Modelling the transition to a more-electric aviation system

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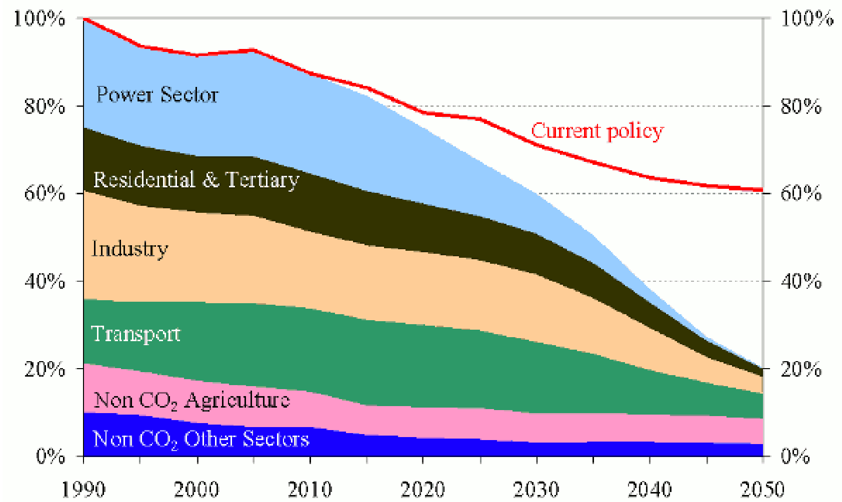
Background

- Future developments in aviation depend on the interaction of multiple stakeholders across different geographic scopes
  - Airlines, airports, passengers, regulators, manufacturers...
  - Complex relationships between capacity, scheduling, fleet, passenger demand, networks etc.
- Multiple projects at UCL ATSLab exploring these interactions:
  - AIM2015, an open-source integrated modelling tool for the global aviation system
  - Airport Capacity Consequences Leveraging Aviation Integrated Modelling (ACCLAIM)
    - Additionally models airline behaviour and how this interacts with capacity expansion
  - **Systems Aspects of Electric Commercial Aircraft (SAECA)**
    - **Applying these modelling capabilities to assess the feasibility of an electric aircraft system**

Motivation - 1

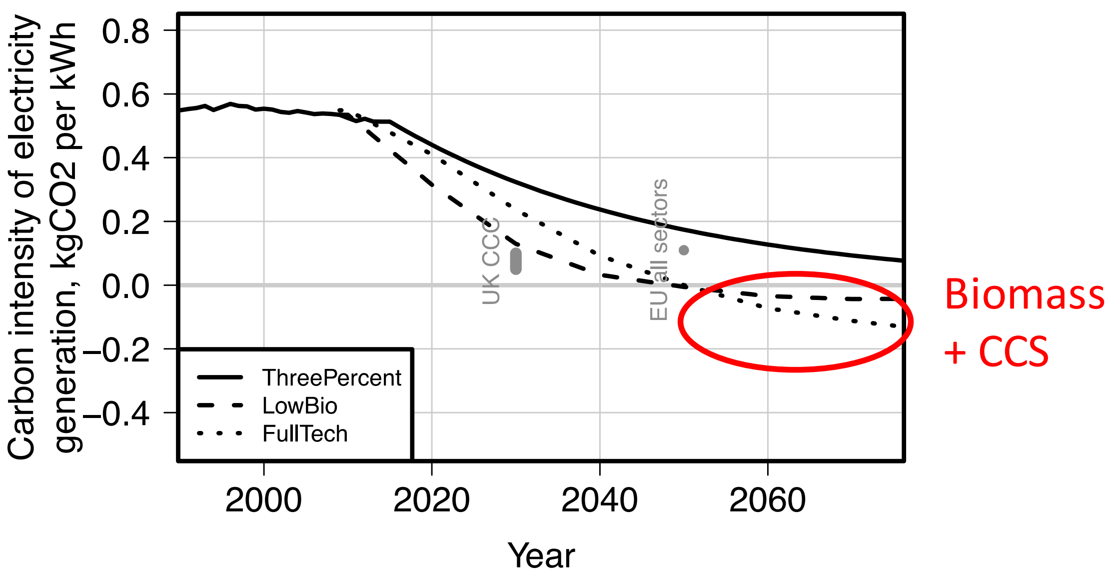
- Current projected global aviation RPK growth rates of 4-5%/year (Airbus, Boeing)
- 2-3%/year reductions possible in fuel lifecycle CO_2/RPK (Schäfer et al. 2016, Dray et al. 2018)
  - Requires a combination of technology, operations, alternative fuels etc.
- Under these assumptions aviation CO_2 will continue to grow
- Compare emissions targets:
  - 80% reduction in GHG from 1990 – 2050 (EU); 60% for transport
  - IPCC AR5: 'Likely' remaining below 2°C temperature rise - 40-70% global GHG reduction from 2010 – 2050



[Source: EU 2050 Low-carbon economy strategy]

Motivation - 2

- Currently the largest projected aviation reductions come from drop-in biofuel
  - Cellulosic biomass fuels offer ~ 80% reduction in fuel lifecycle CO_2 (e.g. Schäfer et al. 2016)
  - Drop-in allows use in current aircraft
  - Still combustion at altitude - contrails, NOx, etc.
  - Highly uncertain – depends on supply, land use, other sectors



[Data: IIASA EMF27 Scenario database]

- But electricity generation is potentially even less carbon-intensive

How feasible is an electric aircraft system?

- Multiple designs in development/testing
  - Hybrid and/or turboelectric designs use jet fuel to generate power for an electric motor - limited benefits
  - All-electric aircraft (AEA) use only batteries for energy
- Light/VTOL/air taxi concepts include:
  - Airbus E-Fan
  - Liaoning Ruixiang RX1E (in production)
  - Uber Elevate

- Narrowbody AEA concepts include:
  - 328/328-LBME^2 (Hepperle 2012)
  - Wright One (in development)
  - Bauhaus Luftfahrt Ce-Liner
  - MIT/SAECA designs used in this work (Gnadt et al., forthcoming)

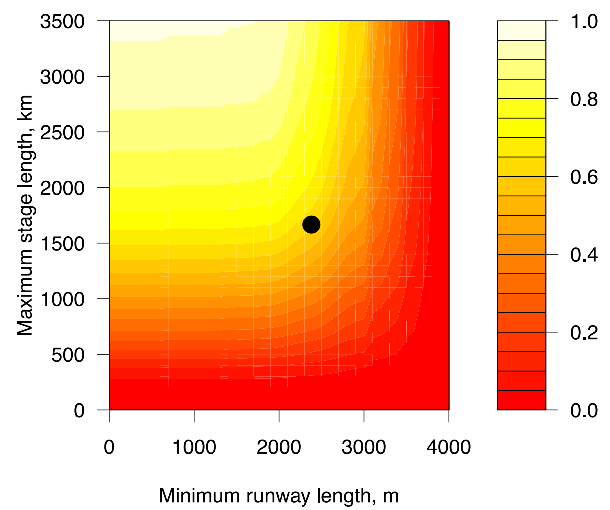
Limitations

- Battery energy density
  - Range/capacity depend on future battery technology improvements
  - Even with these, range is limited (likely < 900 nm, maybe < 500 nm)
- Battery specific power
  - Affects takeoff
  - If lower specific power:
    - Longer runway needed
    - More takeoff noise (than comparable AEA with higher battery specific power)
- Cooling systems
  - Also depend on future technology
- Rate/method of charging
  - Affects turnaround (charge) and/or costs (swap)

Battery	Theoretical Wh/kg	Expected Wh/kg, 2025
Li-ion	390	250
Li-S	2570	500-1250
$Li\text{-}O_2$	3500	800-1750

Narrowbody AEA need roughly 800+ Wh/kg for 500+ nm range

[Data: Hepperle, 2012; Gnadt et al., 2018]



[Data: Sabre, year 2015 schedules]

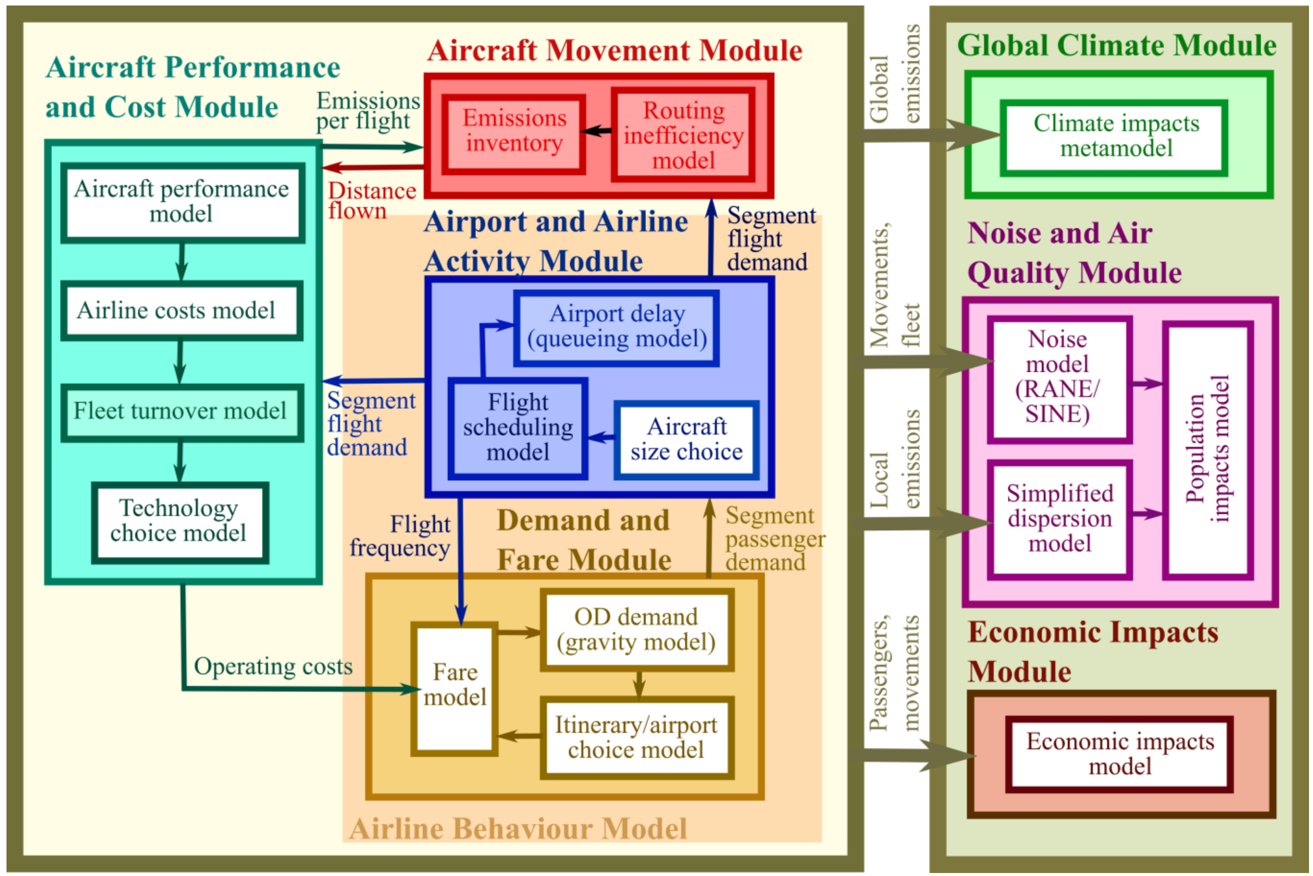
Modelling an electric aviation system

- Use the AIM2015 model
- See www.atslab.org for more information/papers

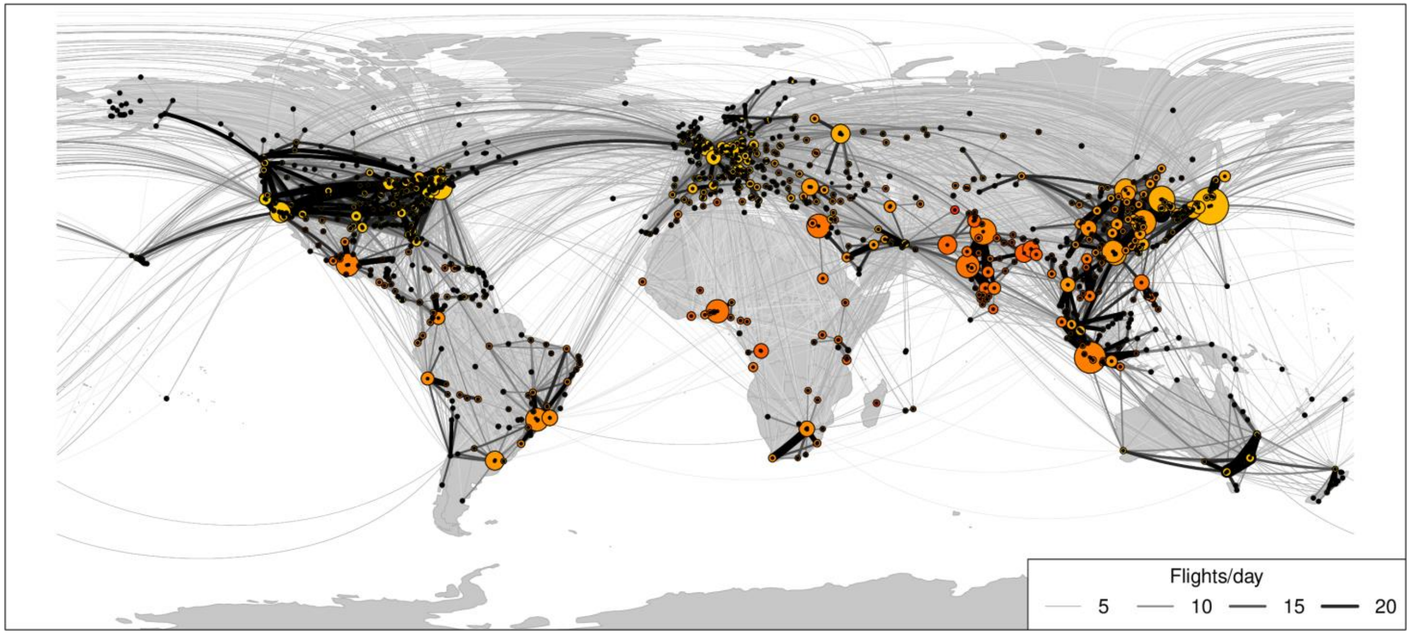
Solve iteratively (AIM2015)

OR

Optimise profit per airline (Airline Behaviour Model)



Scope



- Flights between 1169 airports in 878 cities modelled
- 2015 base year

- Future projections to 2050 and beyond:
  - Given projections of population, GDP/capita, oil price, technology etc.
- Includes uncertainty
  - Lens approach for technologies
  - Plus a range of input scenarios

Extra inputs/outputs for electric aircraft

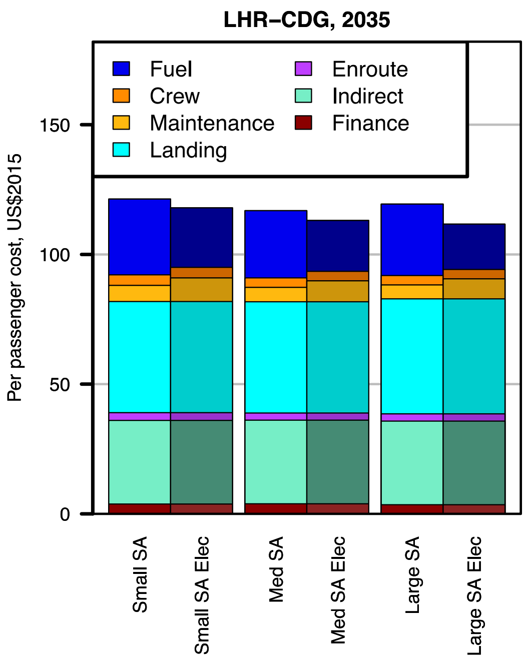
- Electric aircraft performance model (MIT)
- Operating cost study
- Turnaround strategies
- Future scenarios for electricity cost/carbon intensity
- Electric grid implications
- Noise study (University of Southampton)

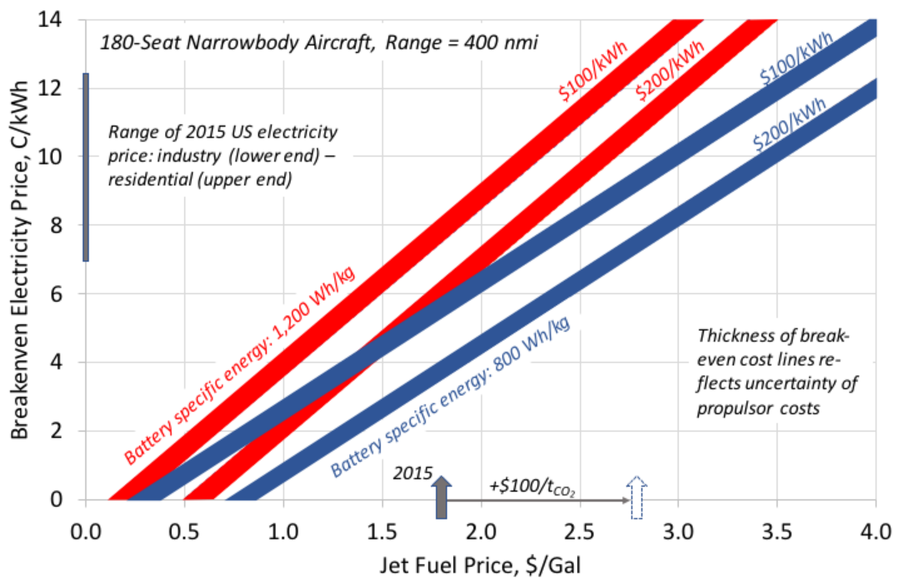
Electric Aircraft Performance Model (MIT)

- See Gnadt et al. (updated version, upcoming)
  - Transport Aircraft System OPTimization – electric (TASOPTe)
    - Simultaneous optimization of airframe, propulsor, operations
    - Uses first-principles methods
- For SAECA:
  - Takeoff length limited to 2.4 km (8,000 ft)
  - 4.5° climb angle; top-of-climb gradient ≧ 1.5%
  - Battery specific energy: 1,500 Wh/kg, 20% reserve
  - A320 geometry; 2-6 propulsors
  - Design range: 900 nm (1,667 km) by 2050
- RJs based on 328-LBME^2 (Hepperle 2012)
- Assume availability from 2035 (2030-2040) with initial range of 450 nm
- These assumptions are relatively optimistic

Operating cost study

- Al Zayat et al (2017)
- Electrification affects:
  - Maintenance and capital costs
  - Fuel costs
  - En-route/airport landing charges



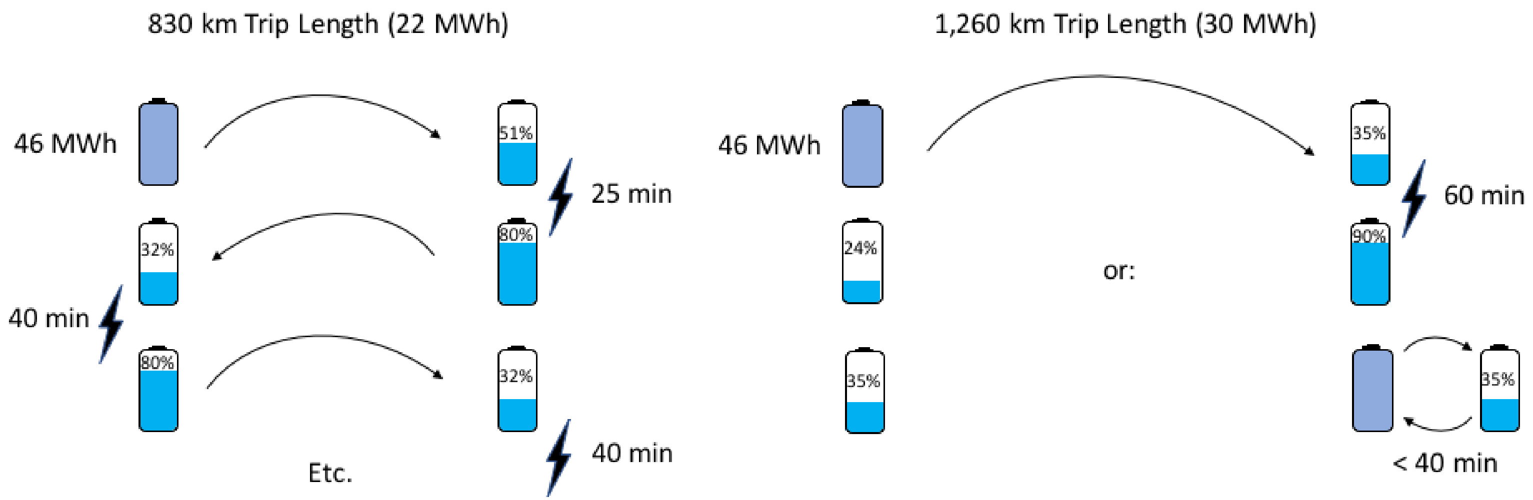


[Figure: Schäfer et al., in preparation]

- Outcome dependent on:
  - Battery characteristics
  - Future fuel prices
- Seems to be a feasible economic window

Turnaround study

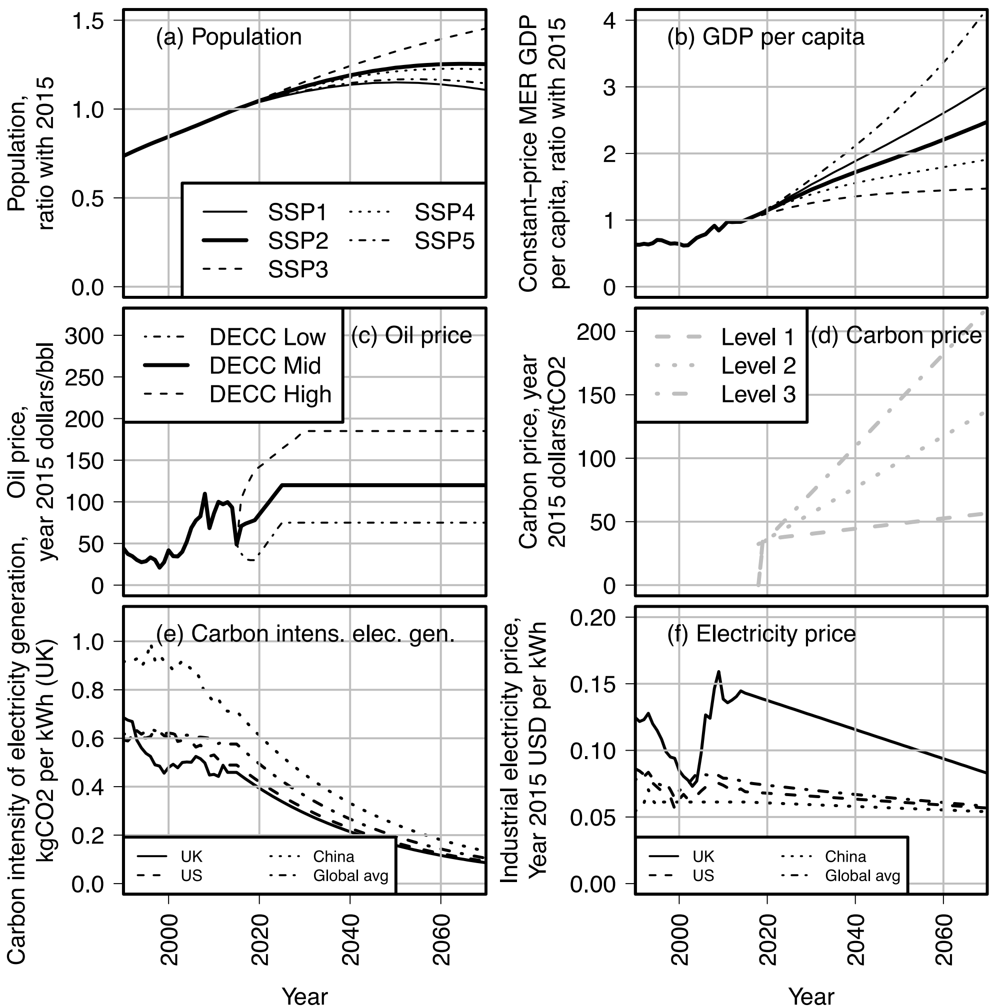
- Strategies depend on distance and swap/charge option



- Assumes 20% reserve battery
- For AIM, minimum turnaround time assumed unchanged
- Strategies for disrupted operations (e.g. diversion) not explored, but would likely be different

Scenario inputs

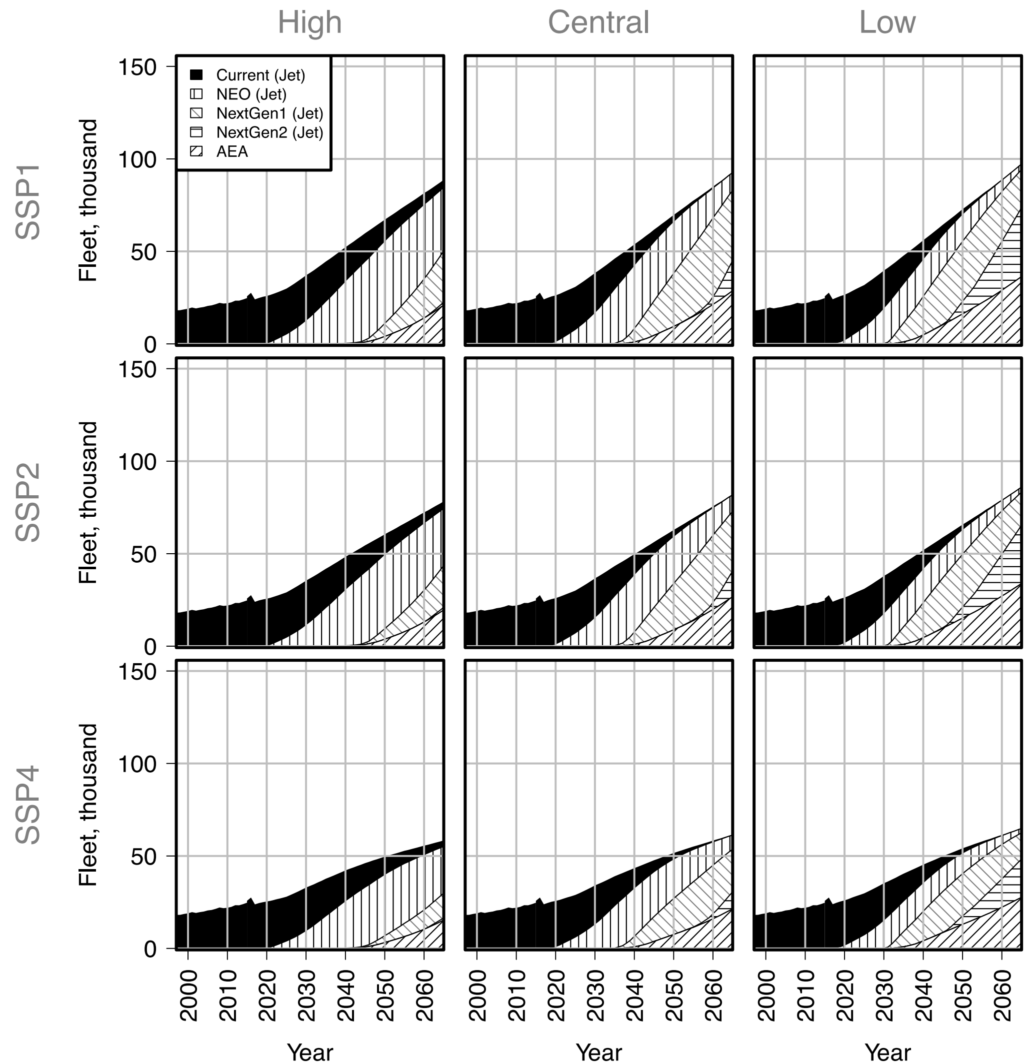
- Sample model inputs, starting from IPCC SSP scenarios
- These runs assume:
  - Mid-range values (SSP1,2,4)
  - No carbon price
  - 3%/year decrease in future carbon intensity of electricity generation
  - Electricity price tends to $0.05/kWh by 2100, all countries



[Data: IEA, 2017; IPCC, 2015; DECC, 2015]

Model outputs

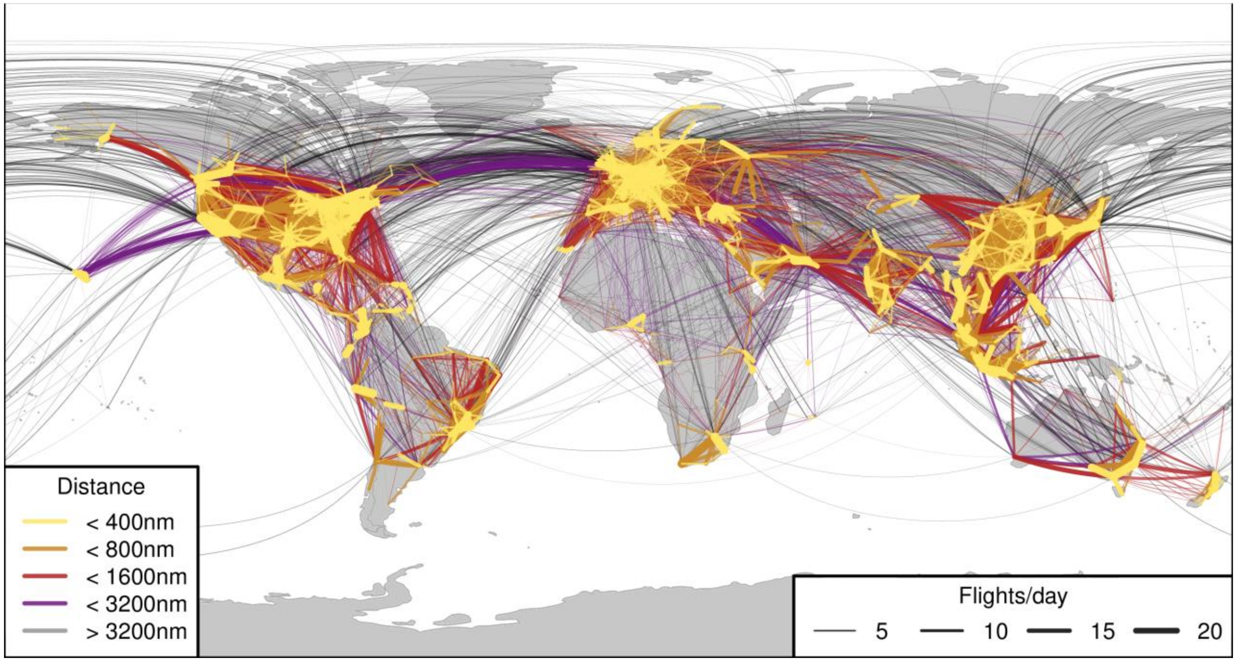
- Under input assumptions, electric aircraft are adopted
  - NPV model for adoption
  - + S-curve early/late adoption model
  - Main factors are relative fuel costs and range limit
  - Project 30-45% of fleet could be electric by 2070

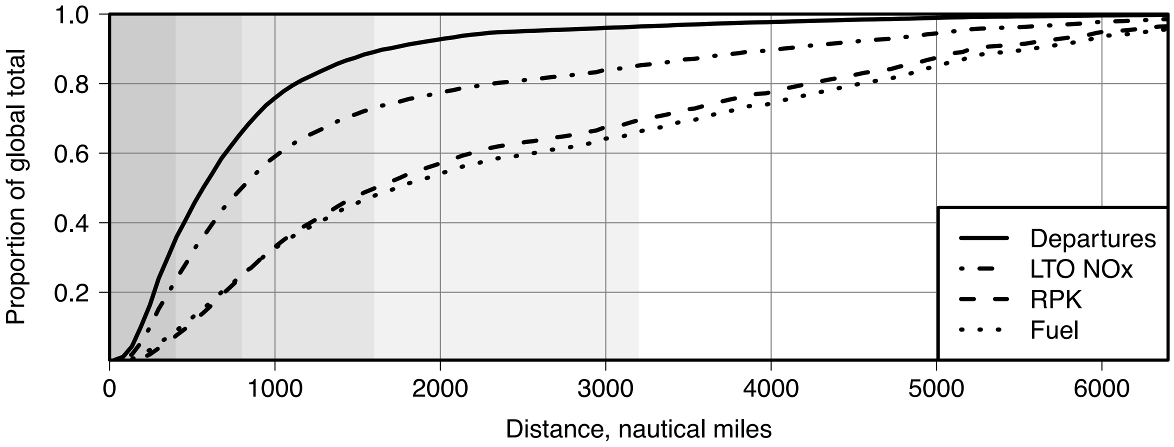


[Past data: FlightGlobal, 2017;
Note AIM runs use interim demand model]

Network

- Range-dependent
- In the most constrained cases only a very local network is possible





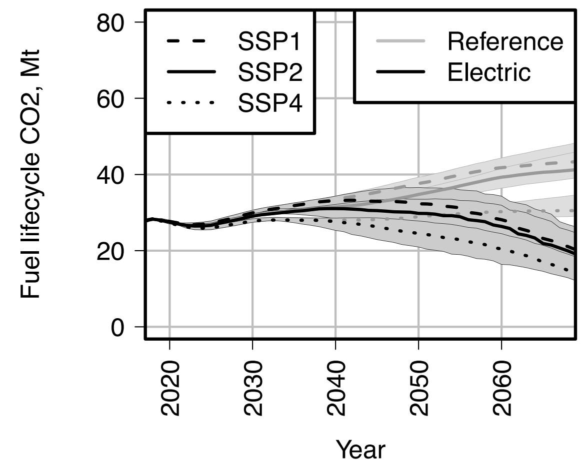
- At 900nm:
  - Could substitute ~ 70% of **current** flights
  - < 30 % of fuel/CO_2 can be substituted
  - Long-haul growing faster than short-haul

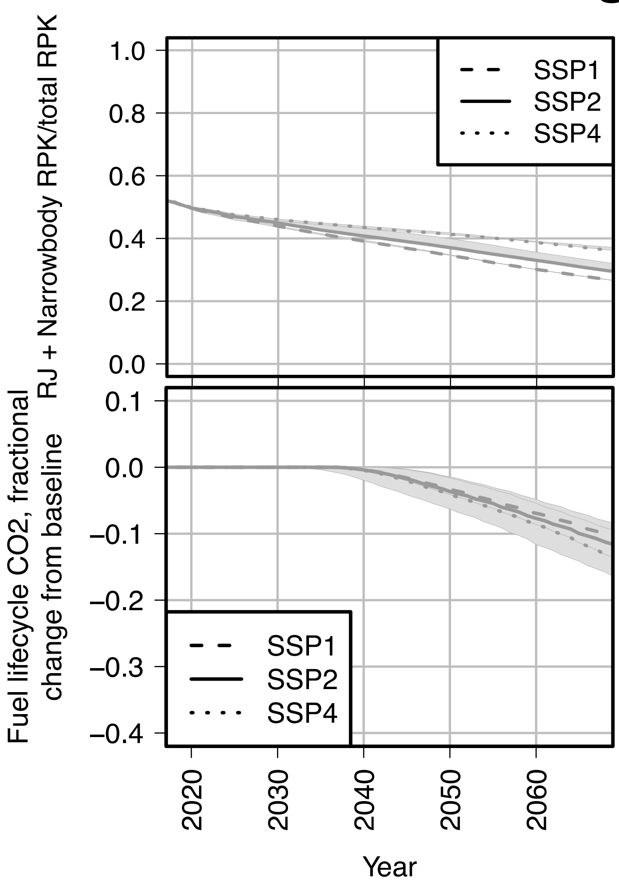
[Data: Sabre, 2017 (from 2015 global schedules)]

Emissions and electricity demand

- Large impact on compatible route CO_2
- BUT compatible routes account for a small fraction of global CO_2

Small narrowbodies, global

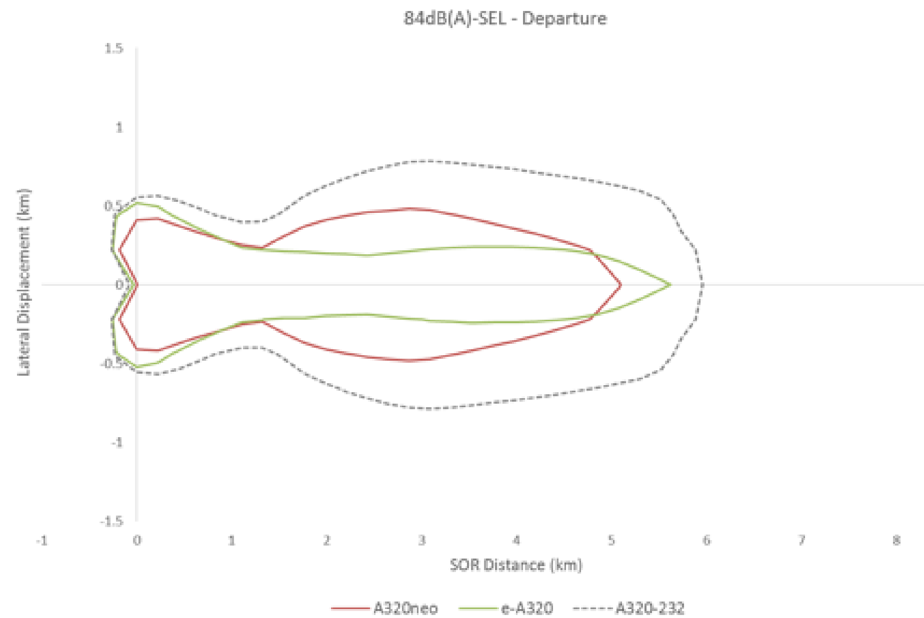




- End result is only ~ 10% global CO_2 reduction from non-electric baseline
  - Still may be important as part of a basket of future measures
  - Local impacts can be significant
- Extra electricity demand relatively small
  - E.g. Electrifying 80% of current UK narrowbodies would add ~4% to UK demand

Noise study (University of Southampton)

- Expect changes in electric aircraft noise due to:
  - Higher MTOW
  - (Much) higher landing weight
    - Batteries remain the same weight throughout the flight
  - Potentially different climb angle
    - Depends on battery specific power assumptions
  - Different engines



- Not necessarily quieter
- Noise signatures will be significantly different to conventional aircraft
  - Understanding public acceptability requires further research
- Airport-area NOx and PM likely to reduce significantly

Conclusions

- Electric aircraft are probably:
    - Technically feasible, given expected improvements in battery tech
    - Cost-effective in at least some scenarios
    - Compatible with (some) current operations

BUT

- Overall impact on aviation emissions is small without significant network/demand change
    - Range limit is key constraint
    - Steeply reduces short-haul emissions
    - However, long-haul is growing faster

Upcoming papers with MIT building on/updating SAECA study: see www.atslab.org for updates

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