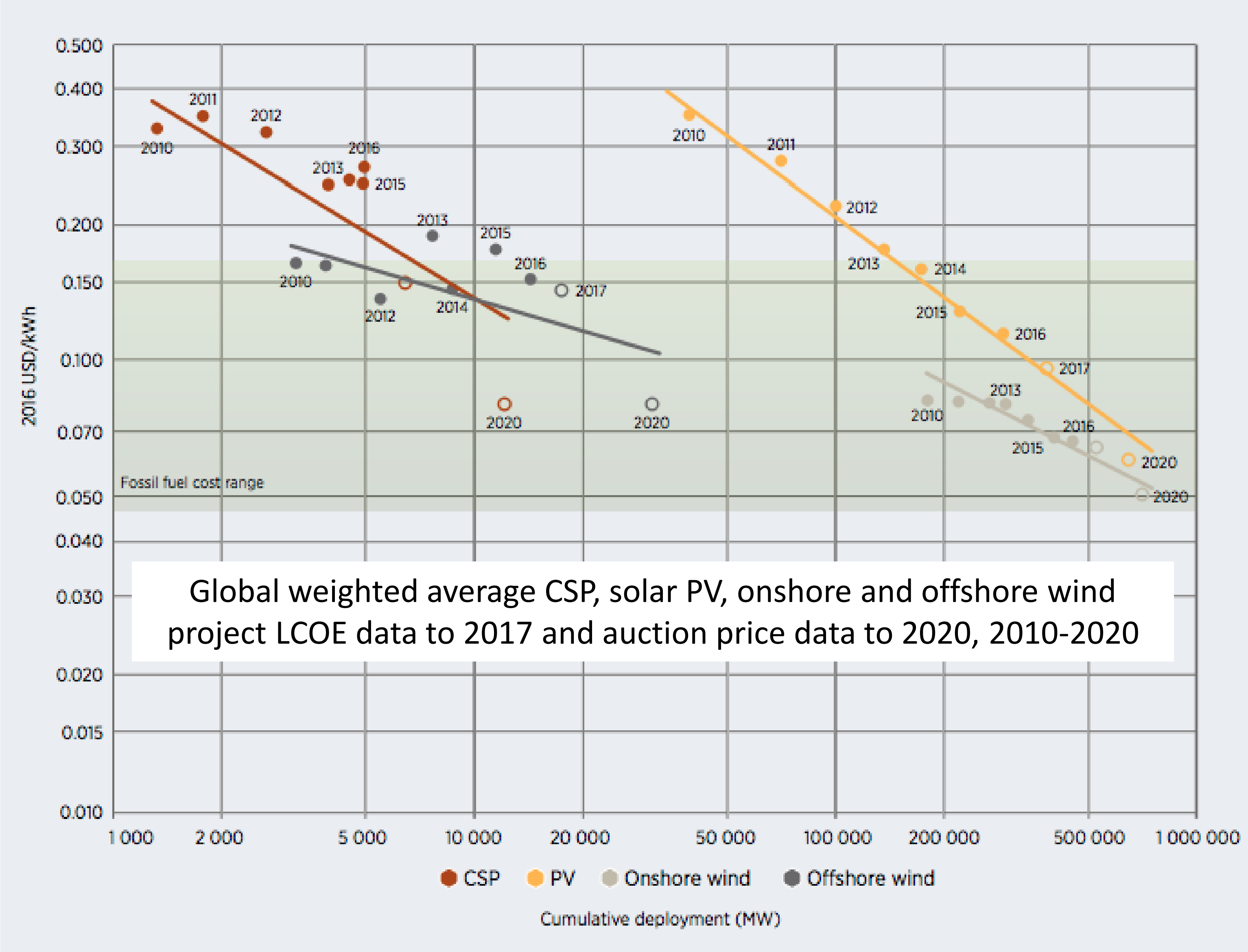
Direct Operating Cost (DOC)

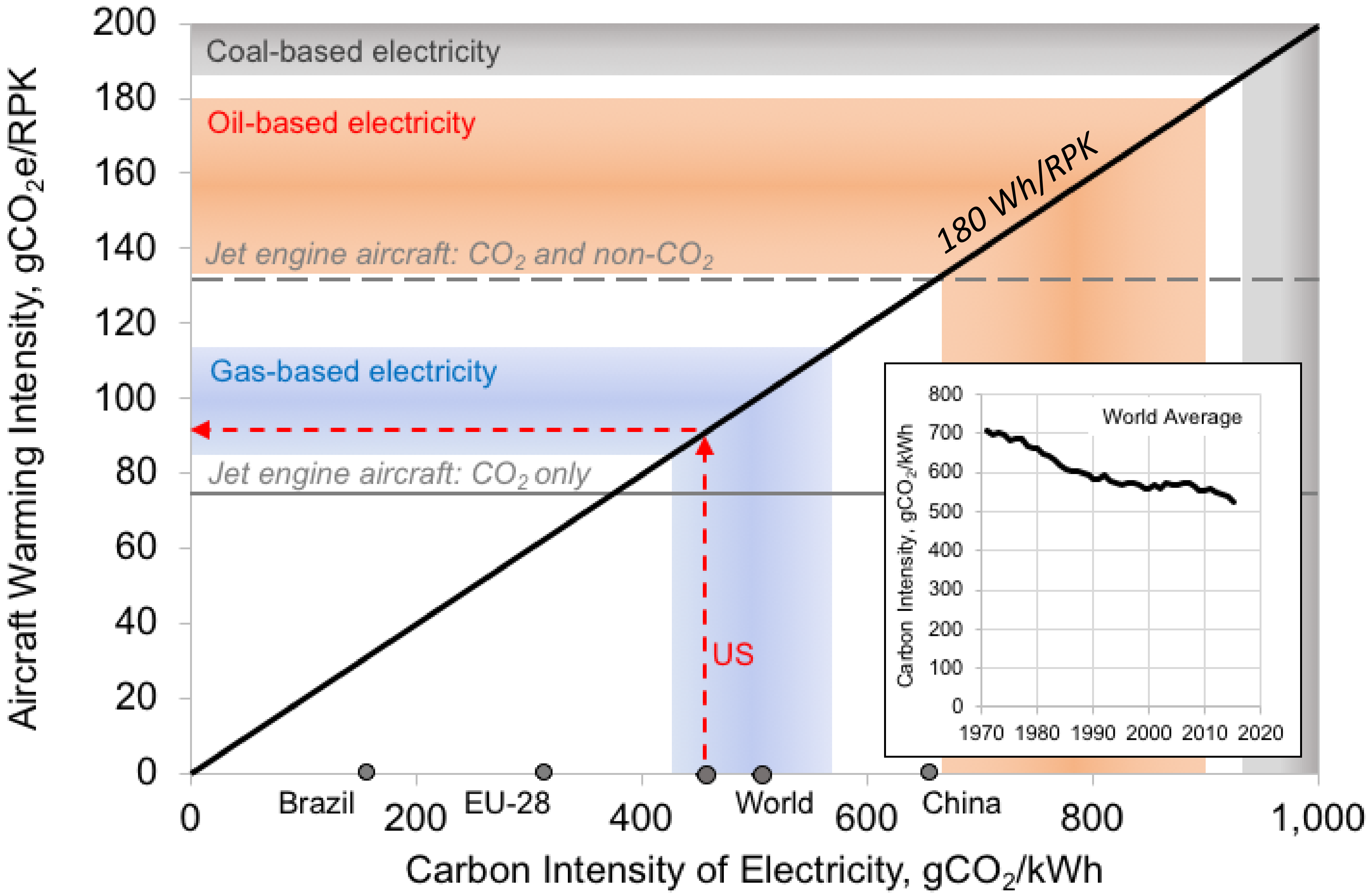
- Electrification affects 75% of DOC (capital costs, maintenance, energy, en-route / airport charges)
- Capital costs: lower-cost propulsors, absence of fuel system and APU versus higher-cost, first set of batteries
- Maintenance costs: potentially lower engine maintenance costs versus higher airframe maintenance and battery replacement costs
- Cost-effectiveness depends mainly on battery performance and costs, jet fuel and electricity price
  - 2015 jet fuel prices ($1.8/Gal) and advanced batteries (800 Wh/kg, $100/kWh) would require electricity prices of max $0.05/kWh
  - A carbon tax of $100/tCO$_2$ would allow electricity prices of max $0.09/kWh

Costs of Renewable Power are declining



IRENA, 2018. Renewable Power Generation Costs in 2017, International Renewable Energy Agency, Abu Dhabi.

Aircraft Warming Intensity



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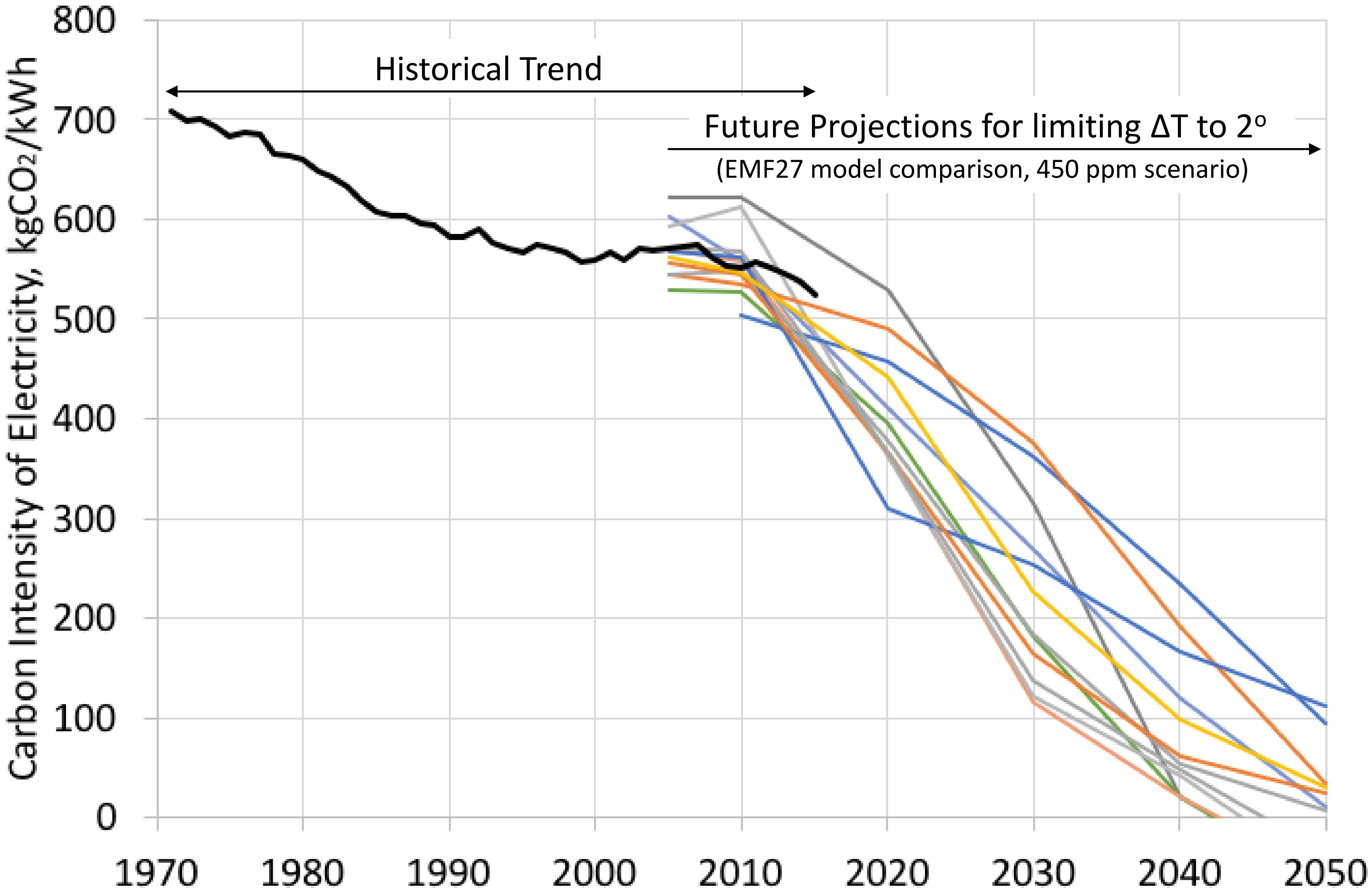
Carbon Intensity of Electricity needs to decline strongly



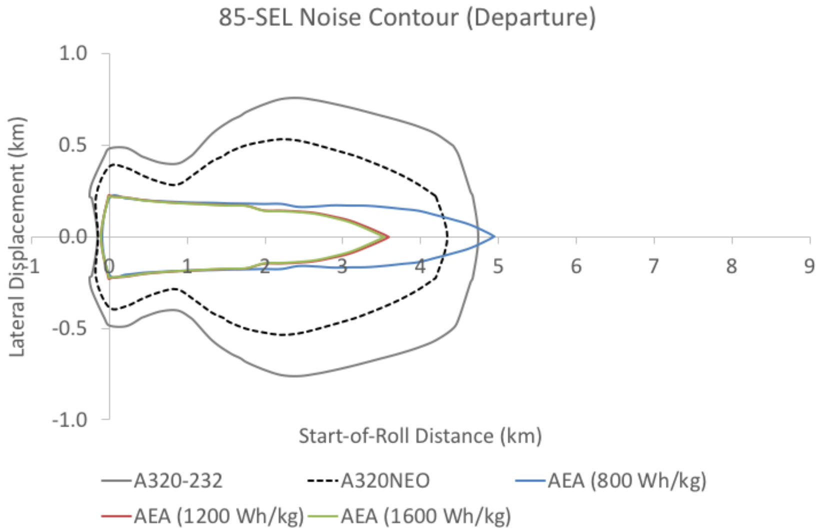
Data source: IPCC AR5 Scenarios Database (http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/IPCC_AR5_Database.html)
IEA, 2018. World Summary Energy Balances.

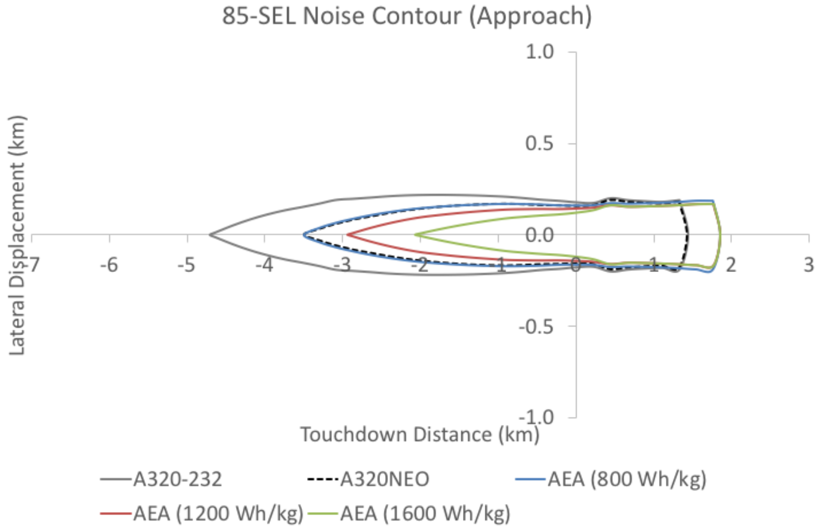
Electric Power Implications

- Using all-electric aircraft for flight segments up to 400-600 nmi (741-1,111 km) within the 2015 flight network would result in extra electricity demand of
  - 110-340 TWh (0.6-1.7%) globally
  - 23-83 TWh (0.6-2.2%) US
  - 11-33 TWh (1.3-3.7%) UK
- Around 15% of all flights in early morning (overnight charging) → remaining 85% determine investments into new power generation capacity (assuming 35% capacity factor)
  - 31-120 GW globally
  - 6.6-27 GW (US)
  - 1.2-3.6 GW (UK)

All-Electric Aircraft Noise Analysis

- Noise contours of All Electric Aircraft
  - Using MIT aircraft specs and flight profile
- Parametric study to evaluate noise vs.
  - Number of propulsors
  - Battery specific energy
  - Battery charging strategies
  - Mission length
- Conclusions
  - Noise benefits could be substantial on short missions
  - Noise highly dependent on all operational constraints and procedures, i.e., flight profiles and recharging strategies
  - Take-off noise lower than conventional aircraft, due to lower fan pressure ratios and absence of combustion noise
  - Approach noise likely higher than conventional aircraft, due to higher aircraft weight





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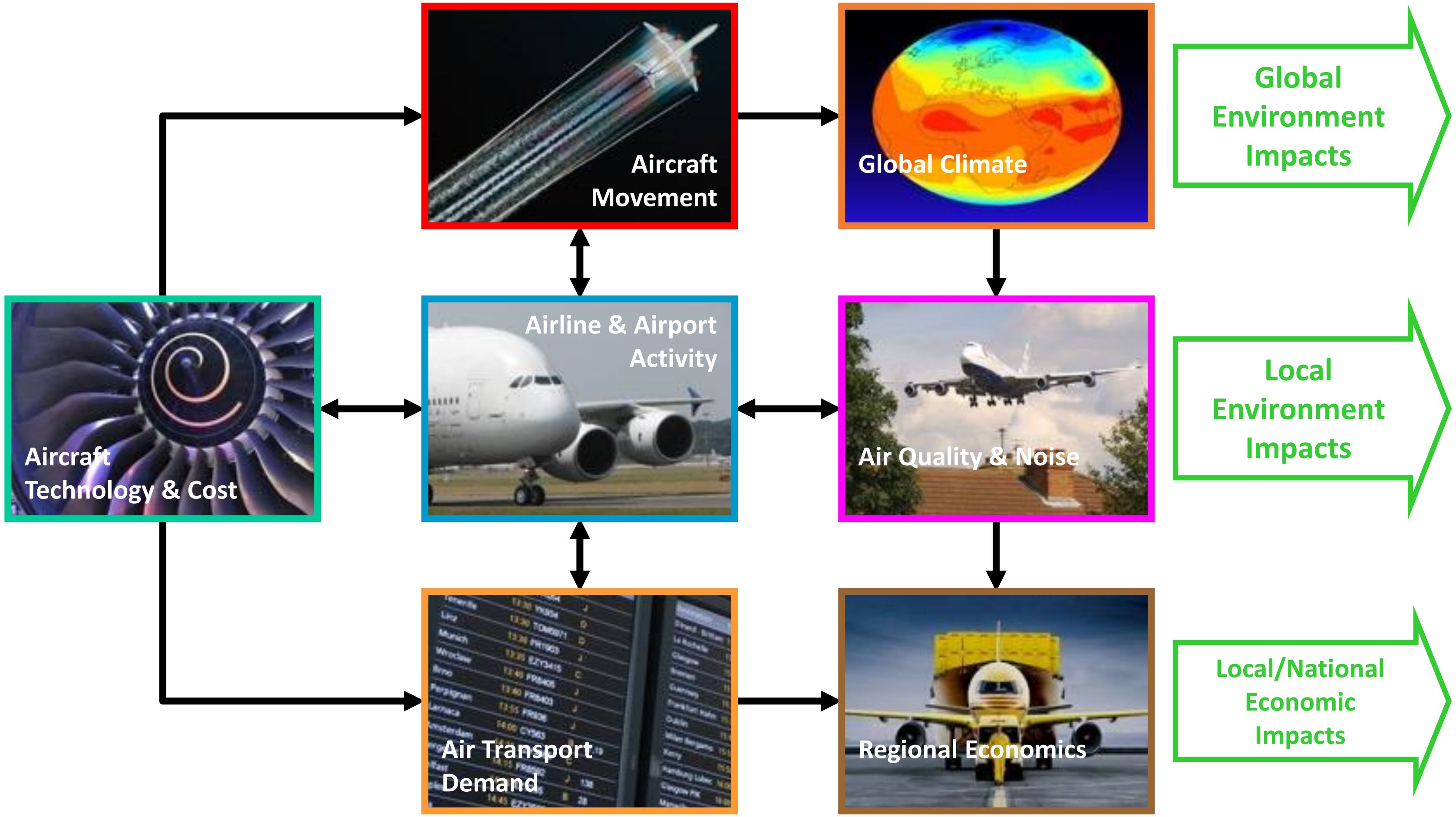
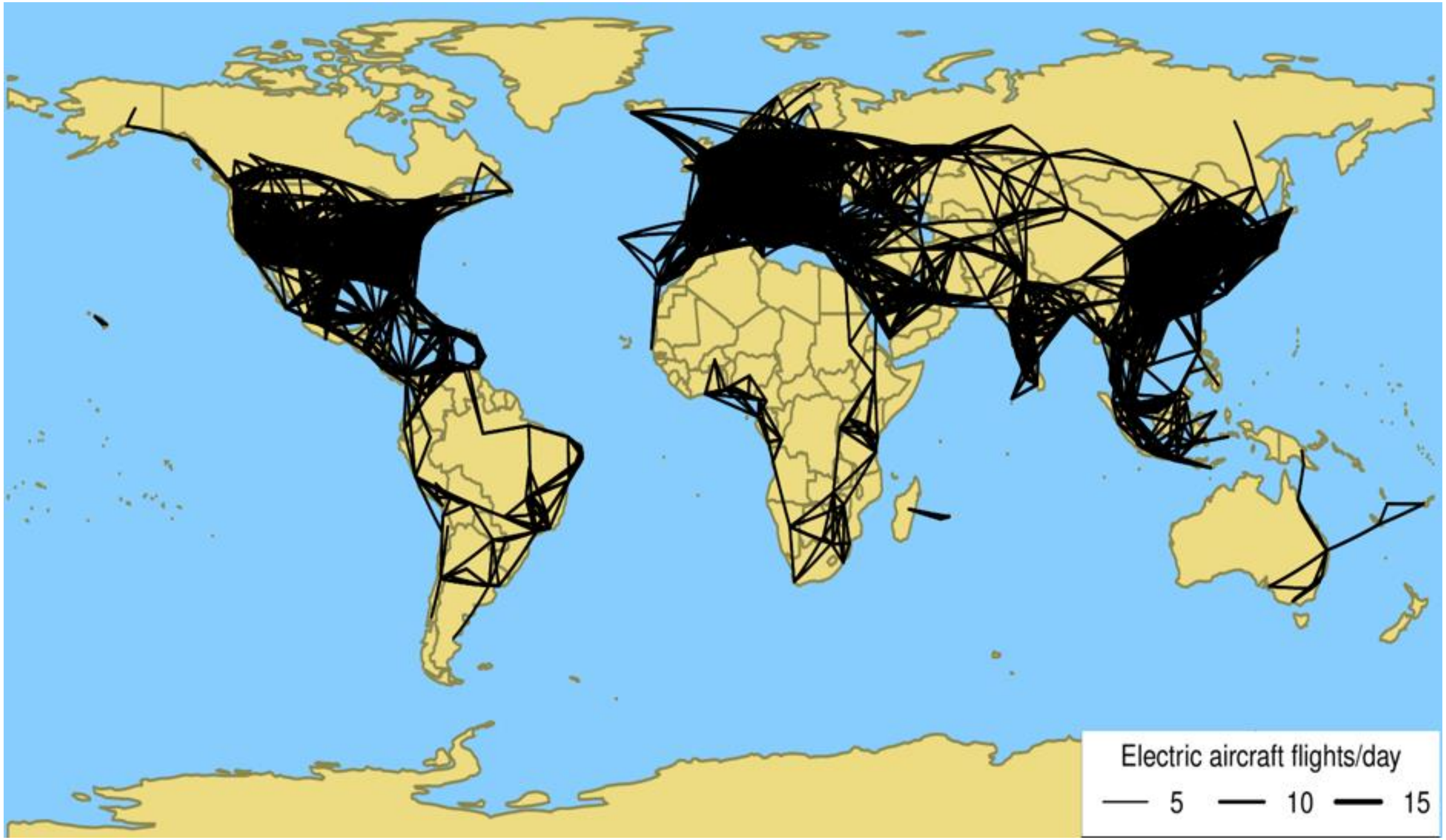
Modelling the Introduction of Battery Electric Aircraft

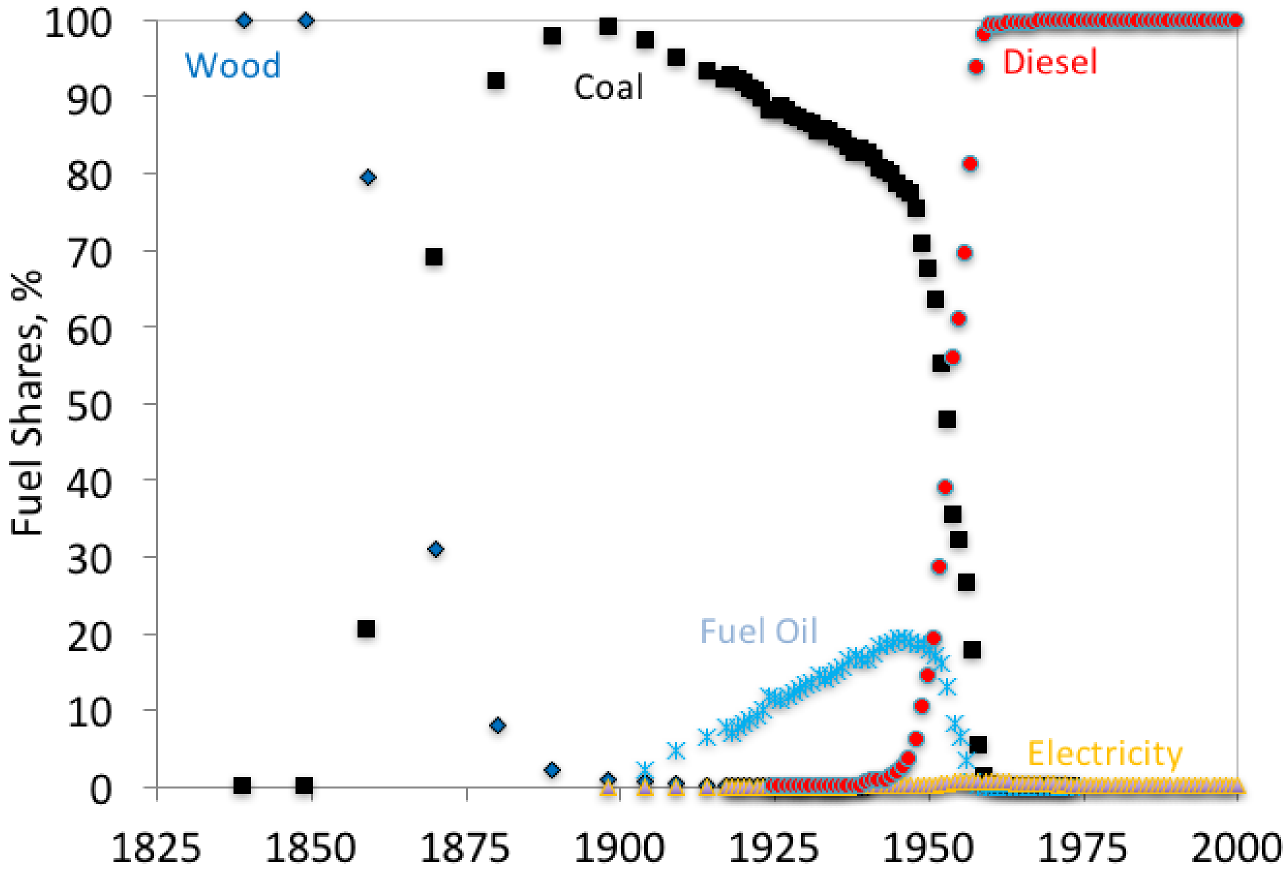


Simulated Future Projected Electric Aircraft Network



Winners and Losers: US Railroads

Fuel Shares: Yard, Passenger, and Freight Sector



Source: Schäfer and Sweeney (2016)

Winners

Losers

Conclusions

- To become a feasible alternative, all-electric aircraft require
  - significantly higher specific energy and power batteries
  - significantly higher specific power aircraft motors and power electronics
  - lower battery costs and enabling economic conditions
- Enabling technologies and factors
  - Electric air taxis
  - Turbo and hybrid-electric aircraft
  - New business models?
- Mutually reinforcing factors with time scales measured in decades
  - Rising battery performance and declining costs, electricity grid decarbonization, strong decline in renewable power generation costs
  - R&D on all-electric aircraft design and key components needs to start now

Electric Aircraft Research Team

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- Mr. Weibo Li (UCL)
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