Decarbonizing Aviation

UCSD Deep Decarbonization Initiative
University of California San Diego
Wednesday November 6, 2019

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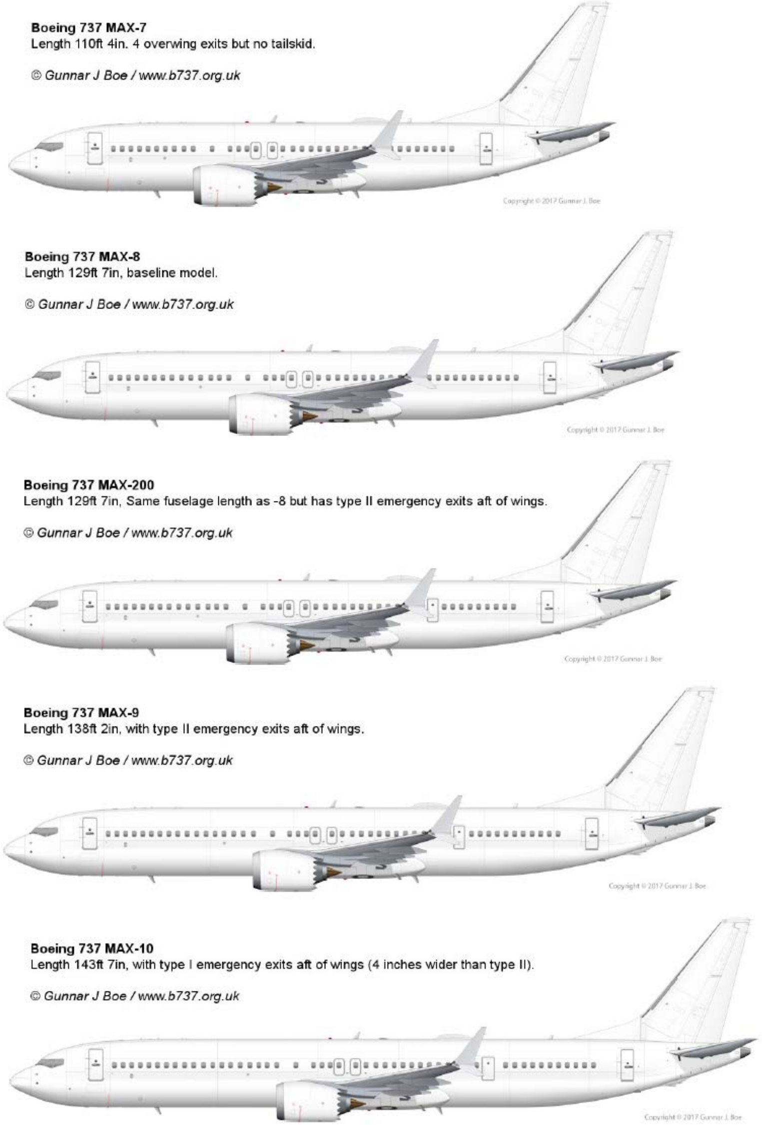
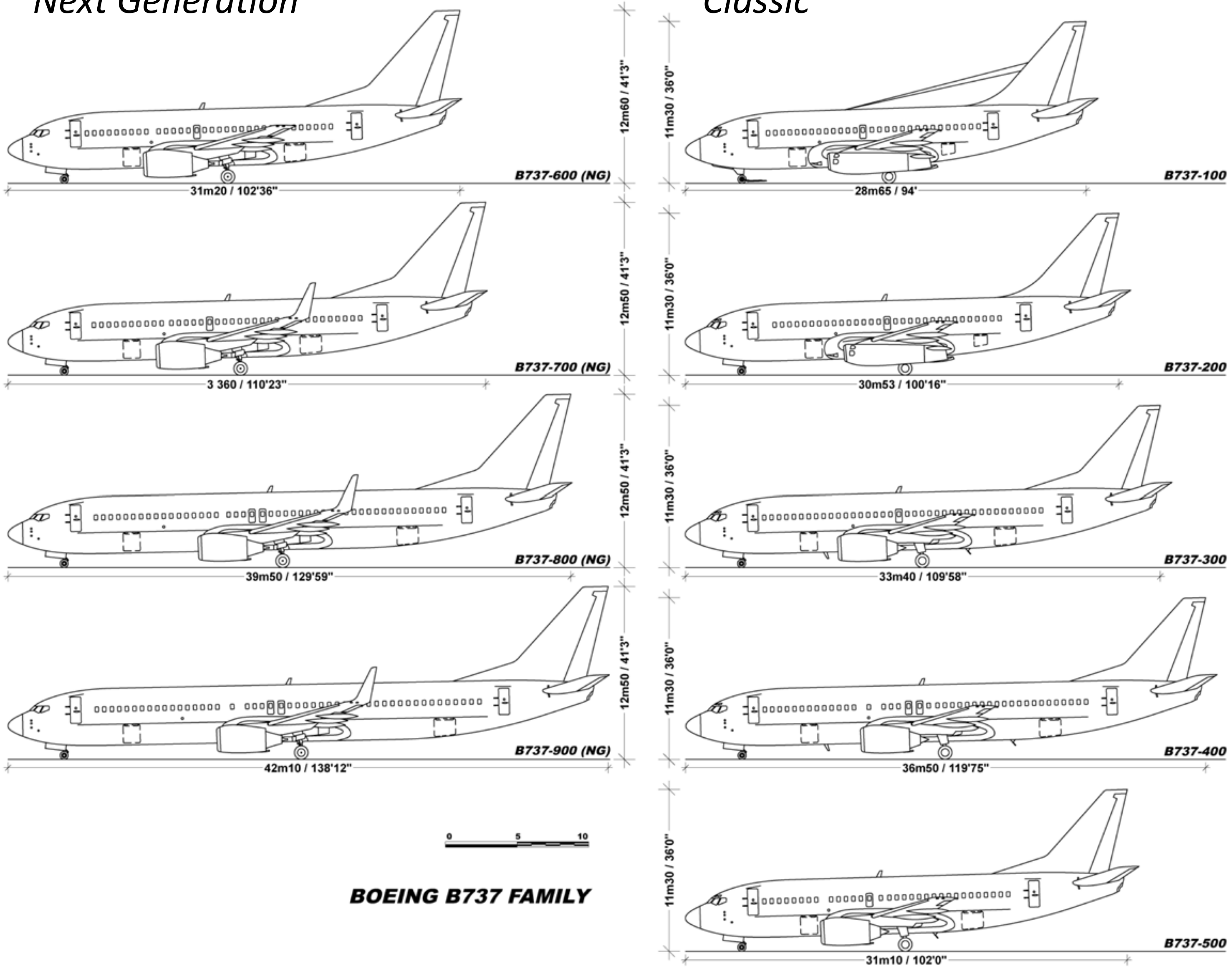
Key Sector Characteristics

- Strong demand growth
- Dependency on high-energy content fuels
- High capital intensity
- Long lifetime of equipage
- Comparatively low profitability
- Cost pressure has resulted in significant fuel efficiency improvements
- Non-CO_2 climate warming $\geqq$ CO_2 warming
- No silver bullet

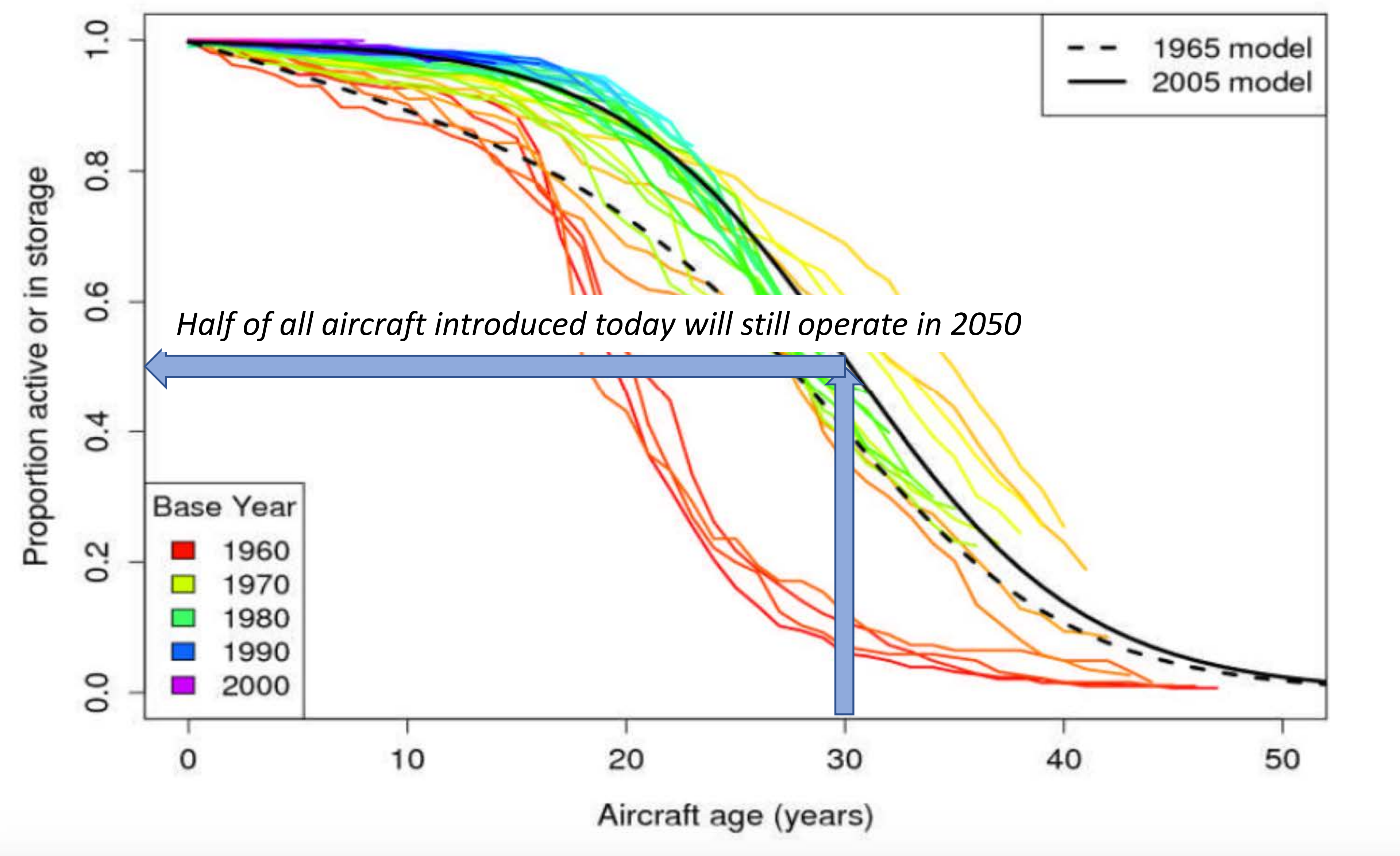
Spot the Difference: Five Decades of B737

MAX | *Next Generation* | *Classic*



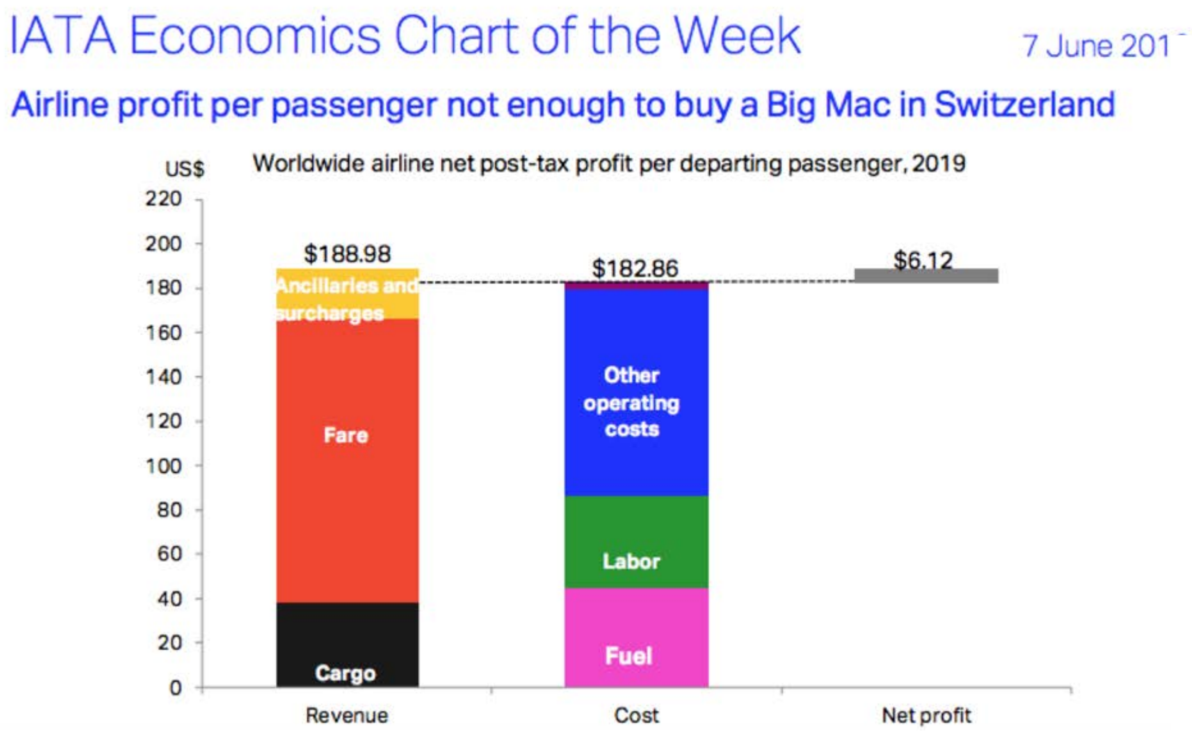


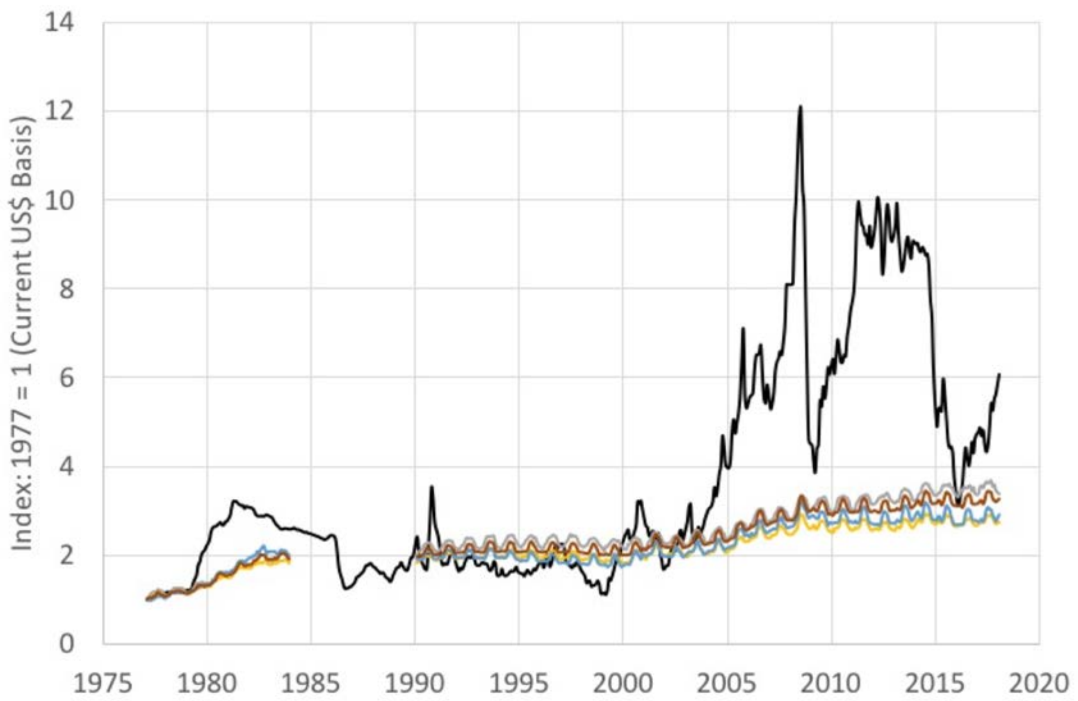
Long Technology Lifetime: Narrowbodies



Morrell P., Dray L.M., 2009. Environmental aspects of fleet turnover, retirement and life cycle, Final Report, OMEGA.

Driver of Fuel Efficiency: Low Airline Profit Margins



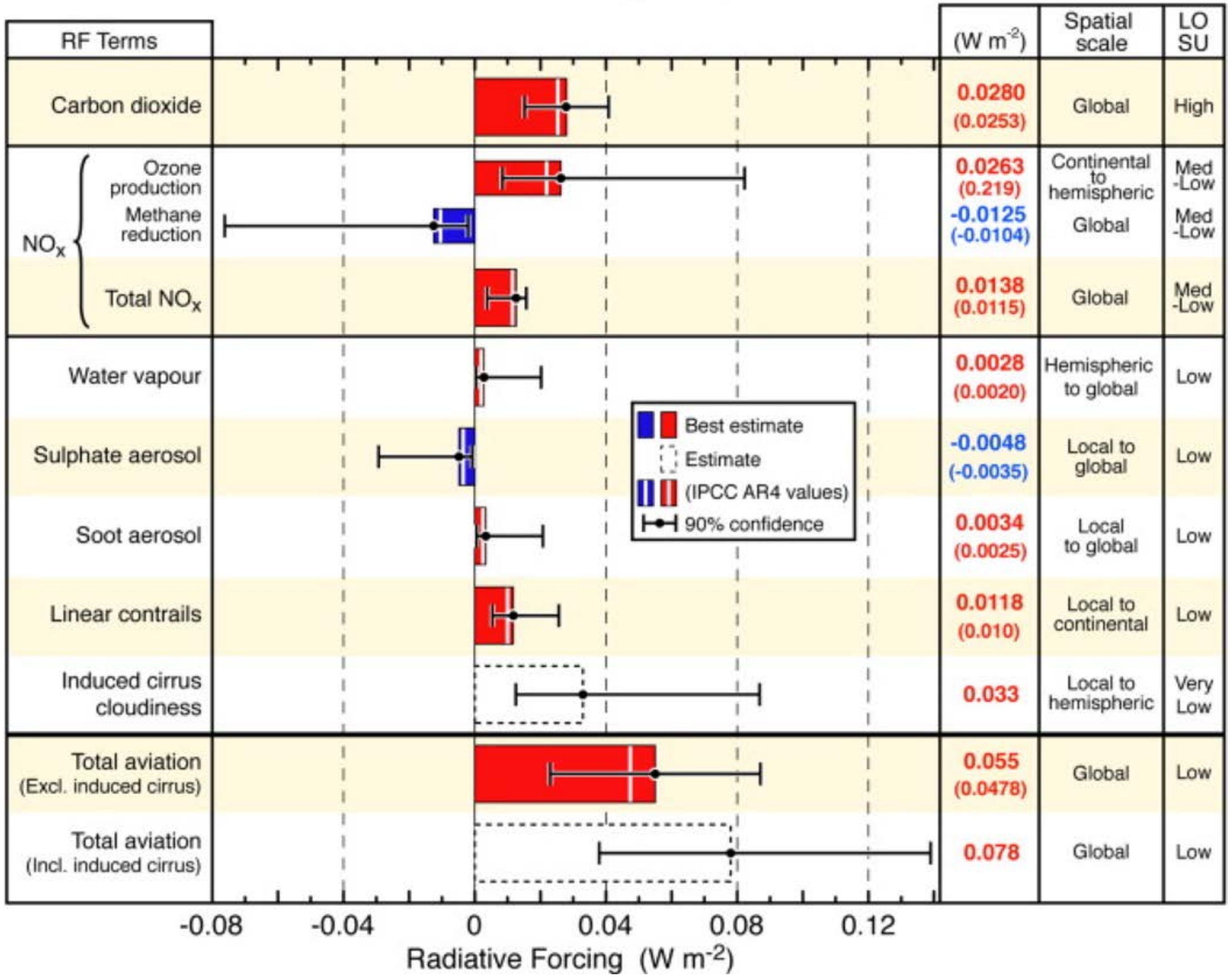


https://www.iata.org/publications/economics/Reports/chart-of-the-week/Chart-of-the-week-7-June-19.pdf

US Energy Information Administration. U.S. Kerosene-Type Jet Fuel Retail Sales by Refiners, Average Retail Prices of Electricity

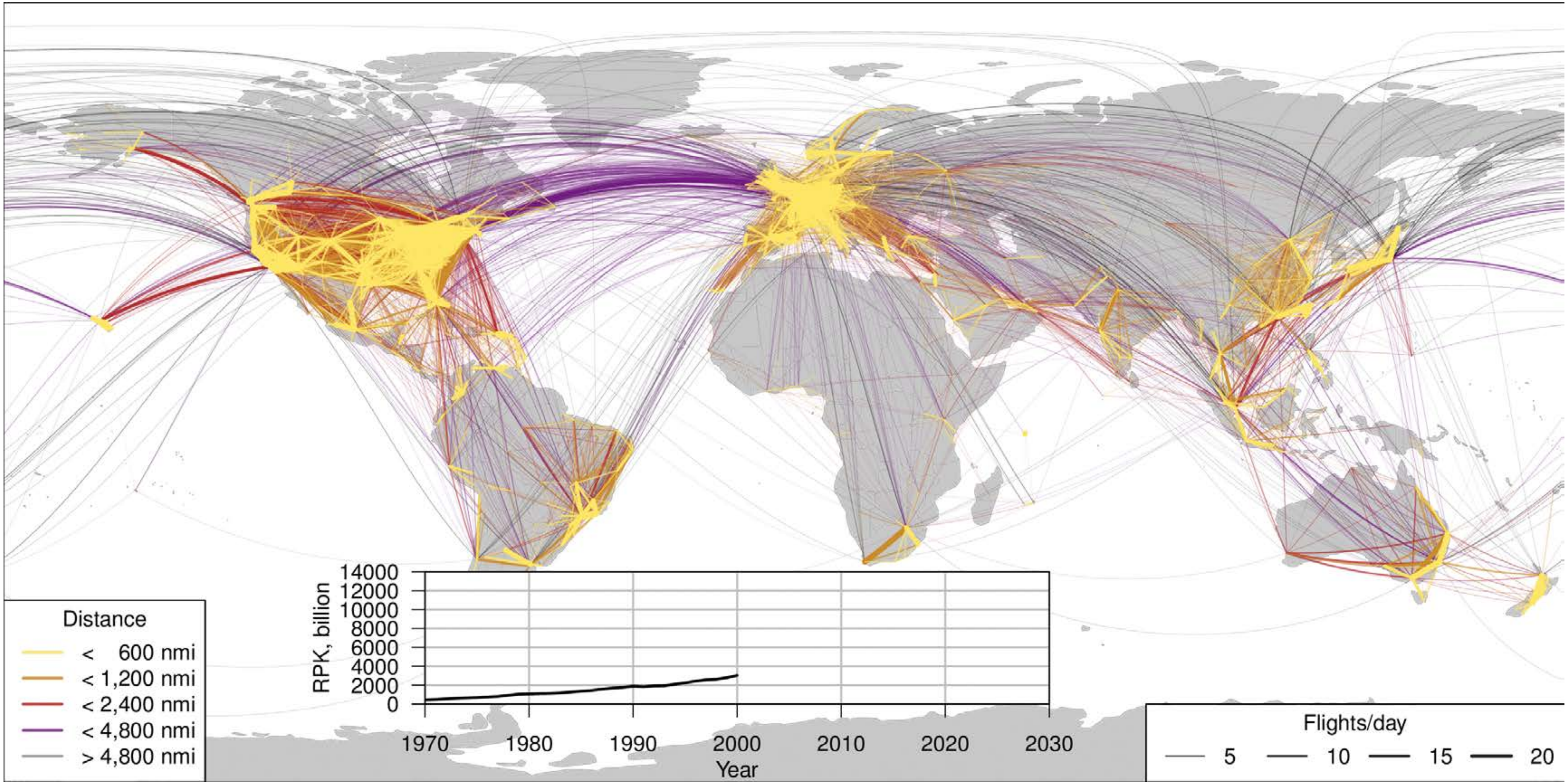
CO_2 is not the only Warming Agent

Aviation Radiative Forcing Components in 2005



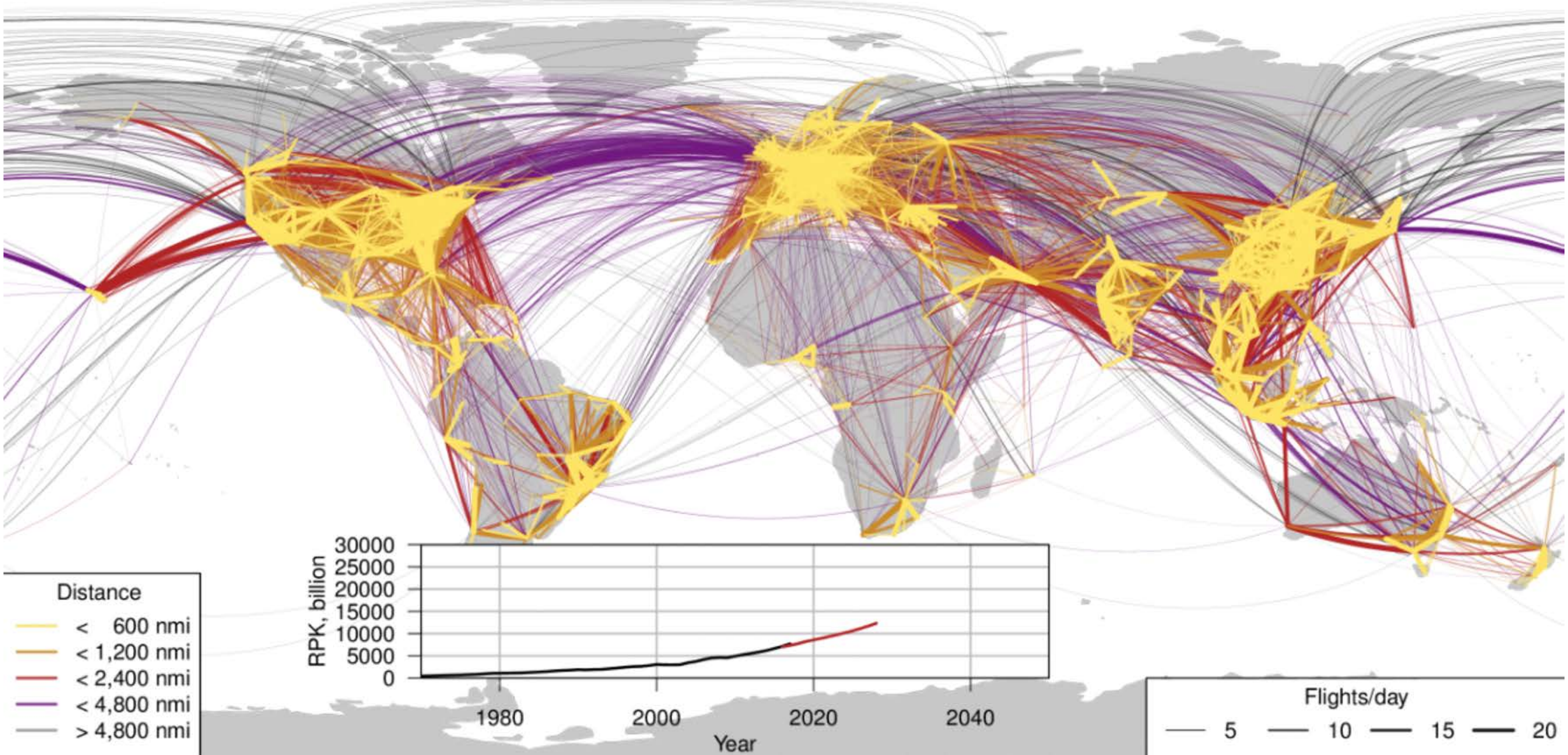
Lee D.S., Fahey D.W., Forster P.M., Newton P.J., Wit R.C.N., Lim L.L., Owen B., Sausen R., 2009. Aviation and Global Climate Change in the 21st Century, Atmospheric Environment 43(22–23):3520-3537.

Demand Growth 2000-2016



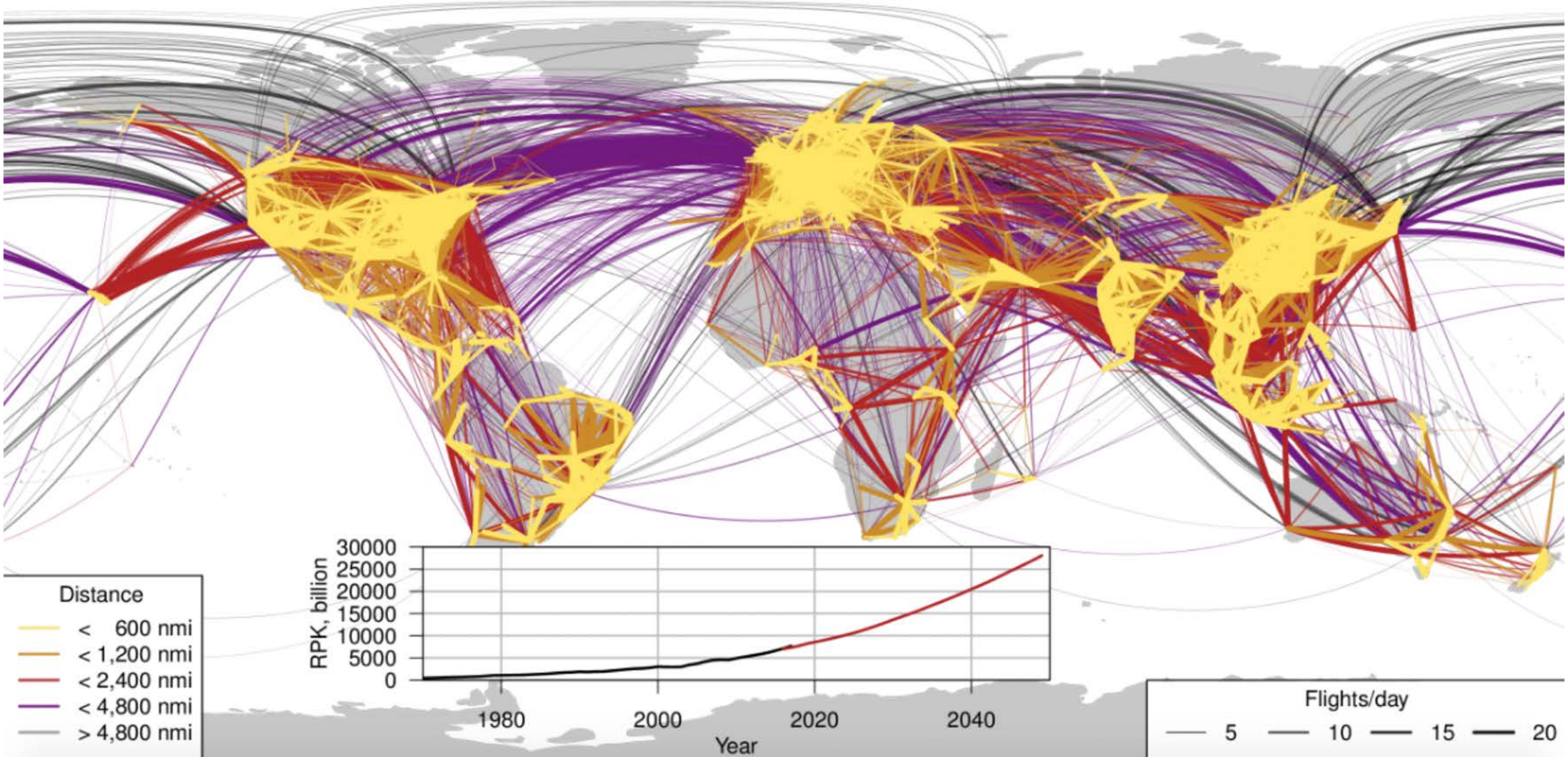
Dray L.M., ATSLab; data: Sabre, 2017; ICAO, 2018

Projected Demand at around 2030



Dray L.M., ATSLab; data: Sabre, 2017; ICAO, 2018

Projected Demand at around 2050



Dray L.M., ATSLab; data: Sabre, 2017; ICAO, 2018

CO_2 Emissions Identity

$$CO_2 = \frac{CO_2}{E} \cdot \frac{E}{RTK} \cdot RTK$$

CO_2 Emissions	Fuel Composition	Energy Intensity	Air Transport Demand

	CO_2 Emissions	Fuel Composition	Energy Intensity	Air Transport Demand
1980-2015:	+2.2%/yr	0	-3.2%/yr	+5.4%/yr
2015-2050:	+2.6%/yr	0	-1.6%/yr	+4.2%/yr

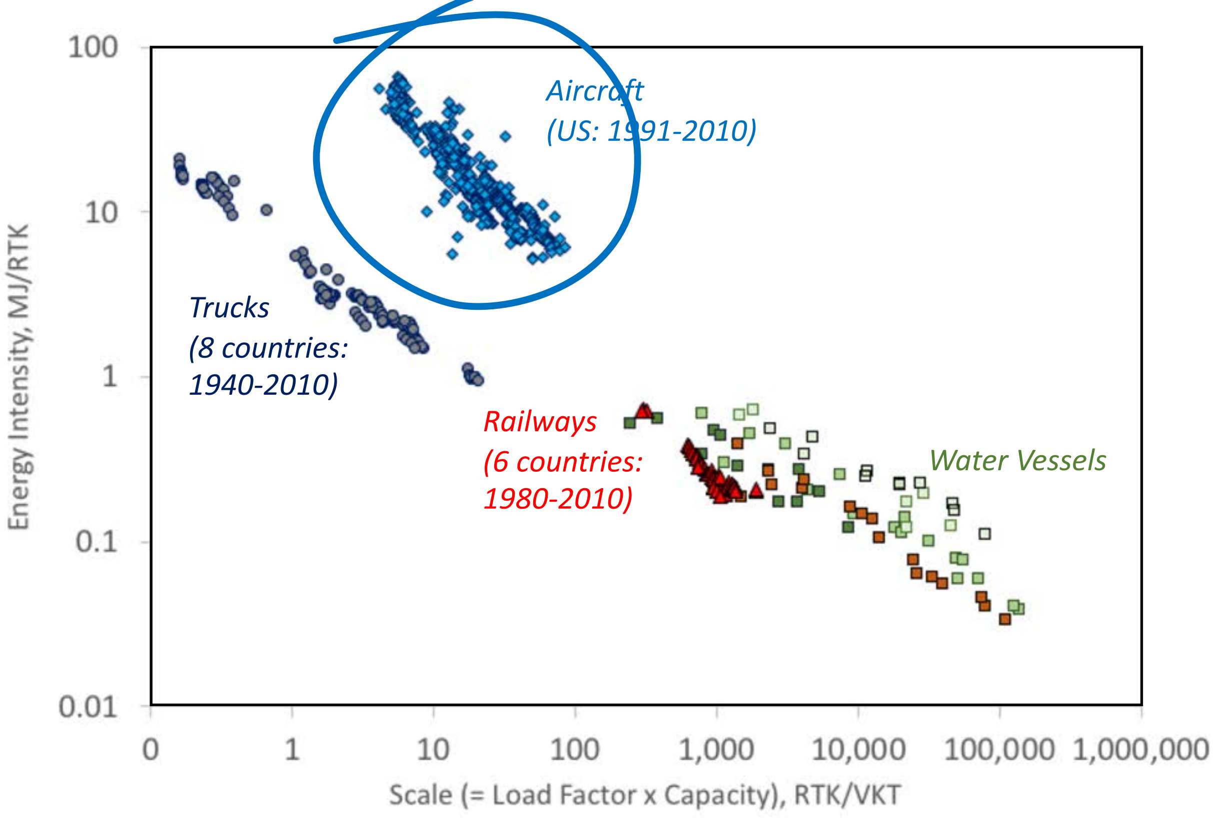
CO_2 Emissions Identity

$$CO_2 = \underbrace{\frac{CO_2}{E}}_{\text{Fuel Composition}} \cdot \underbrace{\frac{E}{RTK}}_{\text{Energy Intensity}} \cdot \underbrace{RTK}_{\text{Air Transport Demand}}$$

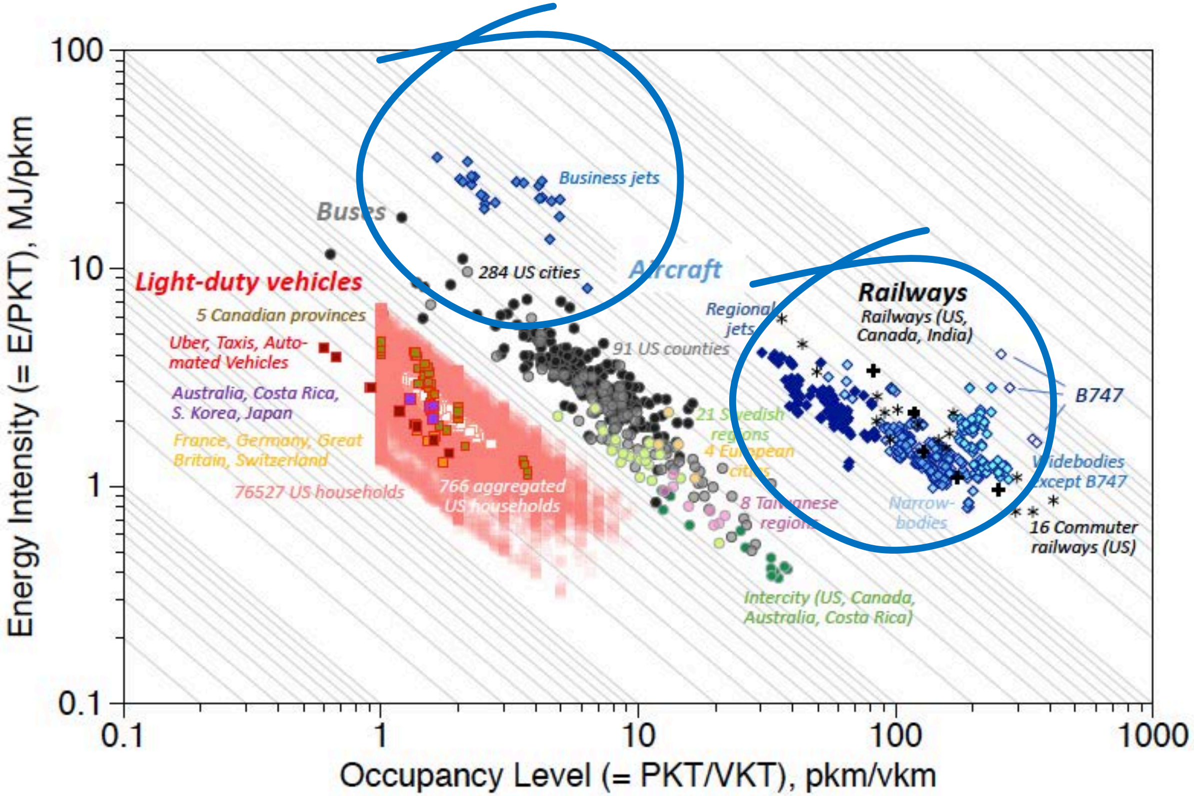
CO_2 Emissions — *Fuel Composition* — *Energy Intensity* — *Air Transport Demand*

Energy intensity across modes: square cube law

Freight Transportation



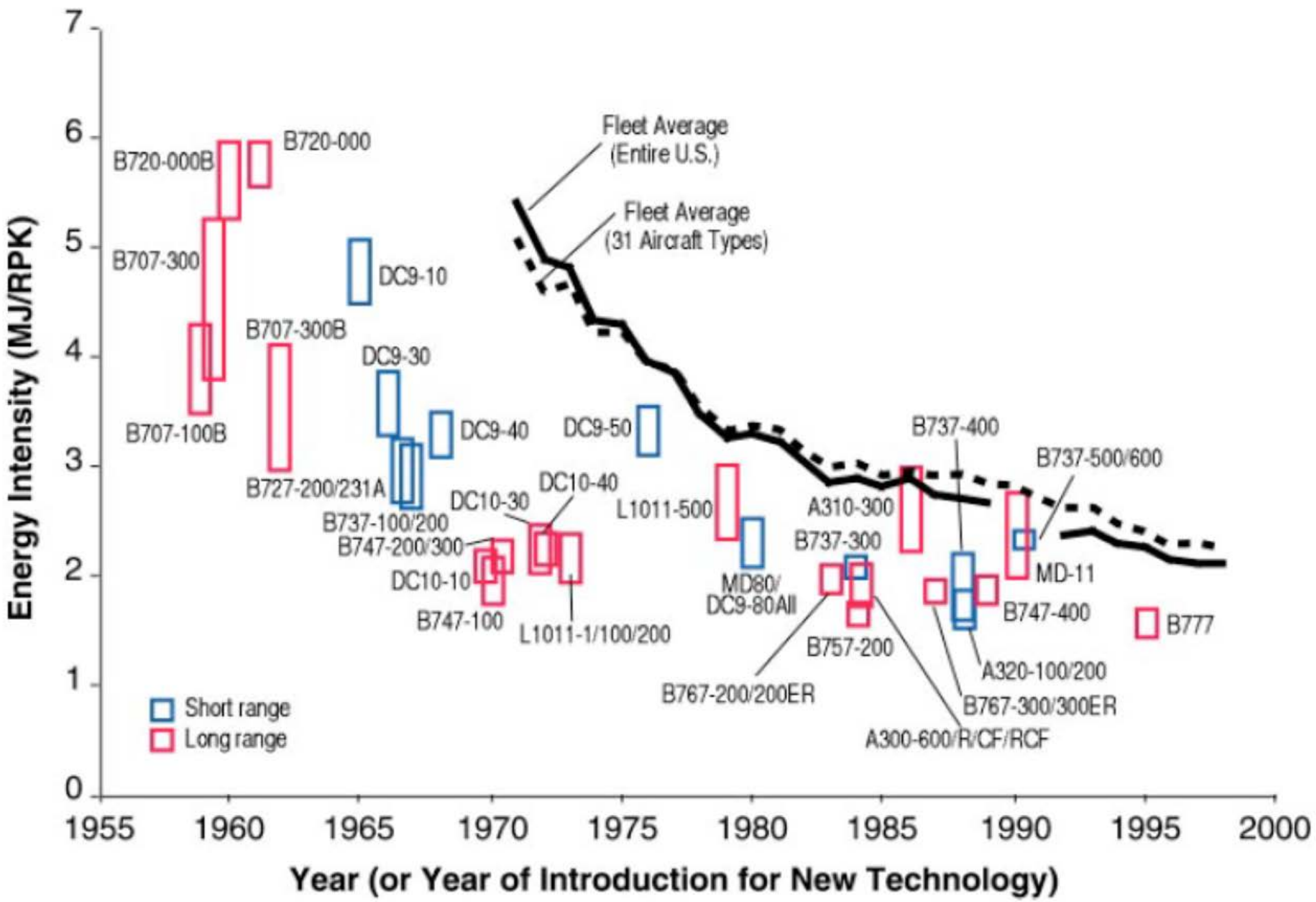
Passenger Transportation



Gucwa M., Schäfer A., 2013. The impact of scale on energy intensity in freight transportation, Transportation Research Part D: Transport and Environment, August.

Schäfer A., Yeh S., A Holistic Perspective on Passenger Travel Energy and Greenhouse Gas-Intensities, under review.

Declining Energy Intensity



Lee J.J., Lukachko S.P., Waitz I.A., Schäfer A., 2001, "Historical and Future Trends in Aircraft Performance, Cost, and Emissions", Annual Review of Energy and the Environment 2001, 26: 167-200.

Marginal Abatement Costs: US Narrowbody Aircraft Fleet

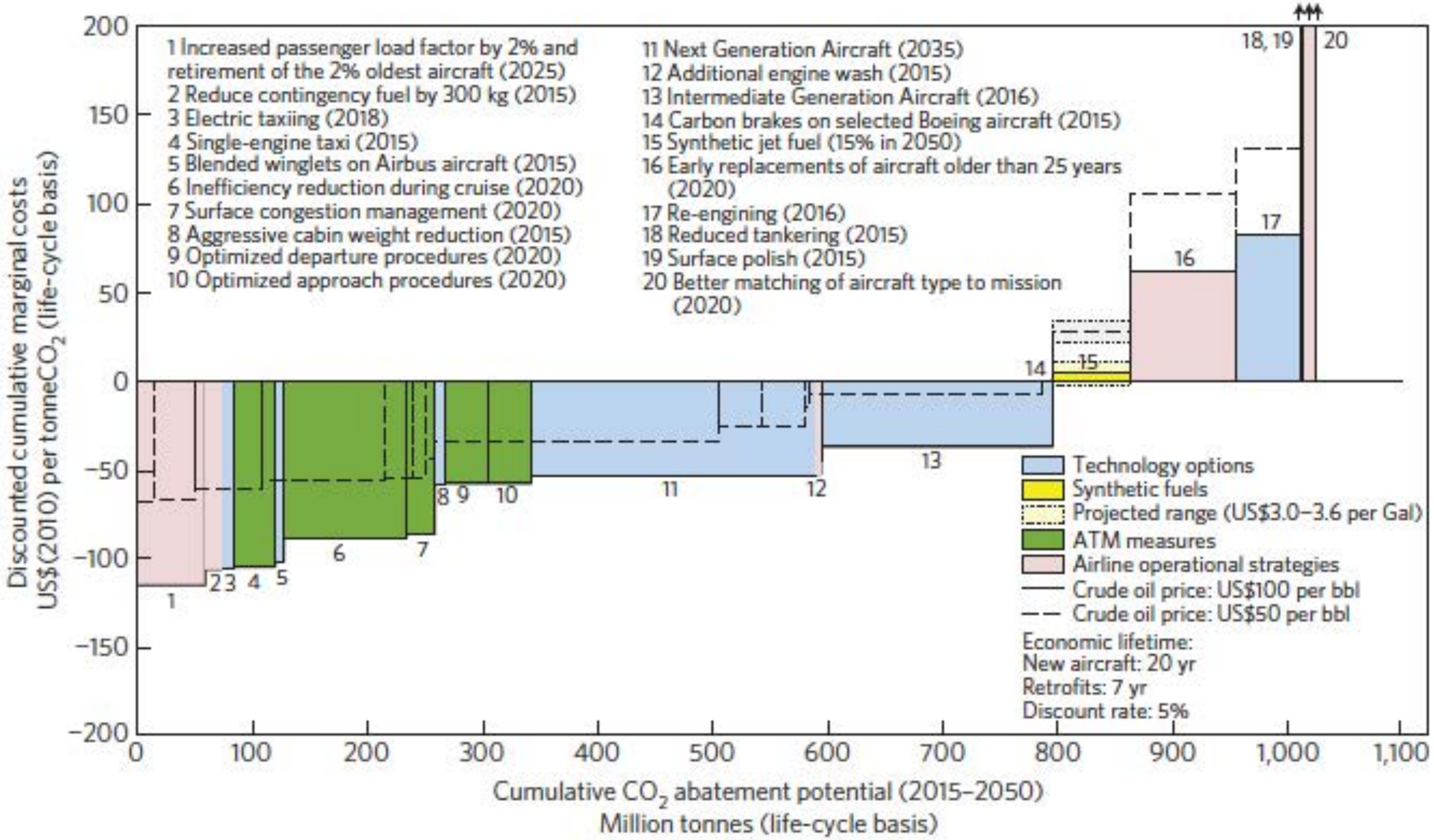
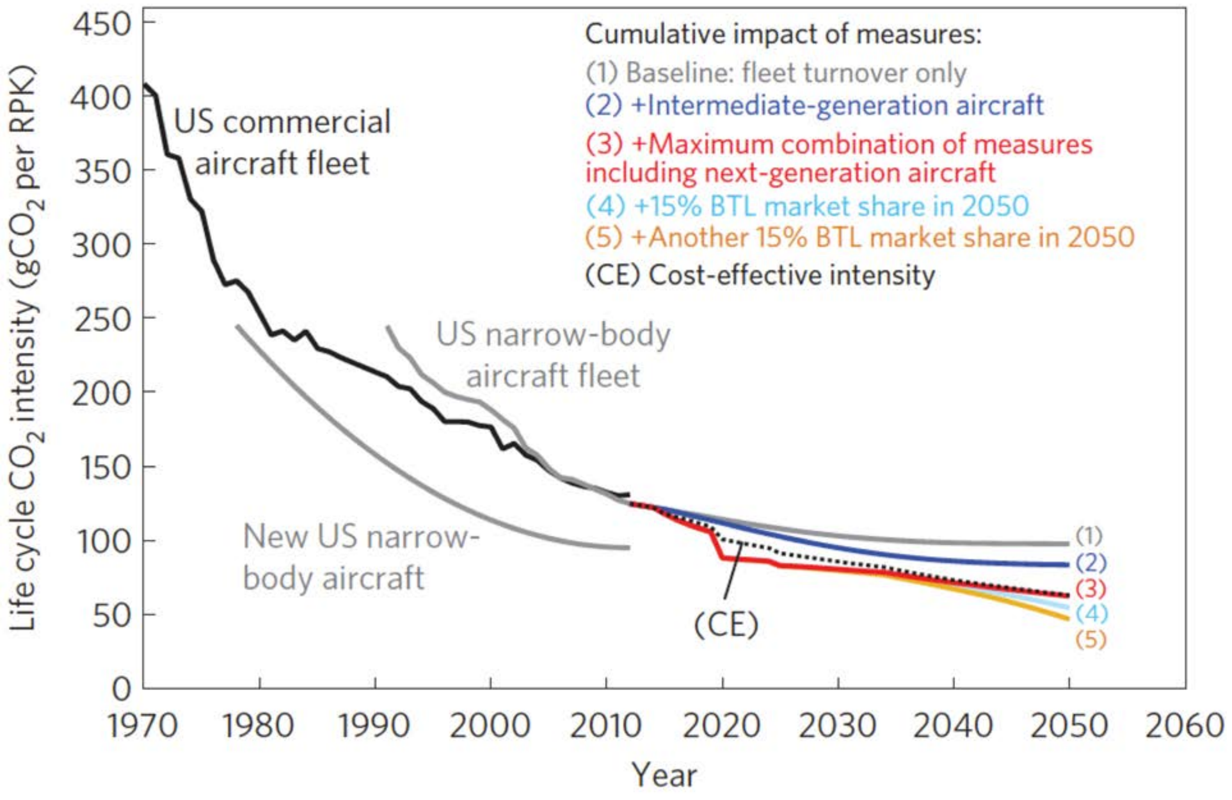
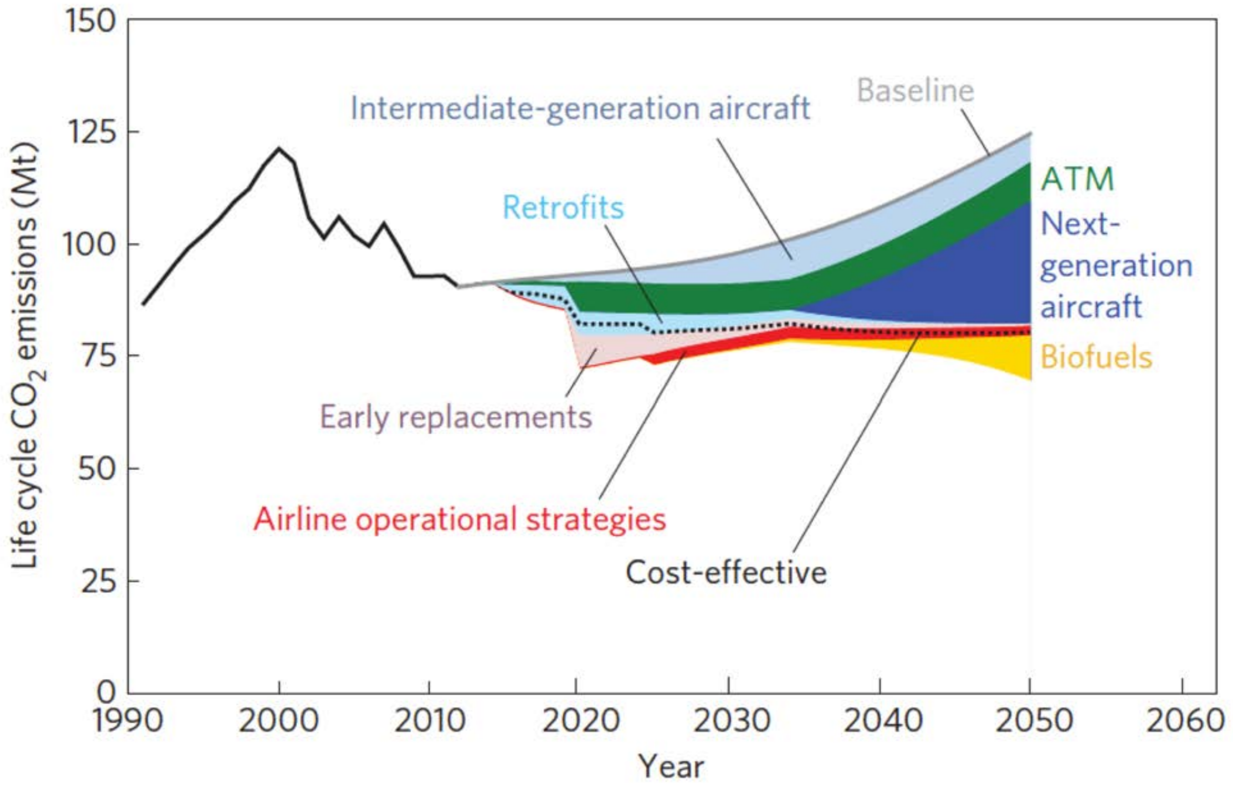


Figure 2 | Discounted marginal abatement costs for cumulative (2012–2050) life-cycle CO_2 emissions from narrow-body aircraft in US domestic passenger service. Mitigation options are ranked in sequence of declining cost-effectiveness. Around one-quarter of the cumulative CO_2 emissions of 4.0 billion tonnes that are based on fleet turnover and growth (1.5% per year) could be mitigated if employing all options. At least 75% of that potential could be reduced at zero marginal costs.

Schafer, Evans, Reynolds, Dray, 2015. Costs of mitigating CO_2 Emissions from Passenger Aircraft, Nature Climate Change, December 2015.

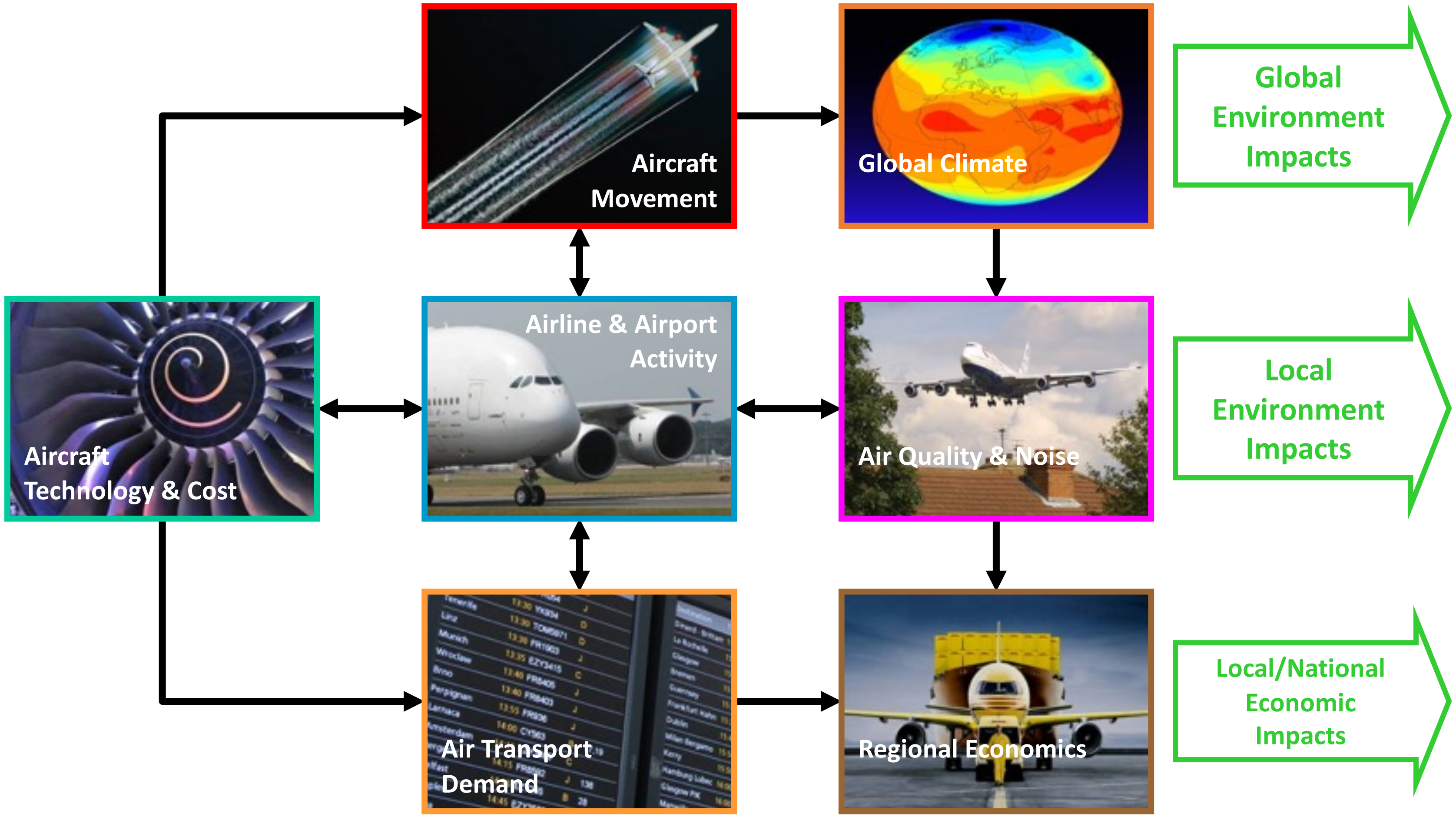
First-order Fleet Impact



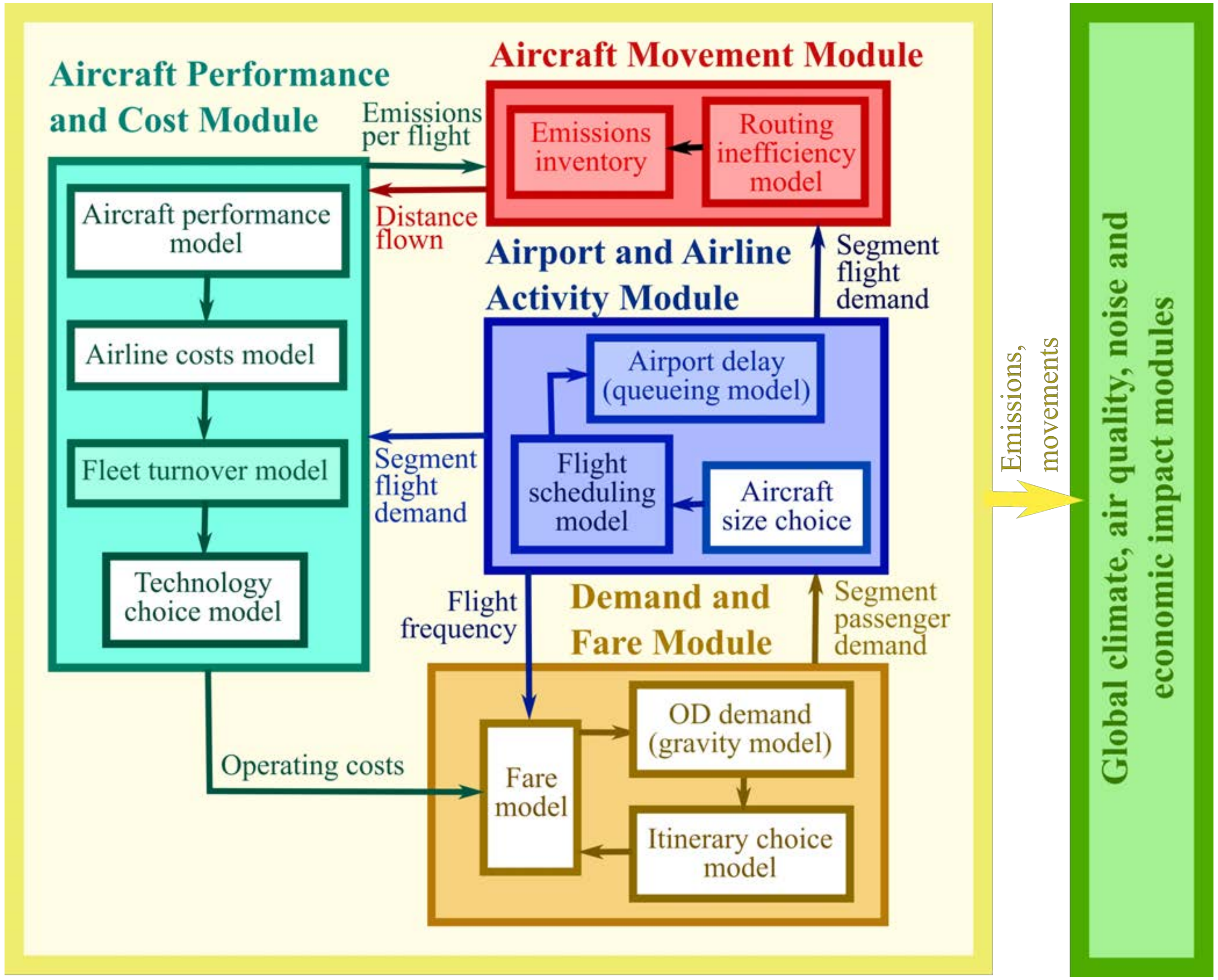


Schäfer A.W., Evans A.D., Reynolds T.G., Dray L., 2016. Costs of mitigating CO_2 emissions from passenger aircraft, Nature Climate Change 6:412-418.

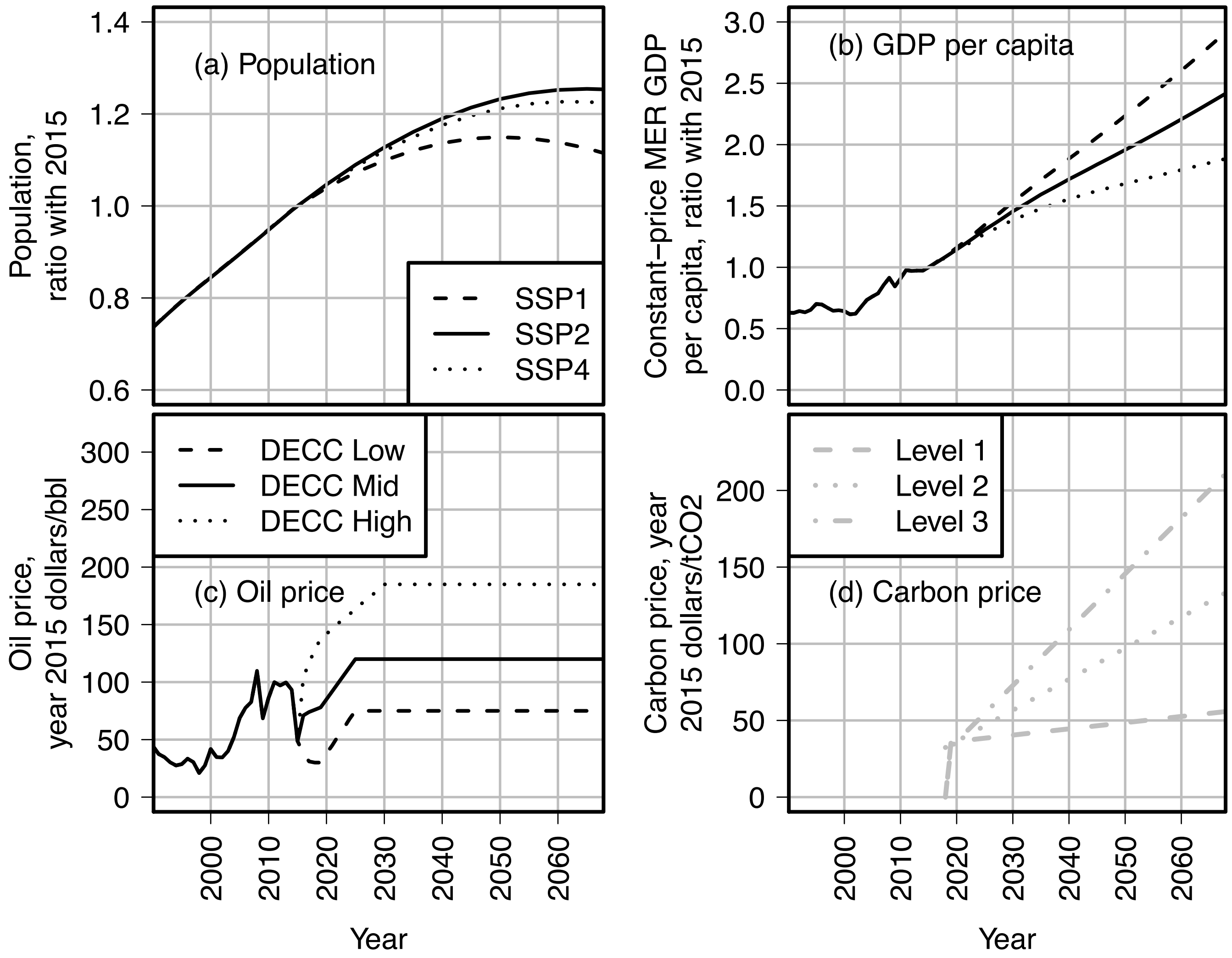
Modelling Aviation Systems



Modelling Aviation Systems

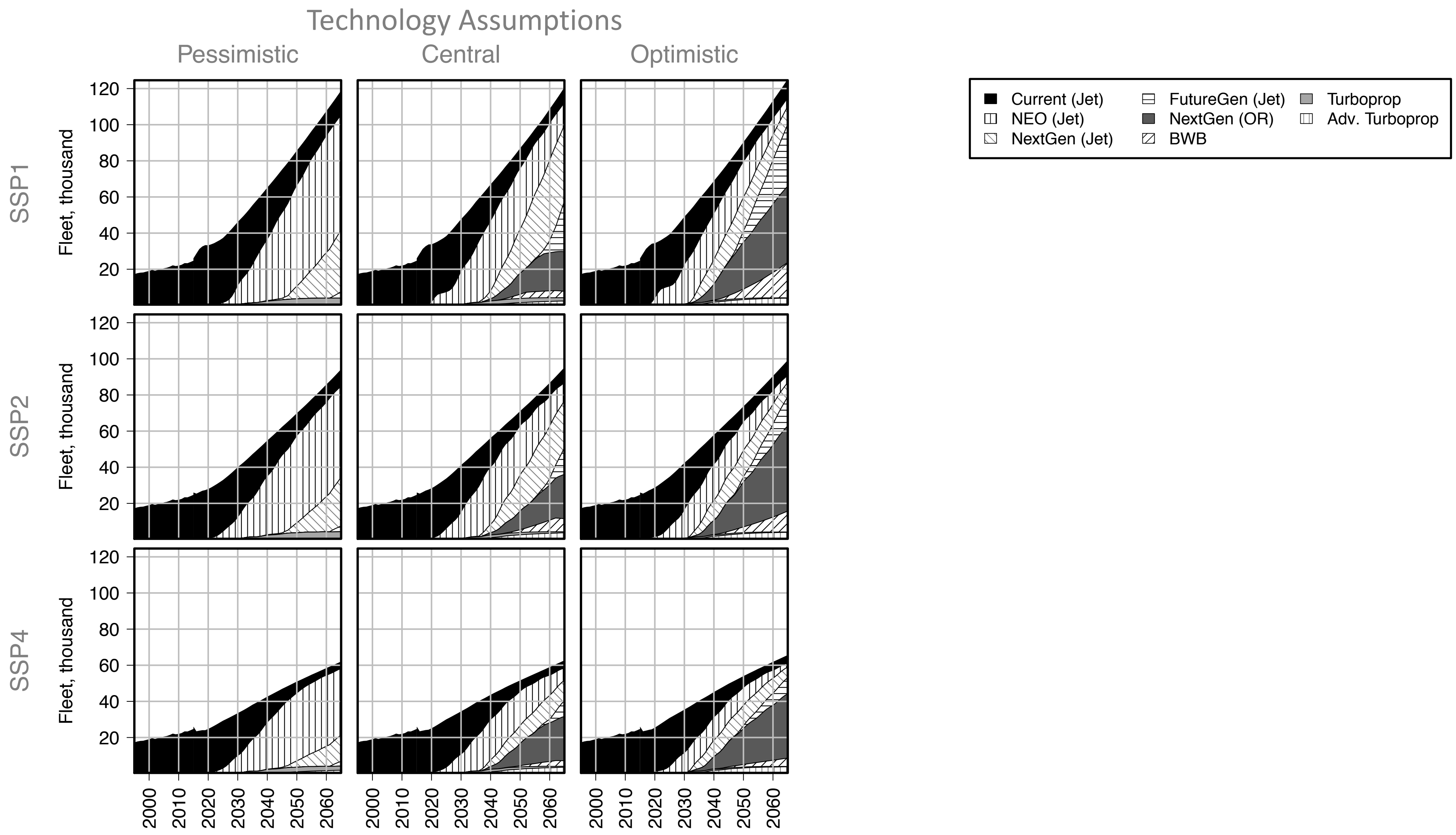


Future Aviation in a Non-Disruptive World: Key Model Inputs



Dray L., Schäfer A.W., Al Zayat K., 2018. "The Global Potential for CO_2 Emissions Reduction from Jet Engine Passenger Aircraft", Transp. Res. Rec., 2672(23), 40-51.§

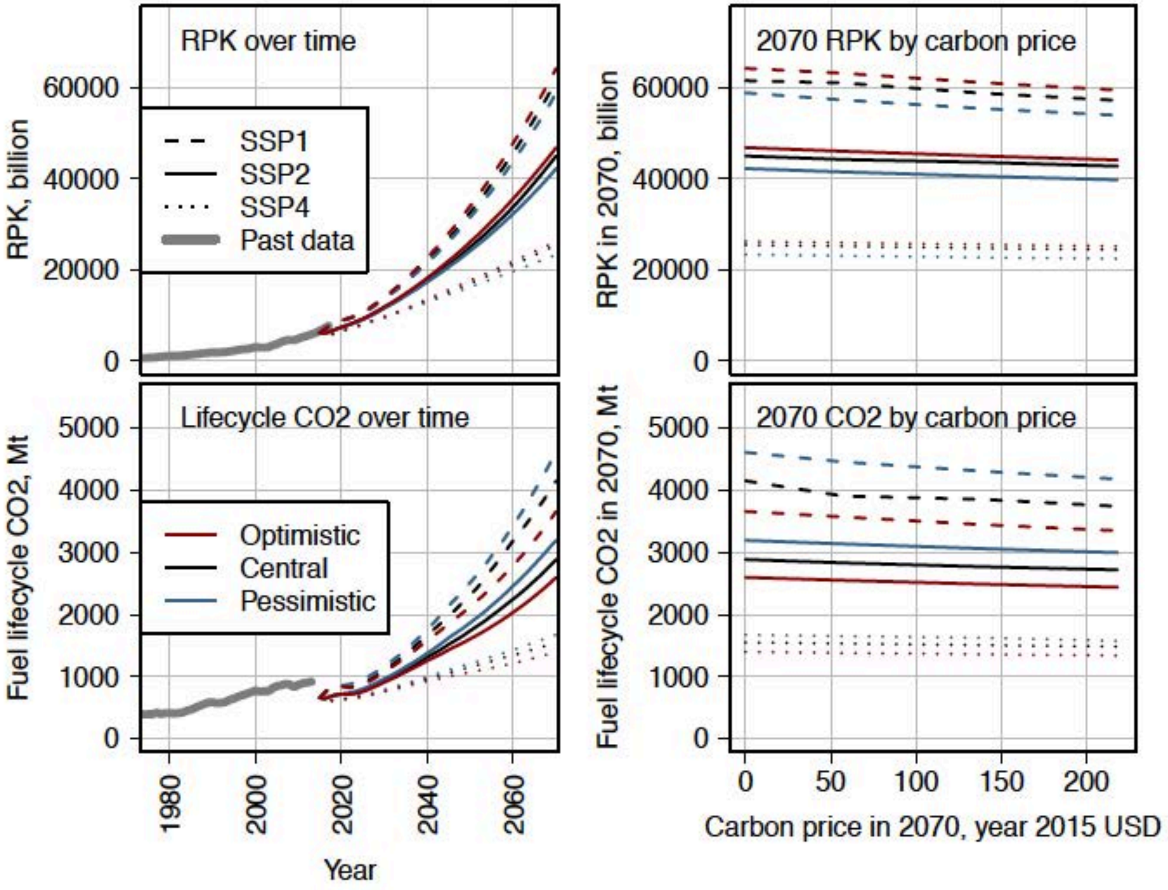
Future Aviation in a Non-Disruptive World: Technology Dynamics



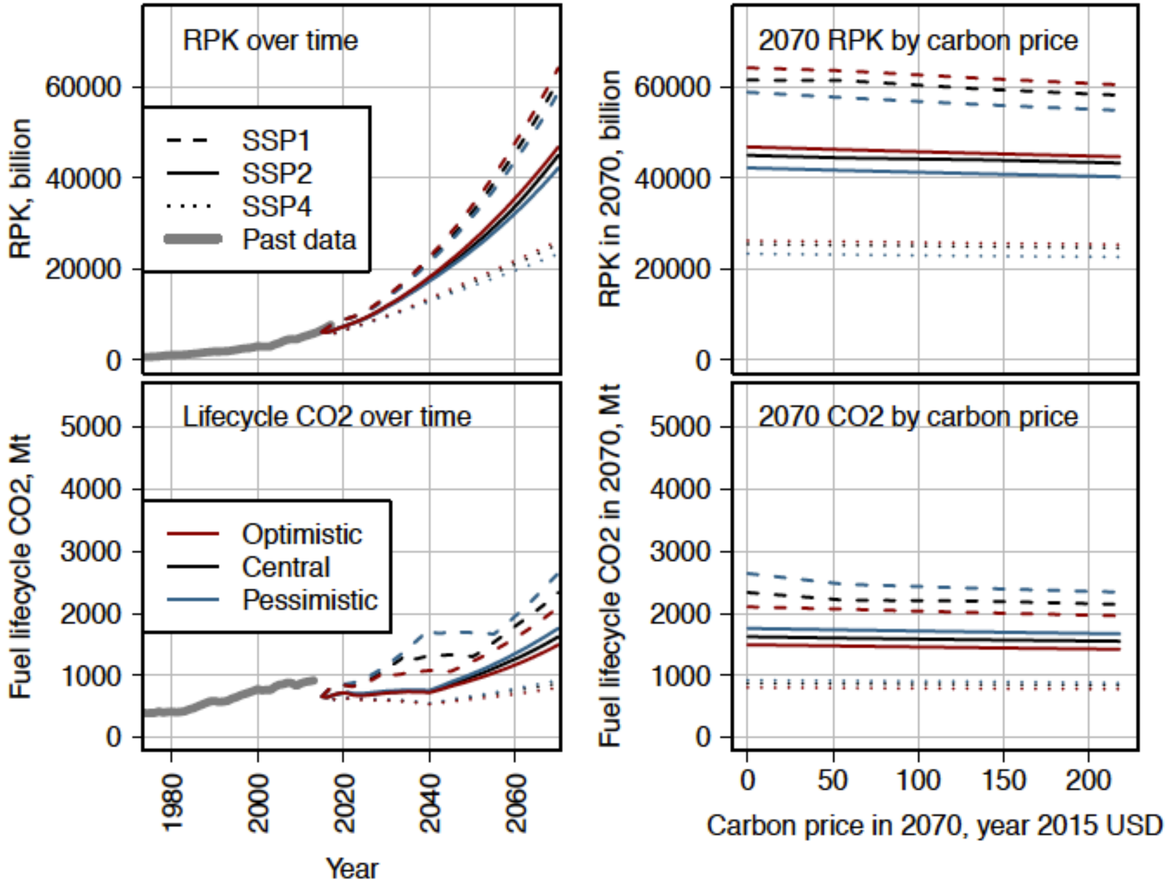
Dray L., Schäfer A.W., Al Zayat K., 2018. “The Global Potential for CO_2 Emissions Reduction from Jet Engine Passenger Aircraft”, Transp. Res. Rec., 2672(23), 40-51.§

Future Aviation in a Non-Disruptive World: Key Model Outputs

Without biomass-to-liquids

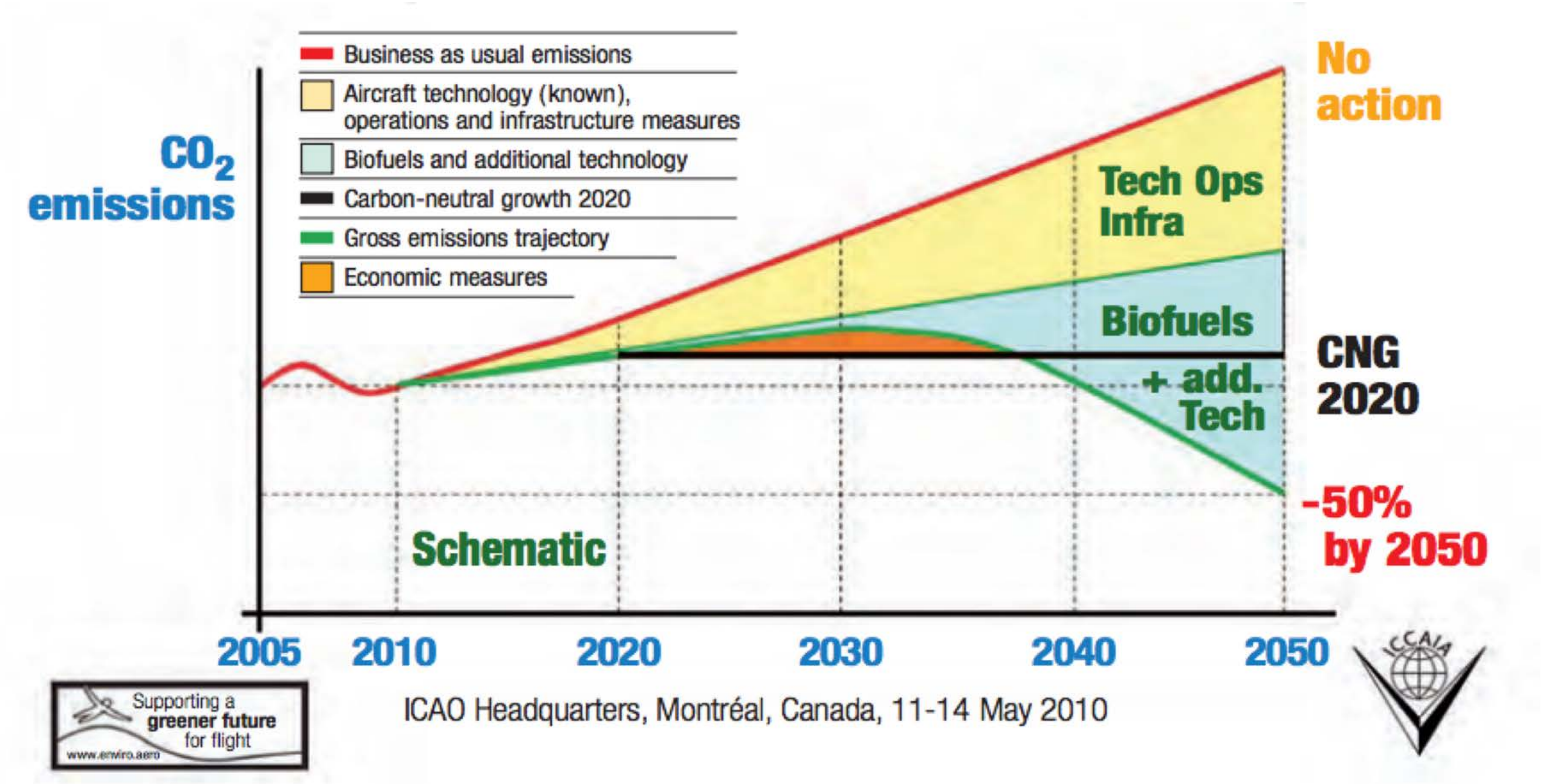


With biomass-to-liquids



Dray L., Schäfer A.W., Al Zayat K., 2018. “The Global Potential for CO_2 Emissions Reduction from Jet Engine Passenger Aircraft”, Transp. Res. Rec., 2672(23), 40-51.

Industry Emissions Reduction Roadmap



Fonta P., Pushing the Technology Envelope, ICAO Environmental Report 2010.

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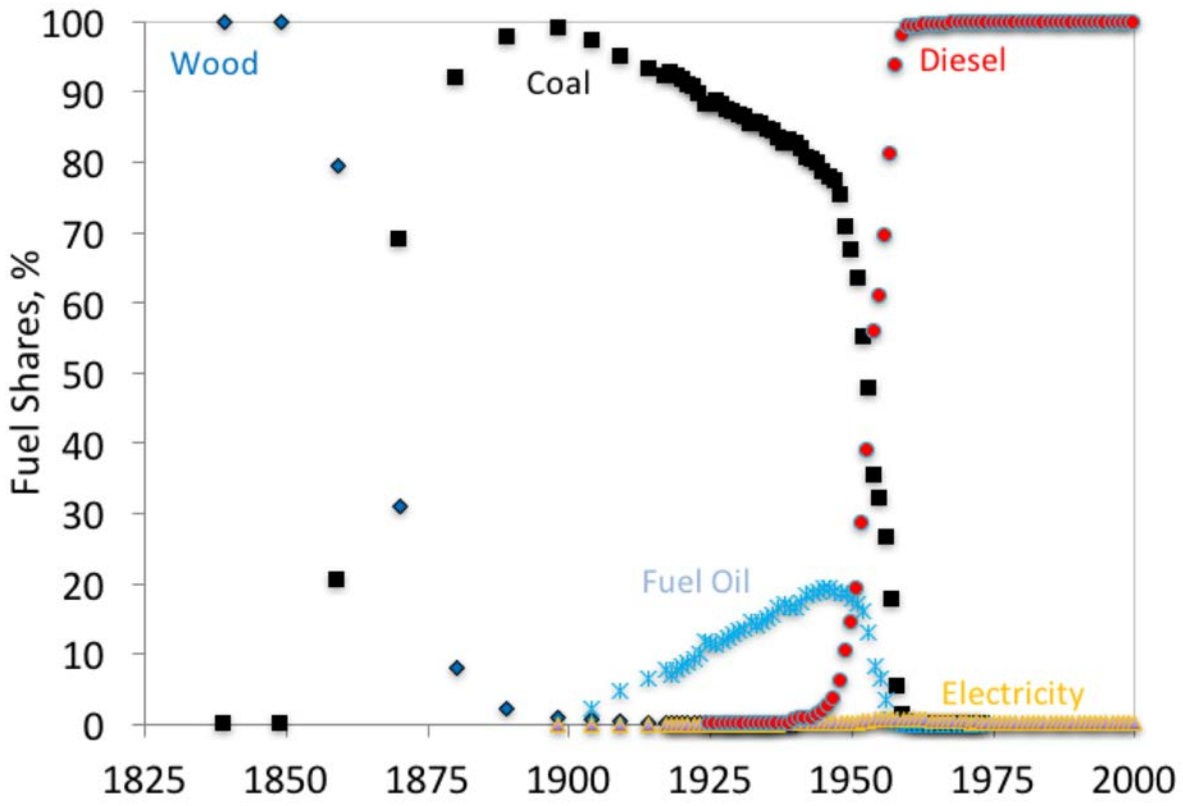
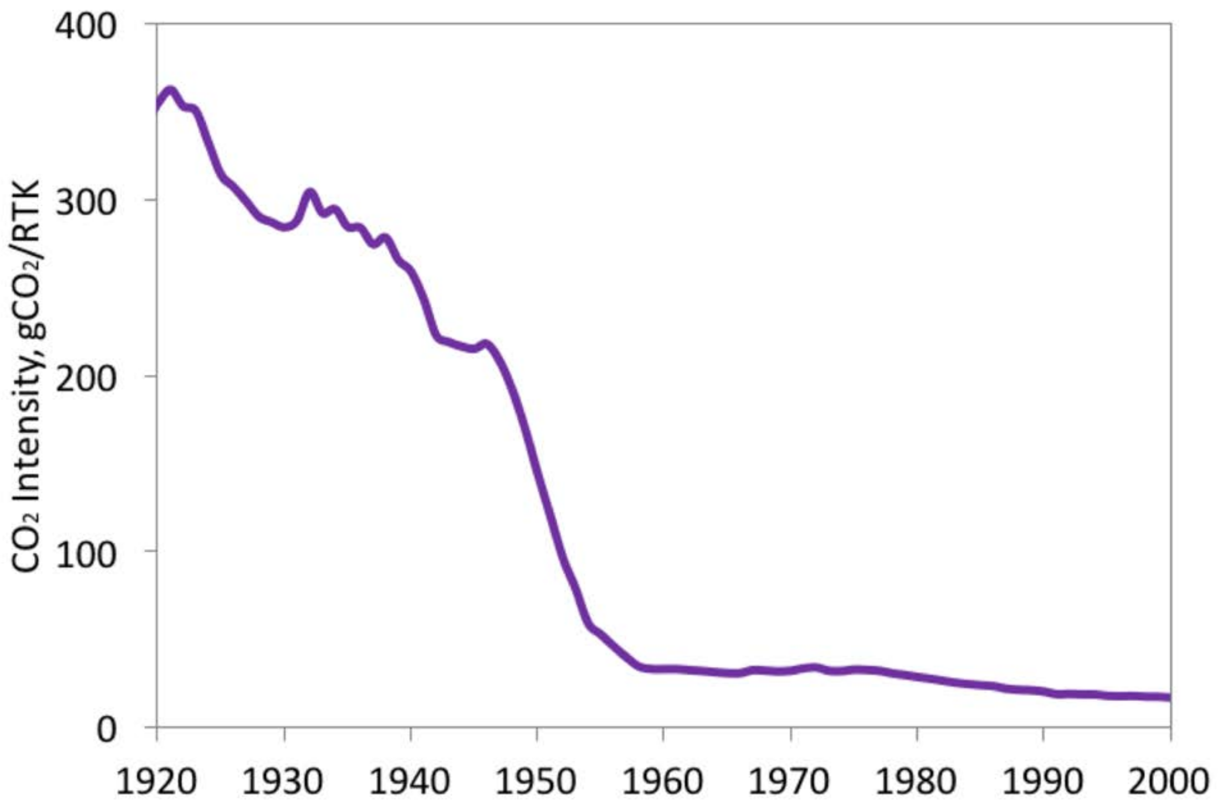
Disruptive Technology Change in Rail Transportation

Fuel Shares: Yard, Passenger, and Freight Sector

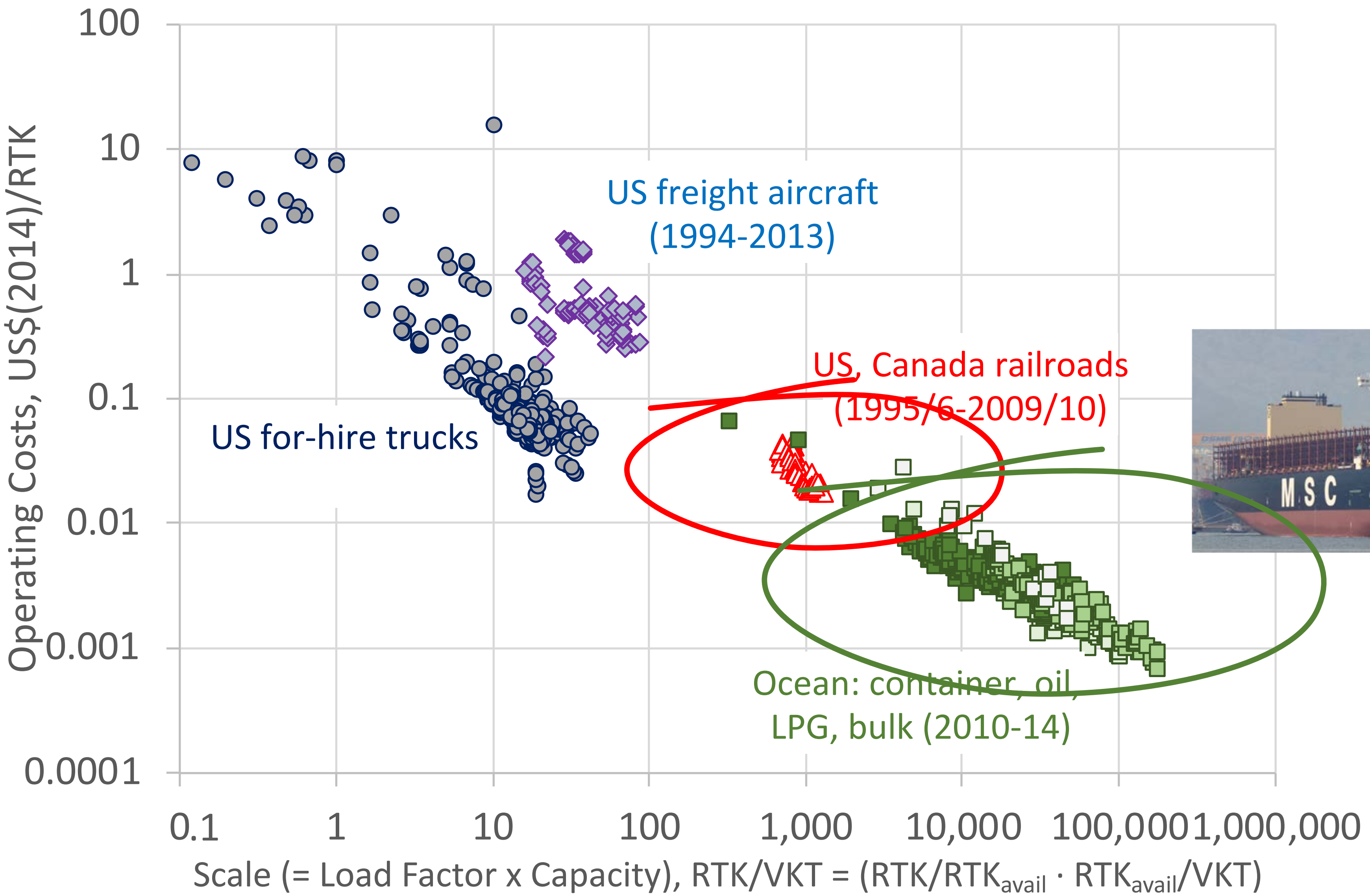


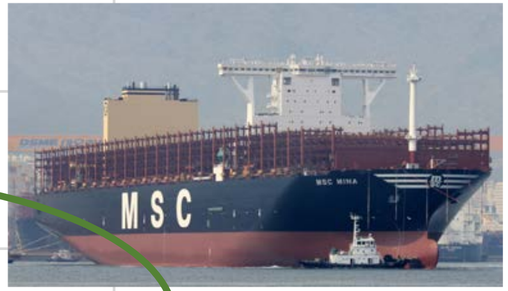
CO_2 Intensity: Freight Railroads



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

Force of Change: Economies of Scale

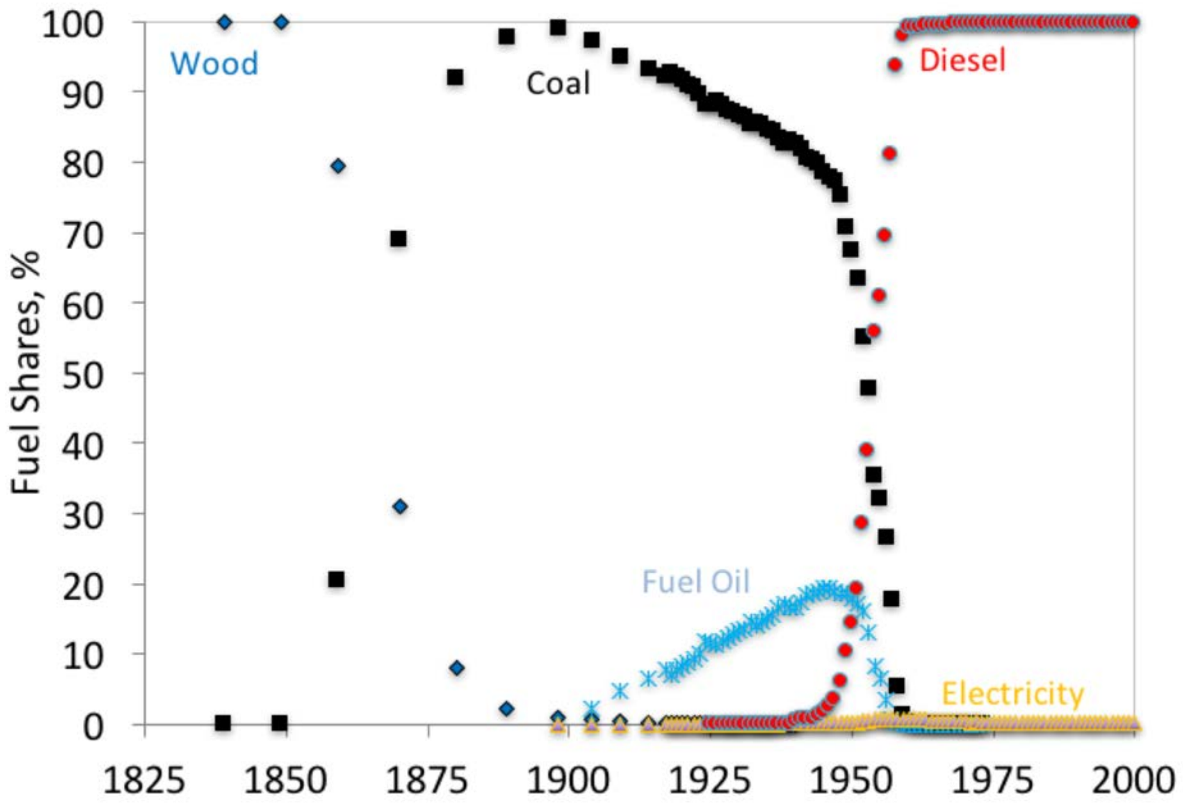




Krammer P., 2017. Simulating the Implications of Emissions Trading Schemes for International Transportation", PhD Thesis. UCL Energy Institute, UCL.

Disruptive Technology Change in Rail Transportation

Fuel Shares: Yard, Passenger, and Freight Sector



Winners

GE

EMD

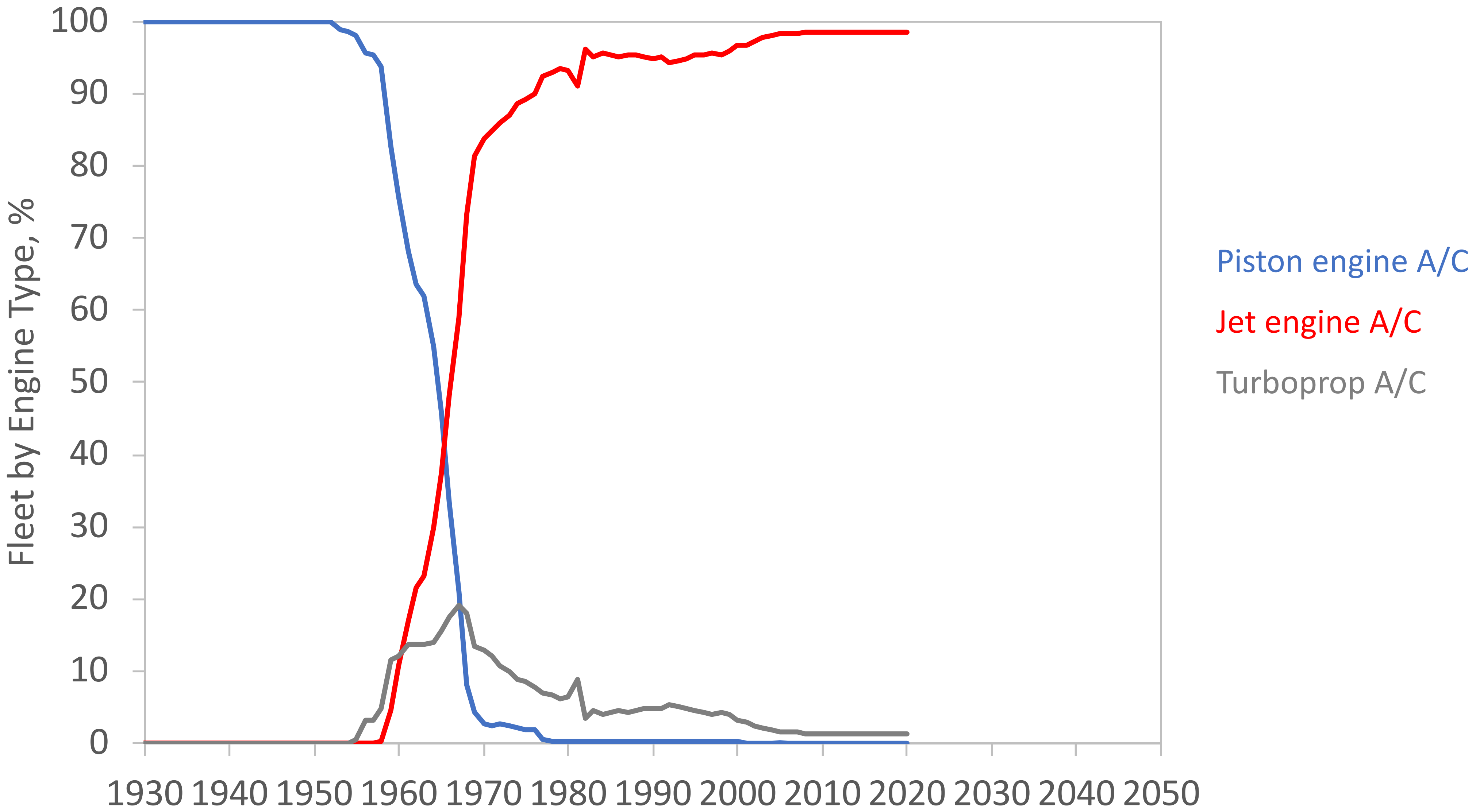
Losers

THE BALDWIN GROUP

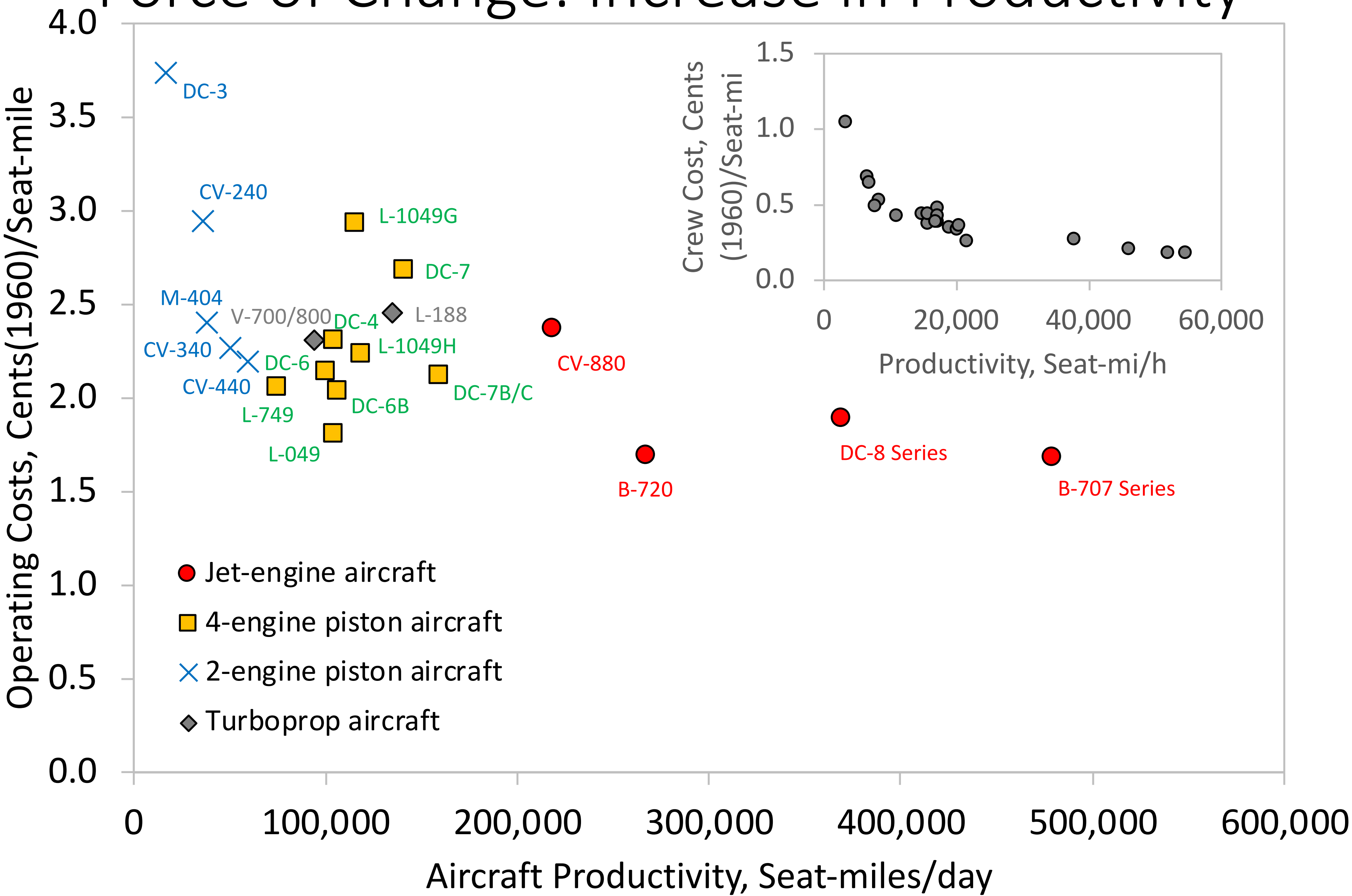
Alco

LIMA LOCOMOTIVE WORKS INCORPORATED

Disruptive Technology Change in Air Transportation



Force of Change: Increase in Productivity



Force of Change: Increasing Environmental & Societal Pressure?

#stayontheground: Swedes turn to trains amid climate 'flight shame'

Swedish rail operator says journeys are up 8% this year due to environmental concerns

Dutch airline KLM calls for people to fly less

The Netherlands' national airline urges people to 'fly responsibly' and to invest in its carbon-offsetting scheme

Environment

Heathrow says it is worried climate change will cause problems to third runway

Controversial expansion plans come amid stark new warnings the UK is failing to hit emissions goals

Harry Cockburn | 1 day ago | Like Click to follow The Independent

Extinction Rebellion stages youth protest at Heathrow airport

Activists all born after 1990 gather at key roundabout to highlight dangers of climate change

Extinction Rebellion and Attenborough put climate in spotlight

Firms ignoring climate crisis will go bankrupt, says Mark Carney

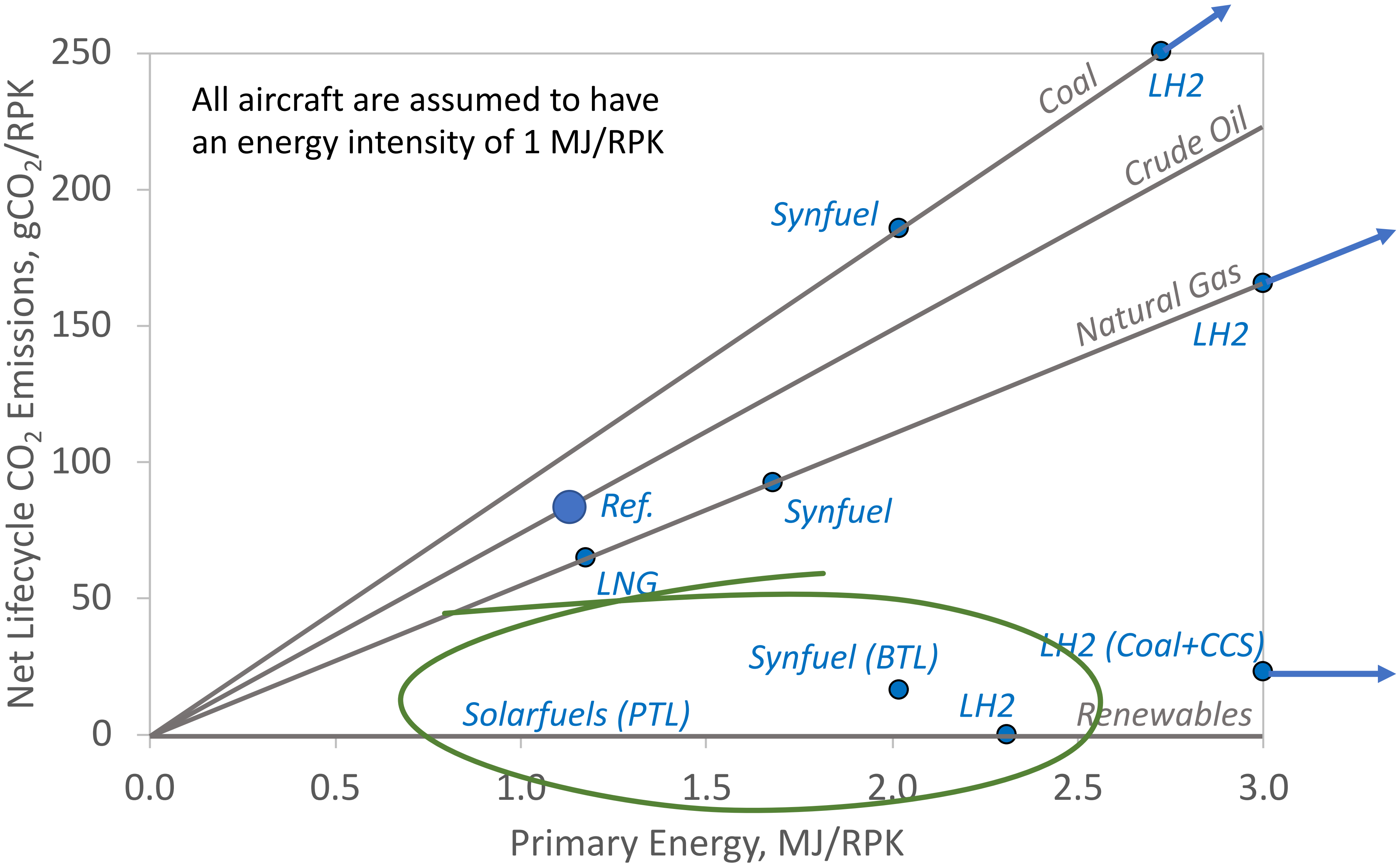
Bank of England governor warns of financial collapse linked to climate emergency

▲ Mark Carney, the Bank of England governor, has led efforts to address the dangers global heating poses to the financial sector. Photograph: Leon Neal/Getty Images

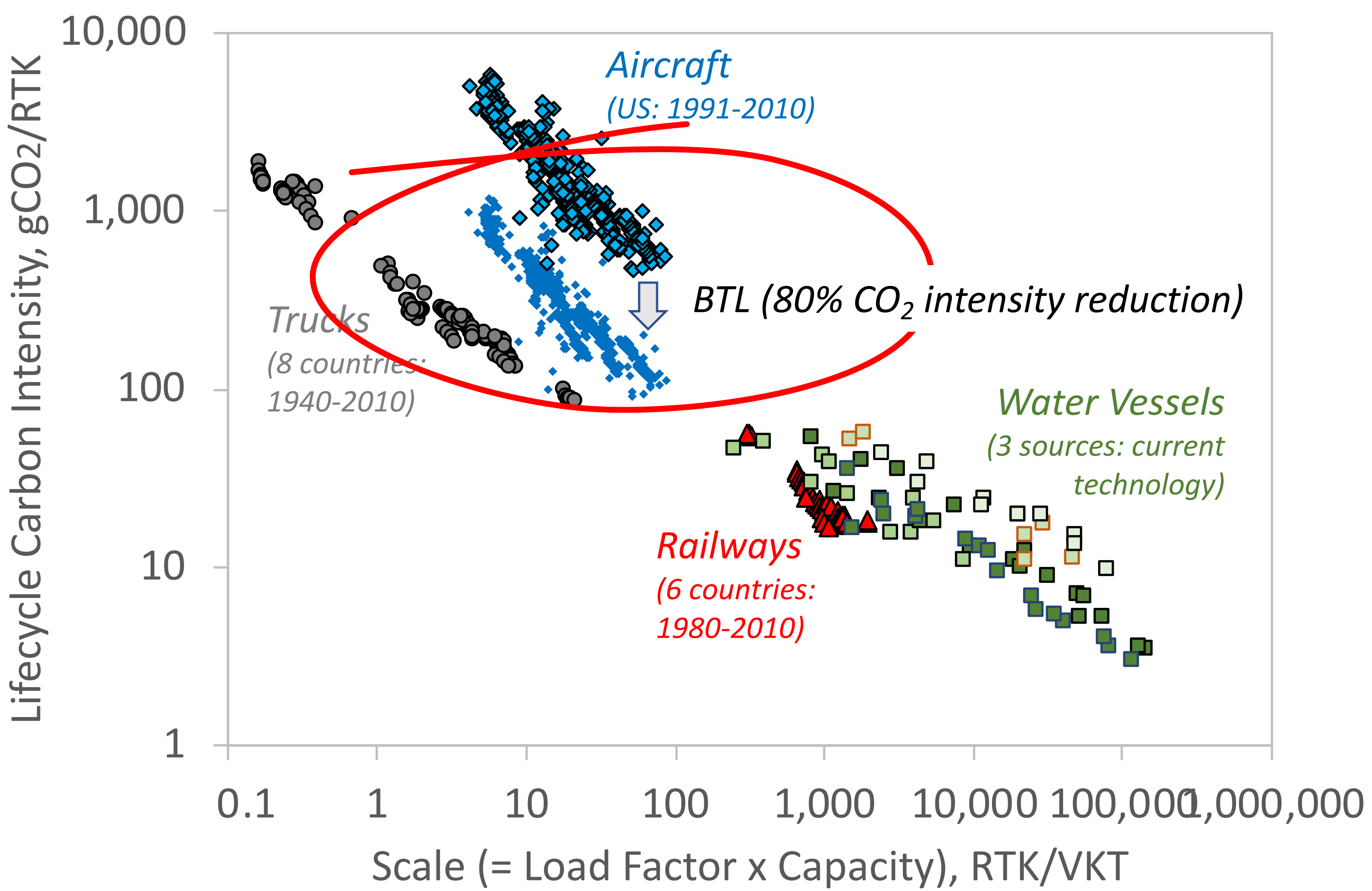
Alternative Aviation Fuels

- **LH2**: 120 MJ/kg but 8.5 MJ/L, capital-intensive infrastructure required from well-to-wake, potentially zero-carbon but increase H_2O emissions
- **LNG**: 50 MJ/kg vs. 23.4 MJ/L, capital-intensive infrastructure required from well-to-wake, little to no benefit over jet fuel on lifecycle basis
- **Drop-in synthetic fuels** (from biomass, H_2 and CO_2, etc.): 42.8 MJ/kg vs. 34.7 MJ/L, upstream infrastructure change, potentially zero-carbon
- **Electricity**: currently 200 Wh/kg (0.7 MJ/kg) but at least 4X required, capital-intensive infrastructure required from well-to-wake, potentially zero-carbon and no non-CO_2 warming

Alternative Aviation Fuels



Impact of Biomass-based Synthetic Fuels on CO_2 Intensity

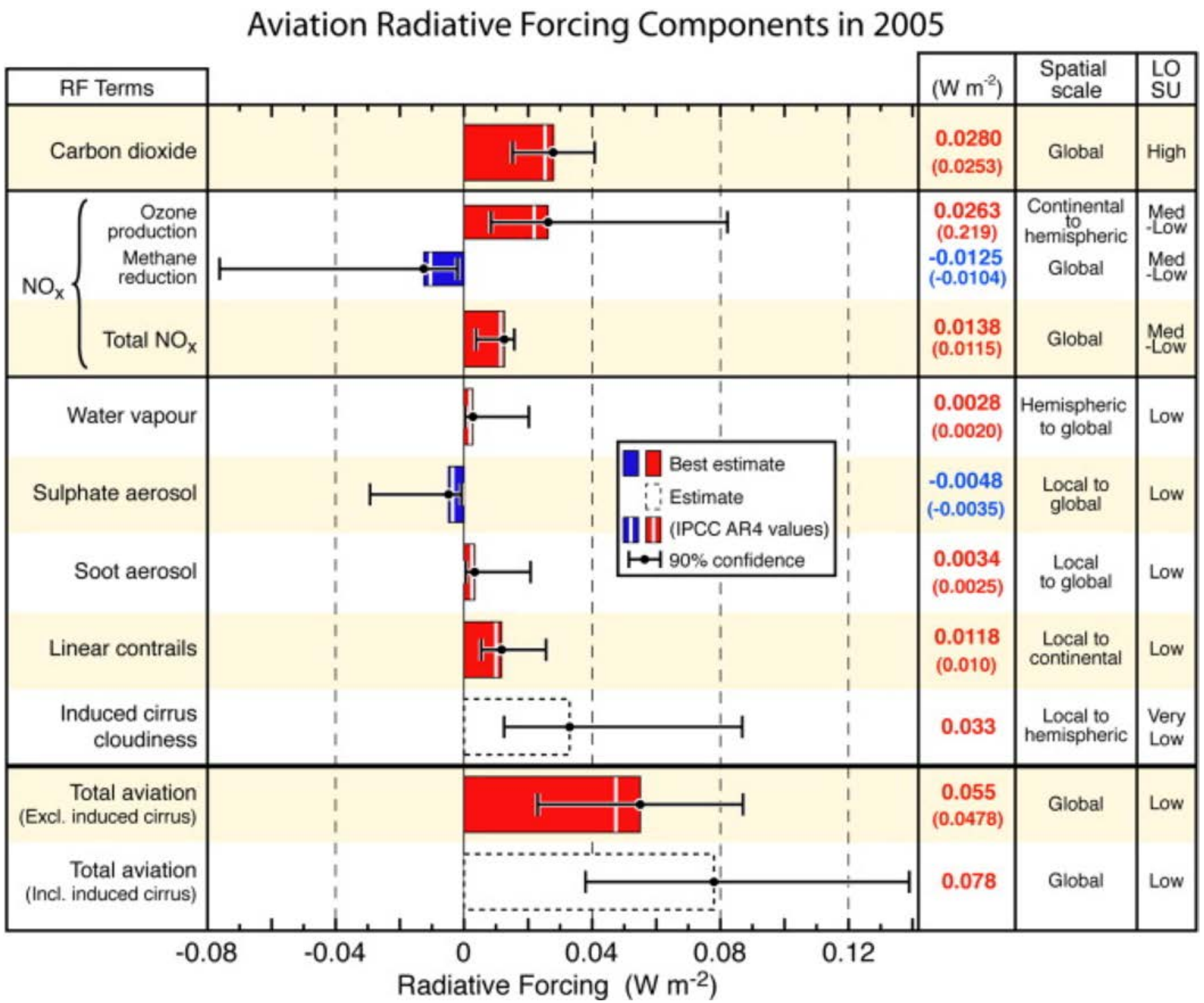


Gucwa M., Schäfer A., 2013. The impact of scale on energy intensity in freight transportation, Transportation Research Part D: Transport and Environment, August.

Removing CO_2 from the Air

- In the absence of disruptive technology, sector-wide net-zero CO_2 emissions can only be achieved through atmospheric CO_2 removal, e.g., direct air capture (DAC)
- Costs of DAC: \$94-232/t(CO_2) (https://www.sciencemag.org/news/2018/06/cost-plunges-capturing-carbon-dioxide-air)
- Very high costs in 2050: \$150/t(CO_2) x 1.5 bln t(CO_2) = \$225 bln or \$18 per PAX >> \$6.12 net profit today
- Detailed, airline-based modelling required to better understand implications.

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.

Electric Aircraft Architectures (leading to Distributed Propulsion)

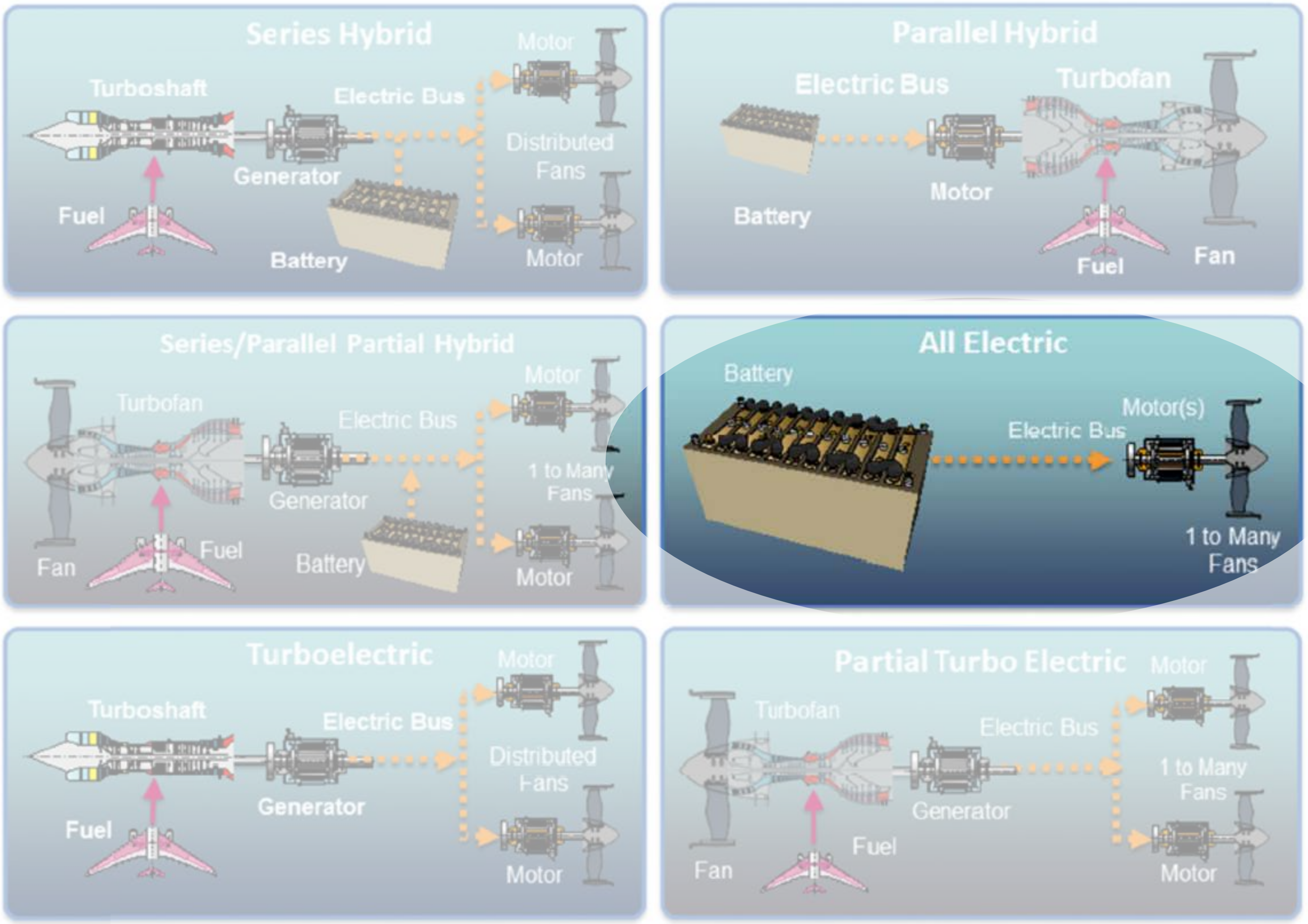


FIGURE 4.1 Electric propulsion architectures. SOURCE: Modified from James L. Felder, NASA Glenn Research Center, "NASA Hybrid Electric Propulsion Systems Structures," presentation to the committee on September 1, 2015.

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

Jet engine aircraft:

$$R = \underbrace{\eta_{total}}_{\frac{\text{Propulsive Power}}{\text{Fuel energy / time}}} \frac{H}{g} \frac{L}{D} \ln\left(\frac{m_{initial}}{m_{final}}\right)$$

All-electric aircraft:

$$R = \underbrace{\eta_{total}}_{\frac{\text{Propulsive Power}}{\text{Battery Power}}} \frac{E}{g} \frac{L}{D} \frac{m_{Battery}}{m_{Aircraft}}$$

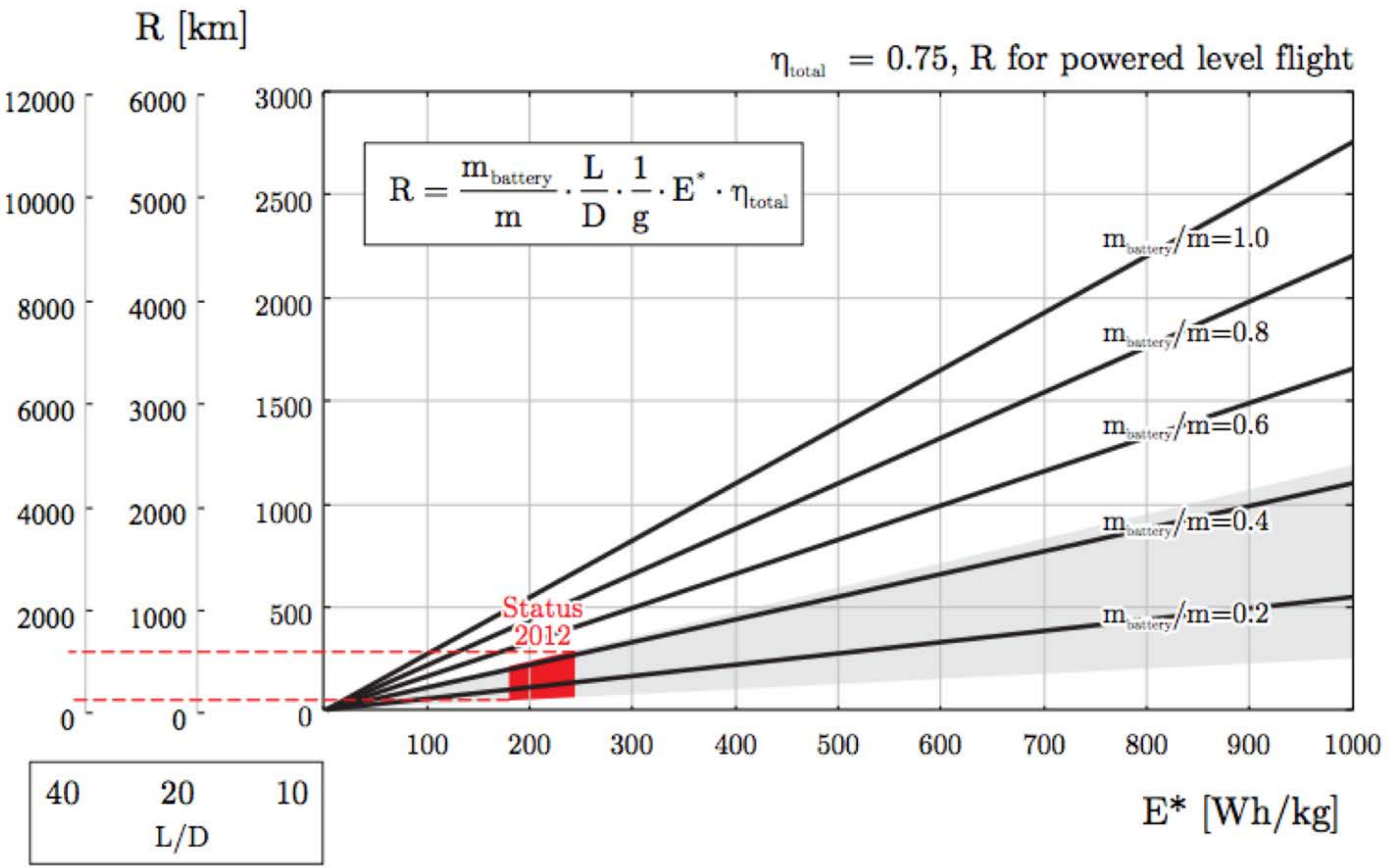
H: Fuel energy content

E: Battery specific energy

L/D: Light-to-drag ratio

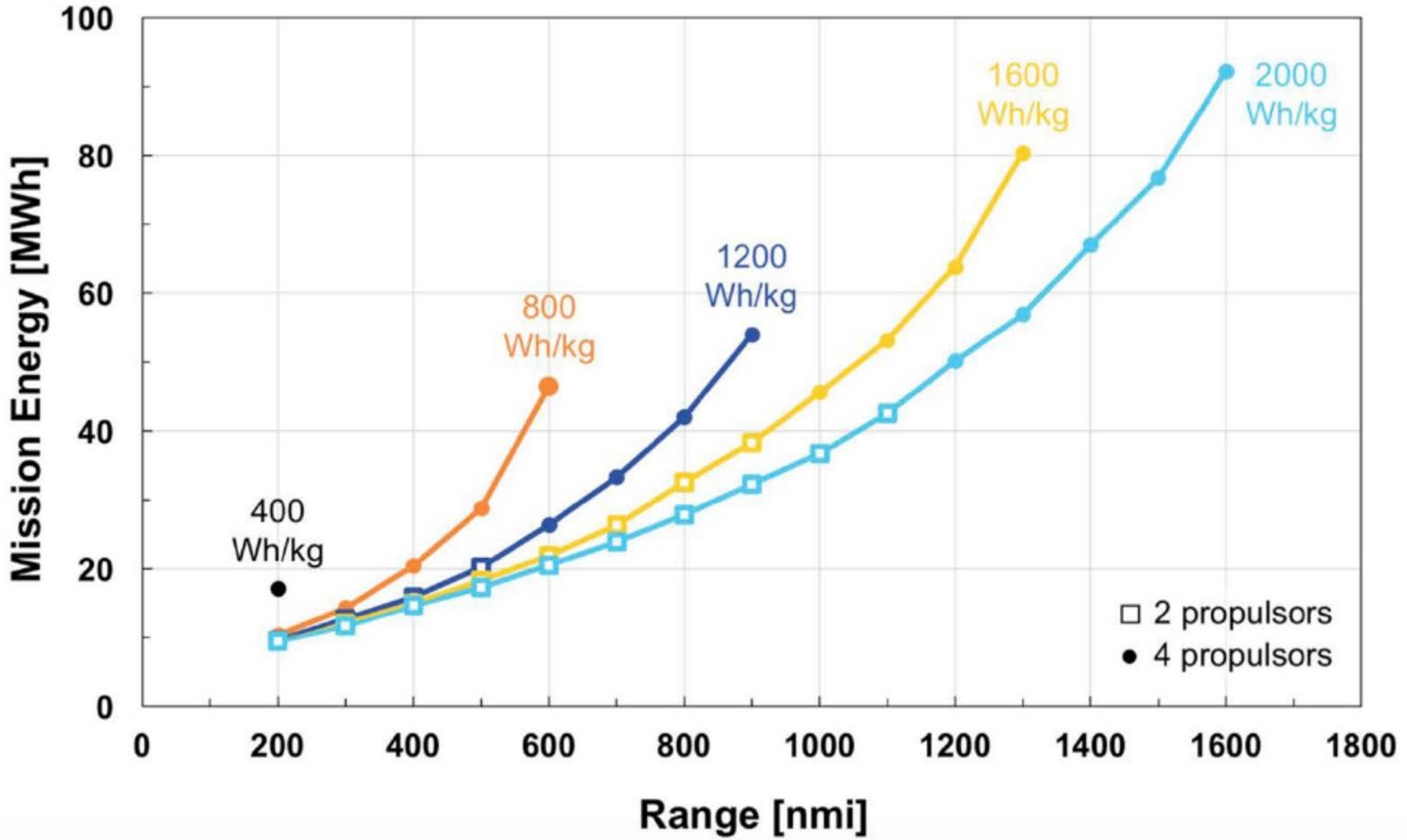
m: Mass

(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.

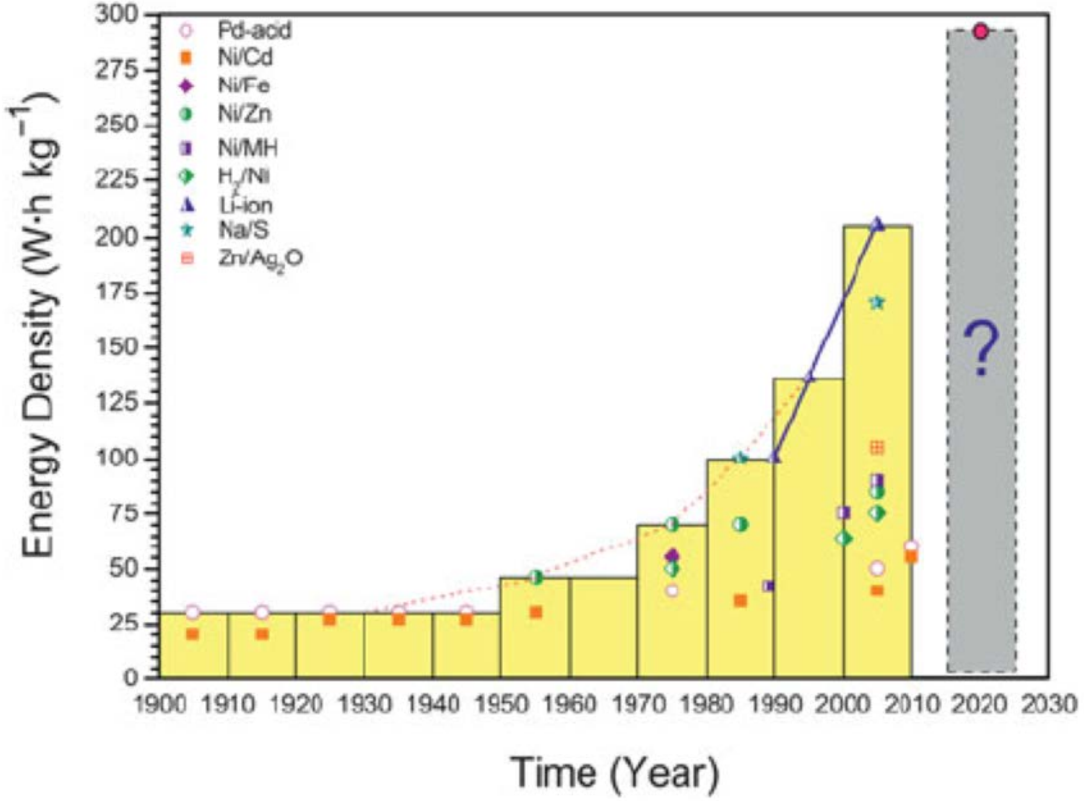
Modelling All-Electric Aircraft Performance

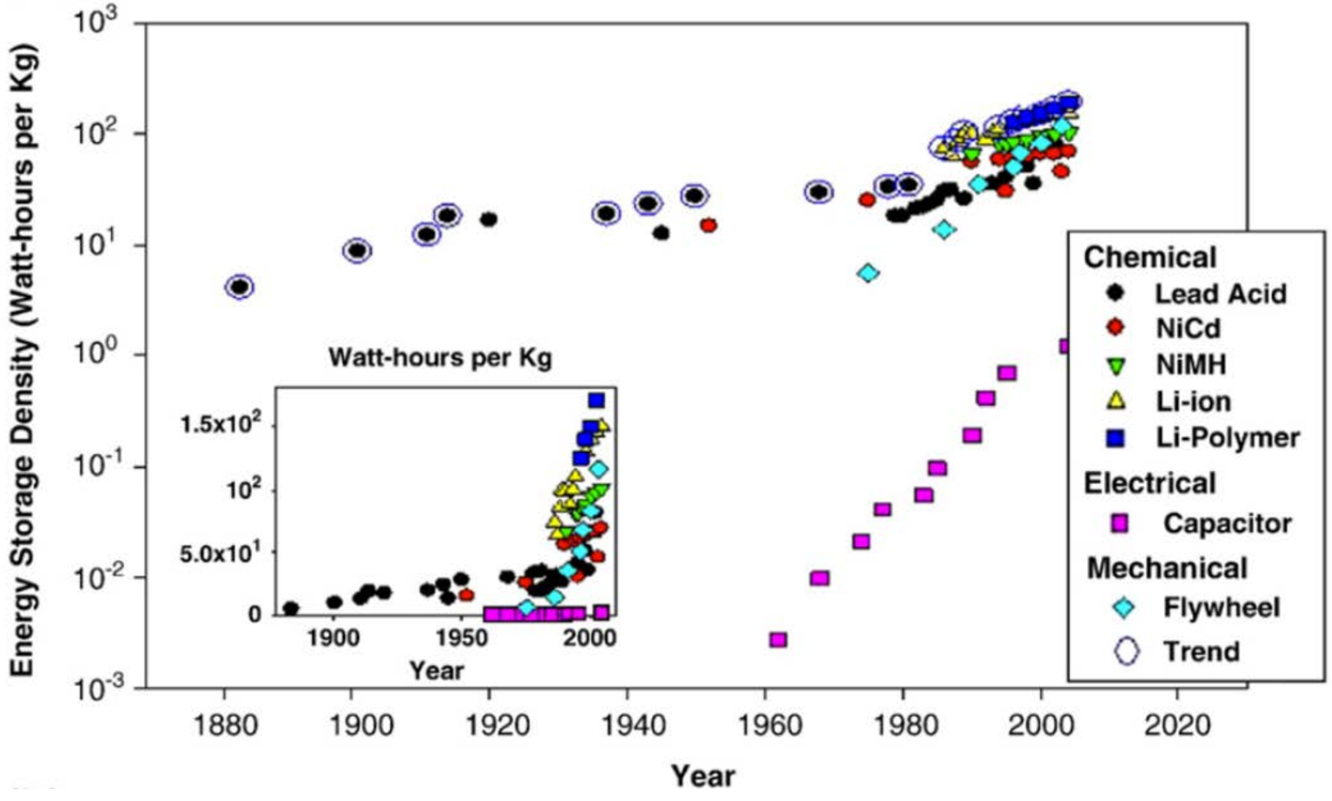


Gnadt A.R., Speth R.L., Sabnis J.S., Barrett S.R.H., 2019. Technical and environmental assessment of all-electric 180-passenger commercial aircraft, Progress in Aerospace Sciences, 105:1-30.

Battery Specific Energy has increased by ~ 3%/yr

(A doubling every 20-25 years)

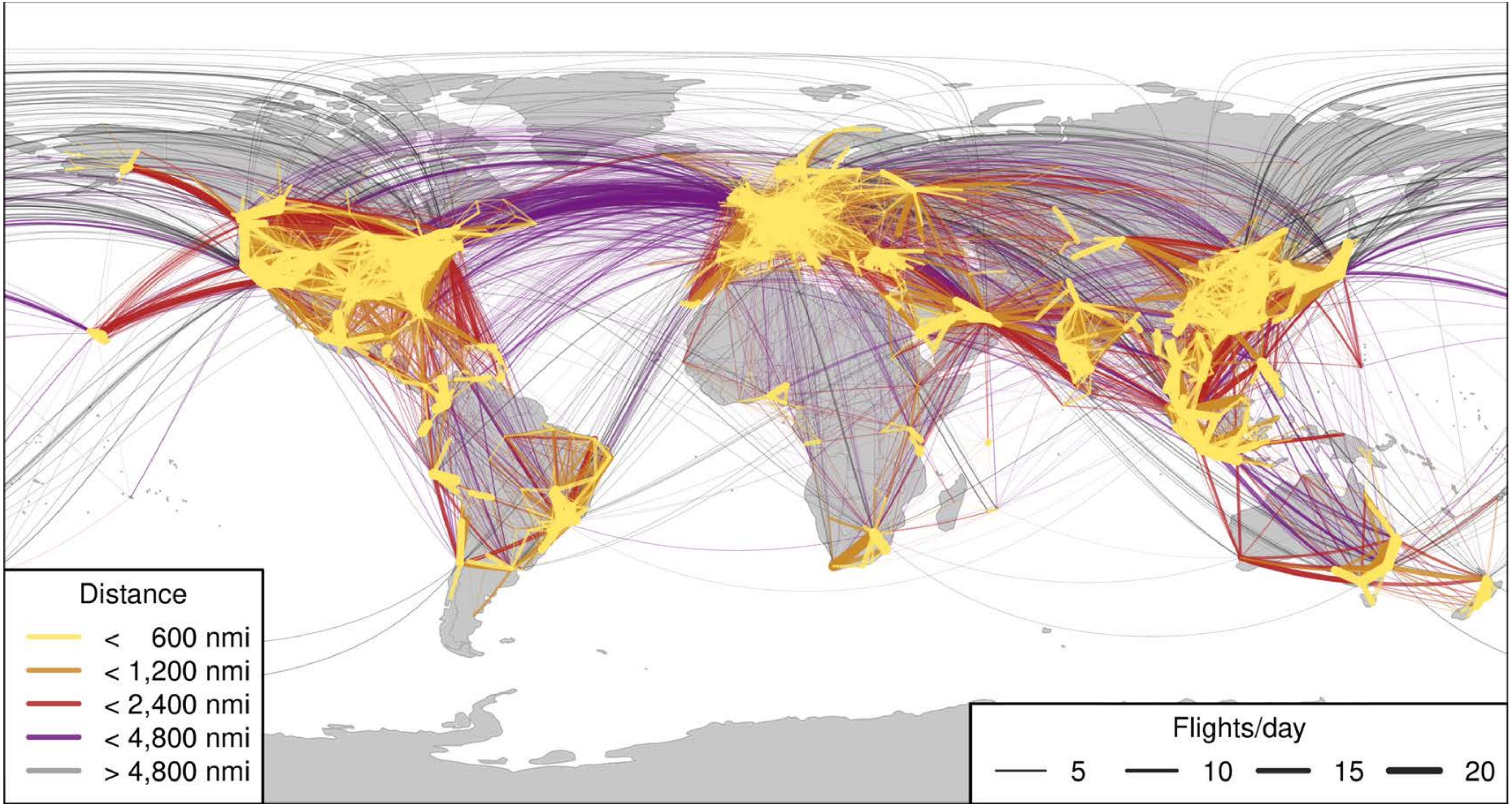




Crabtree G., Kócs E., Trahey L., 2015. The energy-storage frontier: Lithium-ion batteries and beyond. MRS Bulletin 40, 1067-1076.

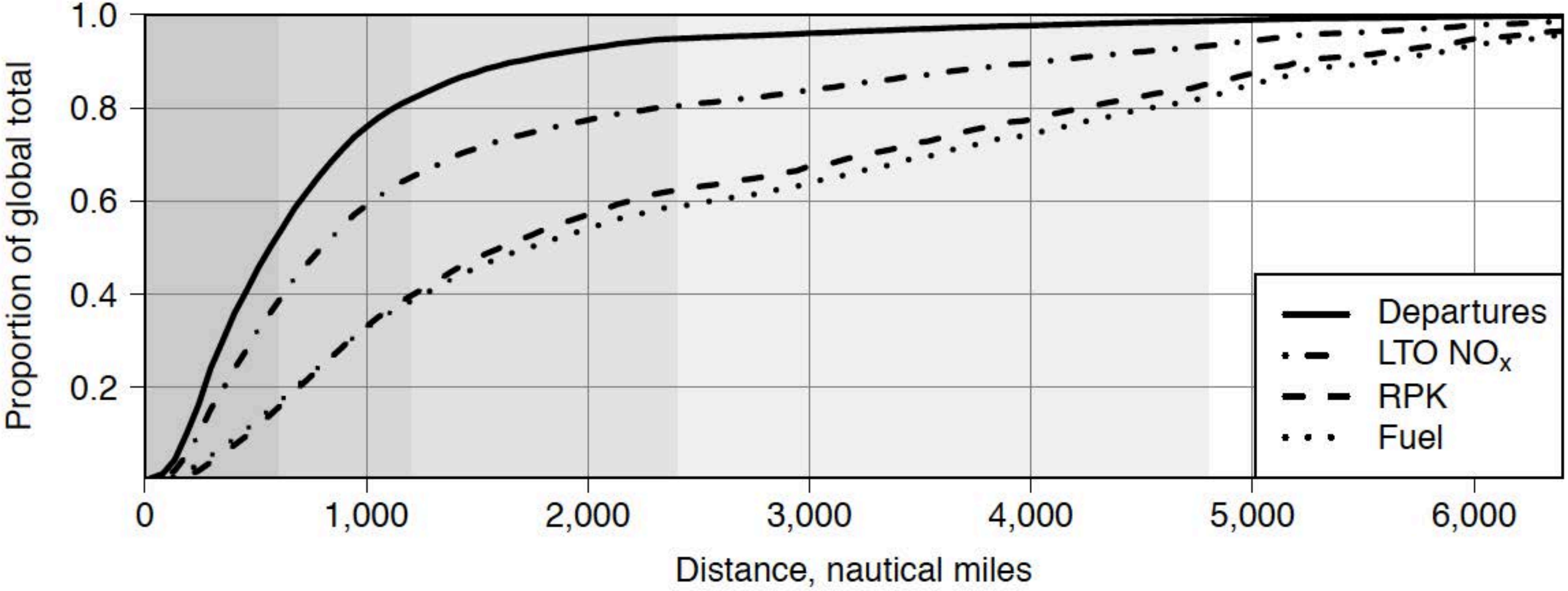
Koh H., Magee C.L., 2008. A functional approach for studying technological progress: Extension to energy technology, Technological Forecasting and Social Change 75(6):735-758

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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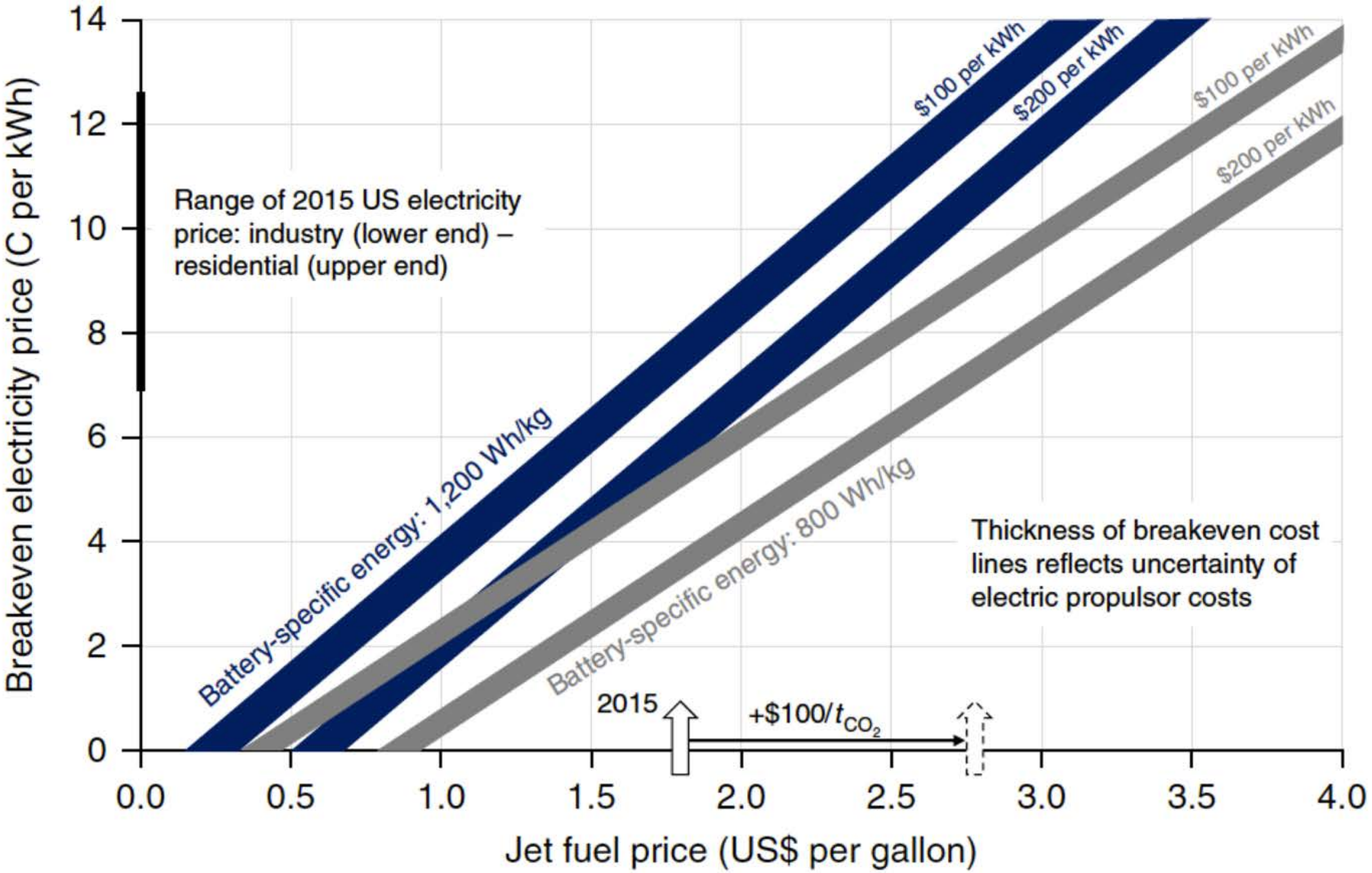
Direct Operating Cost (DOC)

- 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

Break-Even Electricity Price



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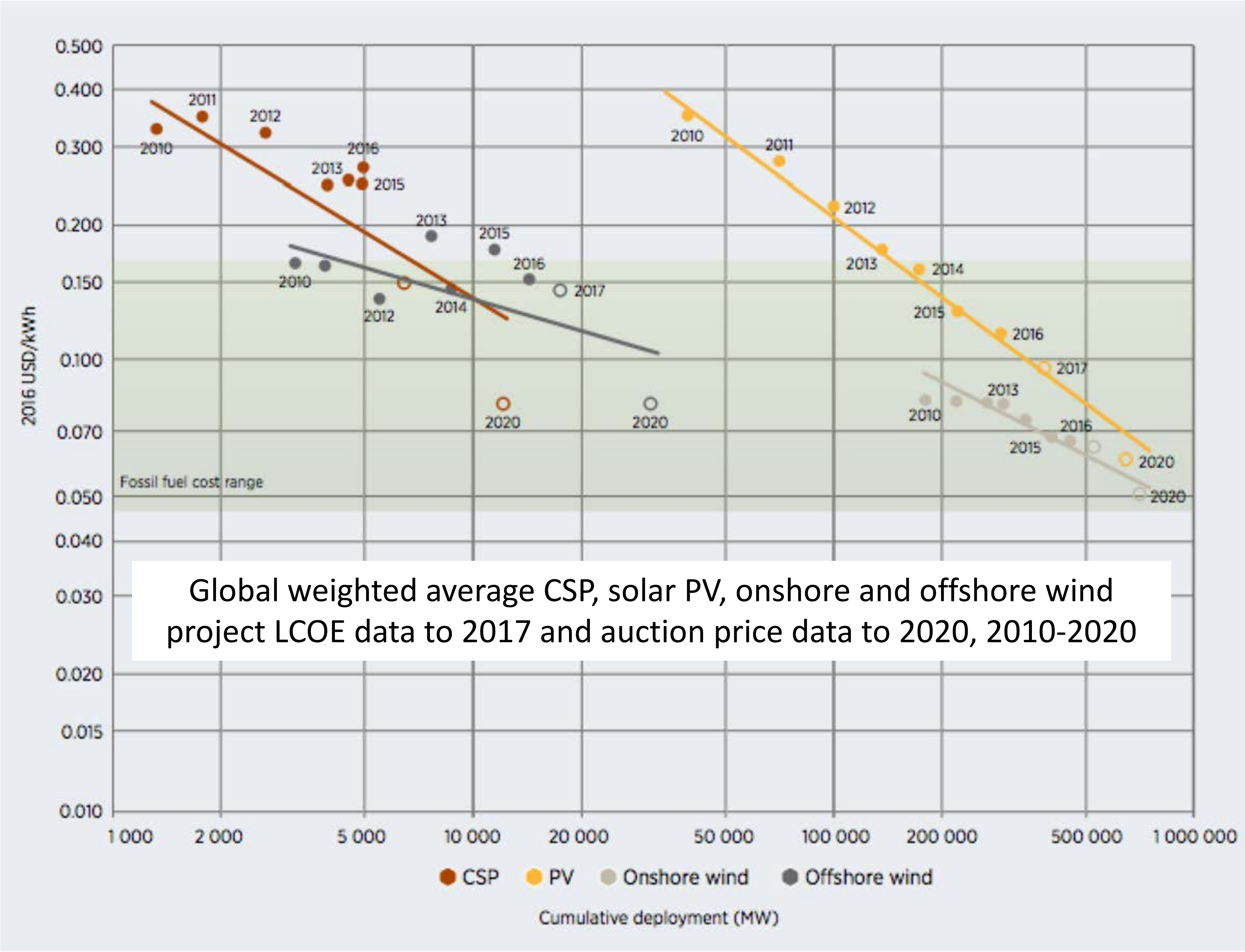
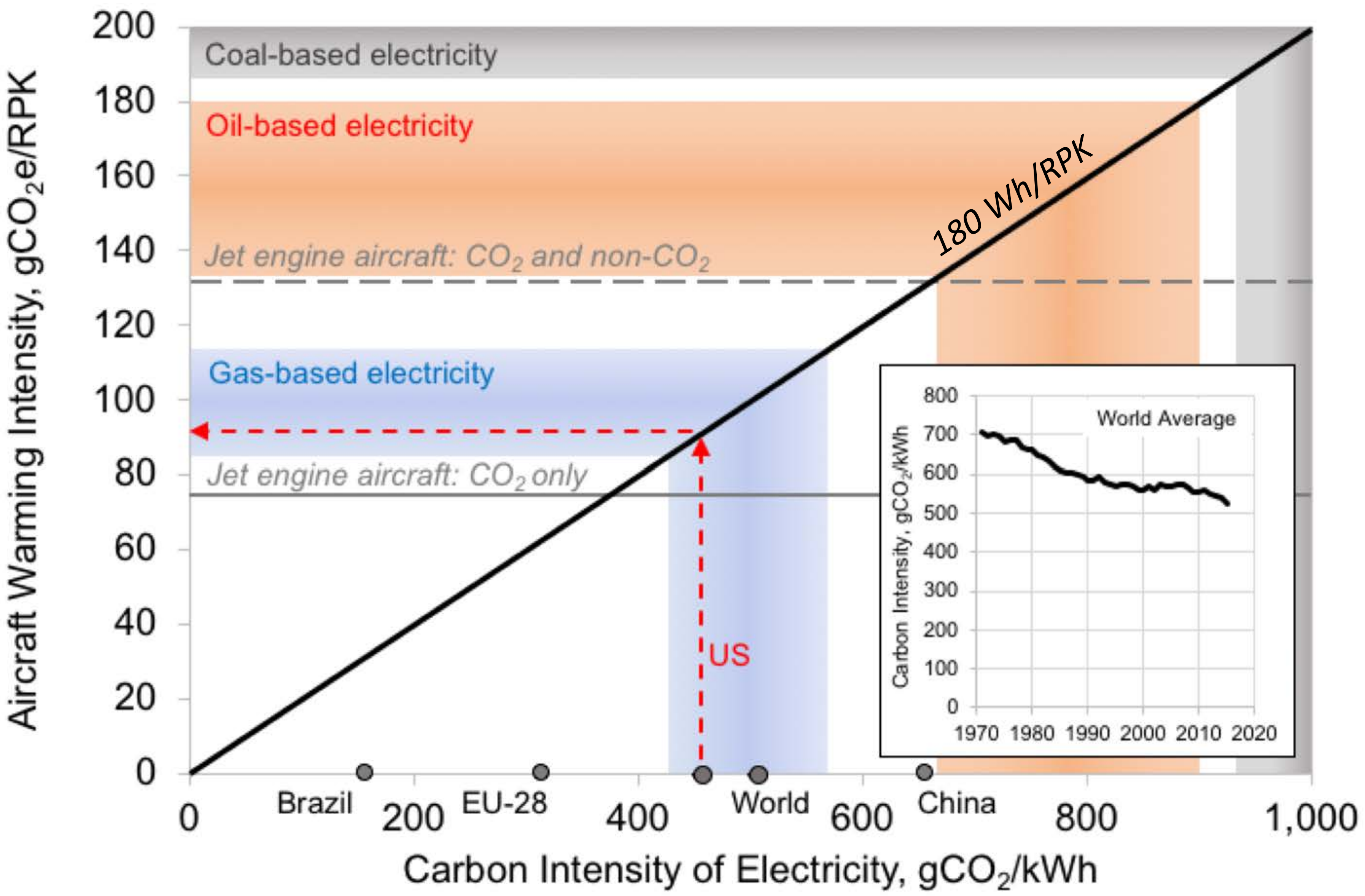
Costs of Renewable Power are declining



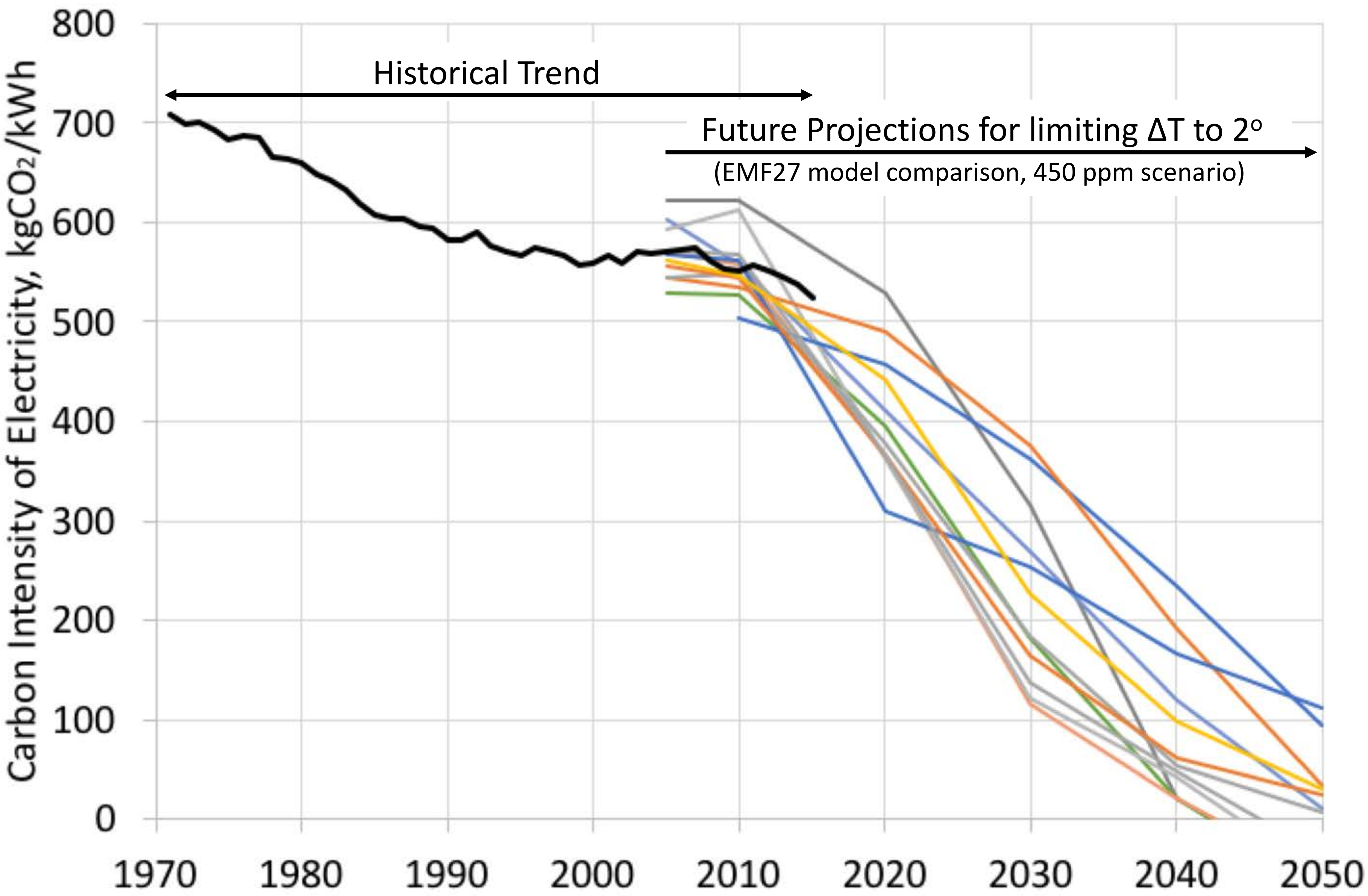
IRENA, 2018. Renewable Power Generation Costs in 2017, International Renewable Energy Agency, Abu Dhabi.

Aircraft Warming Intensity



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.

Carbon Intensity of Electricity needs to decline strongly



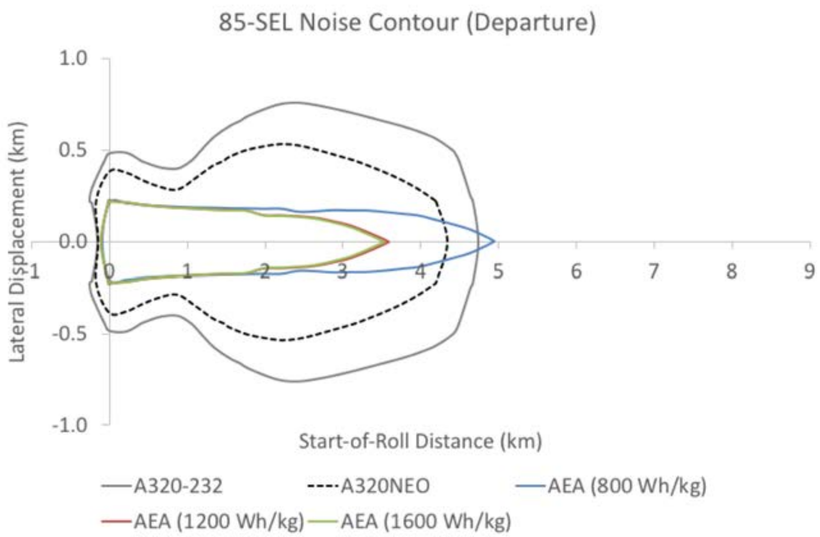
Data source: IPCC AR5 Scenarios Database (http://www.iiasa.ac.at/web/home/research/researchPrograms/Energy/IPCC_AR5_Database.html)
IEA, 2018. World Summary Energy Balances.

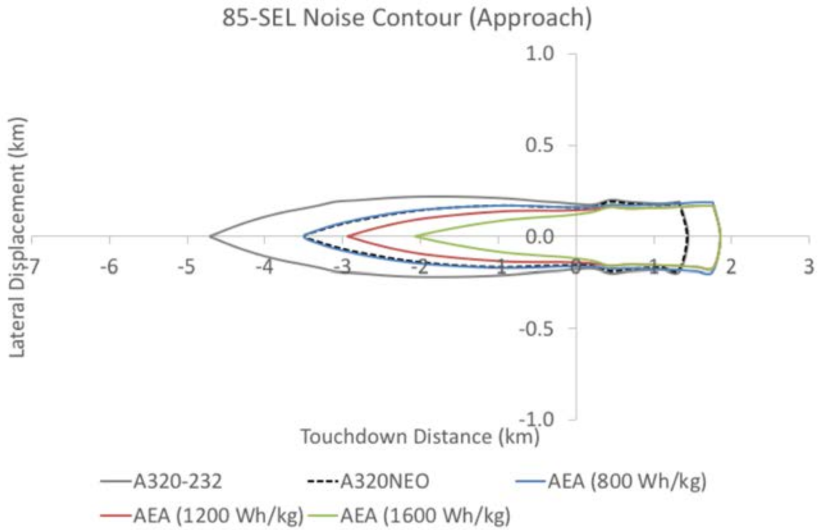
Electric Power Implications

- 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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Conclusions: Electric Aircraft Study

- 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

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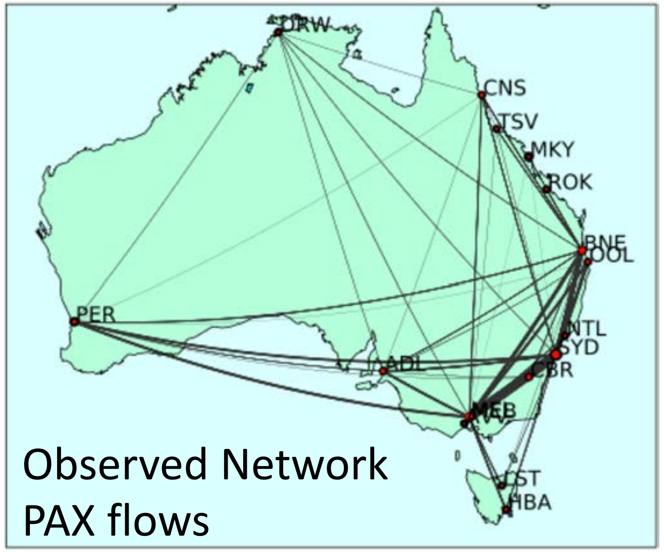
Next Steps: Aviation Integrated Model with Airline Competition

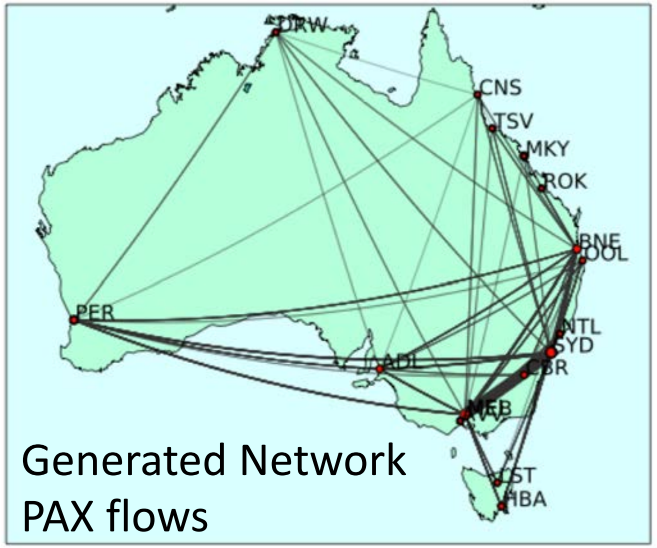
- Each airline sequentially maximizes profit (P) within its network (objective fct.)
- Three decision variables: airfare (F), flight frequency (FF), type of aircraft (a)

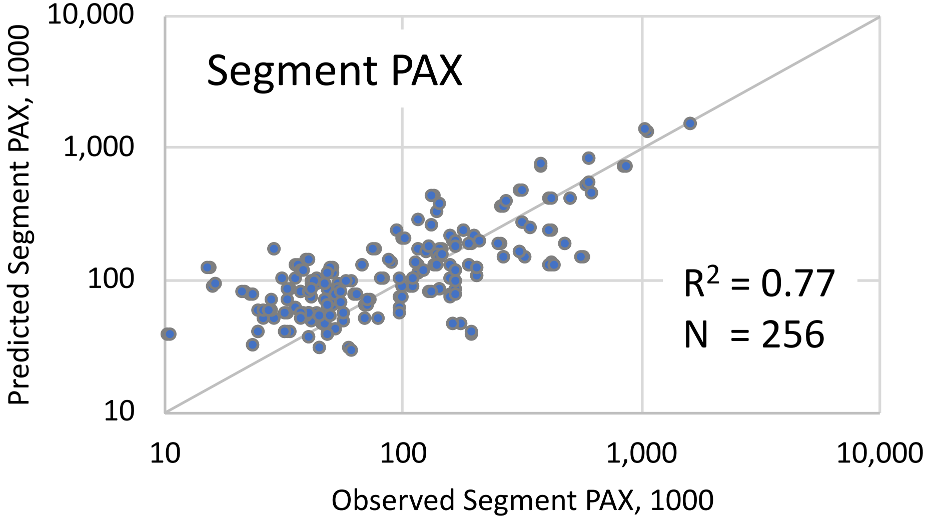
$$P = \underbrace{\sum_{i \epsilon itn} (Itn\,F_i \cdot Itn\,PAX_i)}_{\text{Revenues}} - \underbrace{\sum_{l \epsilon seg} \left(\sum_{a \epsilon A/C} DOC_{Flight,a,l} \cdot FF_{a,l} \right)}_{\text{Flight-related costs}} - \underbrace{\sum_{l \epsilon seg} \left(\sum_{a \epsilon A/C} DOC_{PAX,a,l} \cdot PAX_{a,l} \right)}_{\text{PAX-related costs}}$$

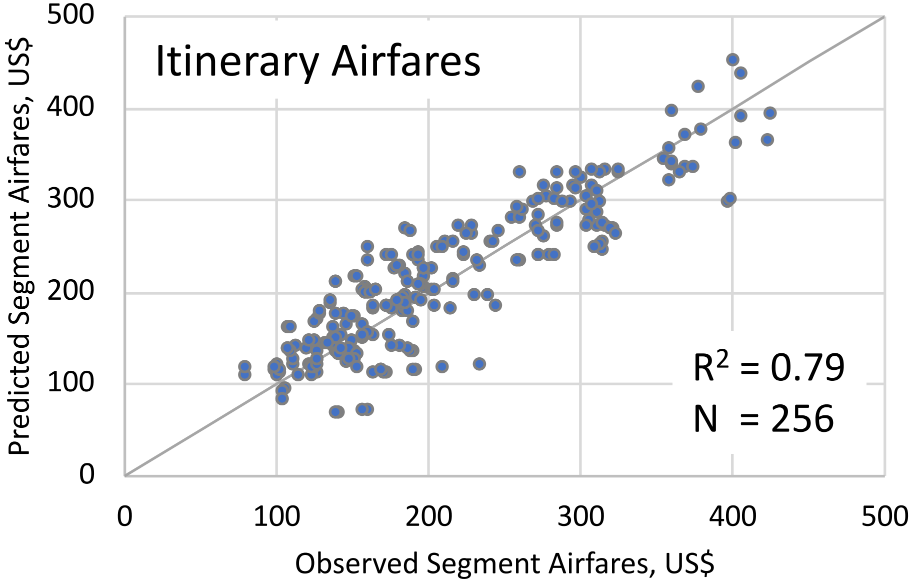
- Set of around 10 linearized constraints
- Iteration until equilibrium
- IBM CPLEX linear programming solver

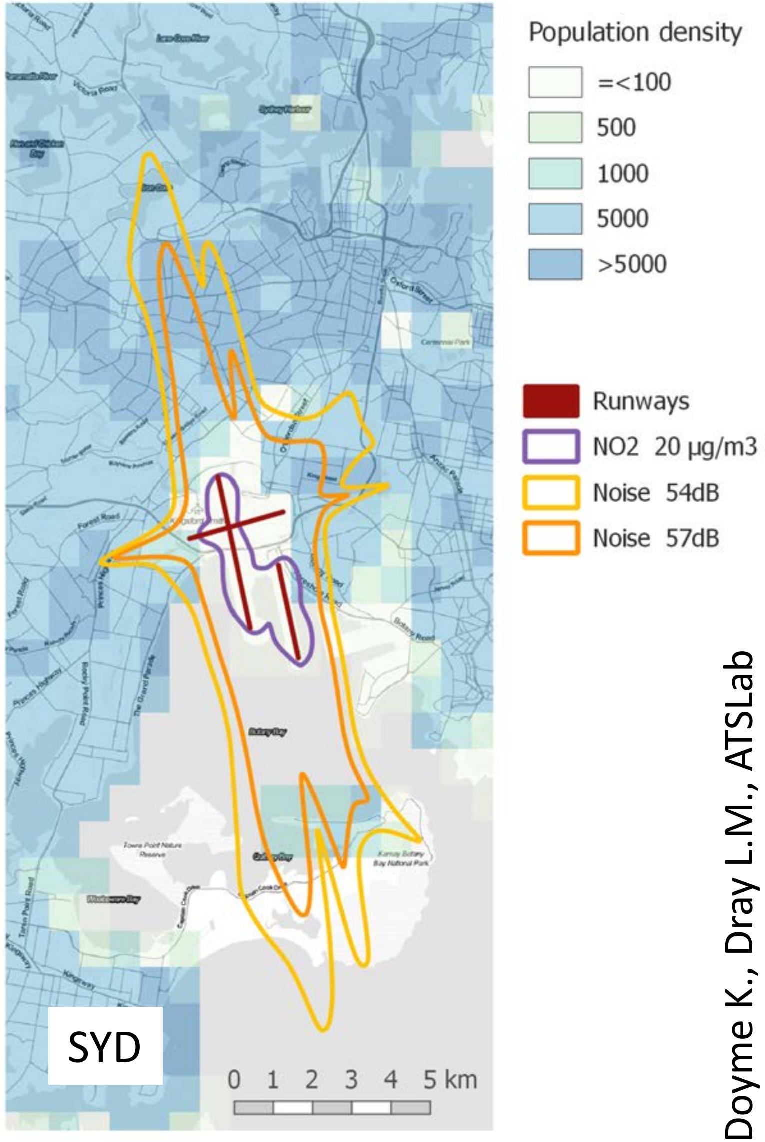
Aviation Integrated Model: Sample Results – Australia











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