Air Transportation Systems Lab

UCL

Low-carbon aviation: how far can we go?

Lynnette Dray

Air Transportation Systems Laboratory,

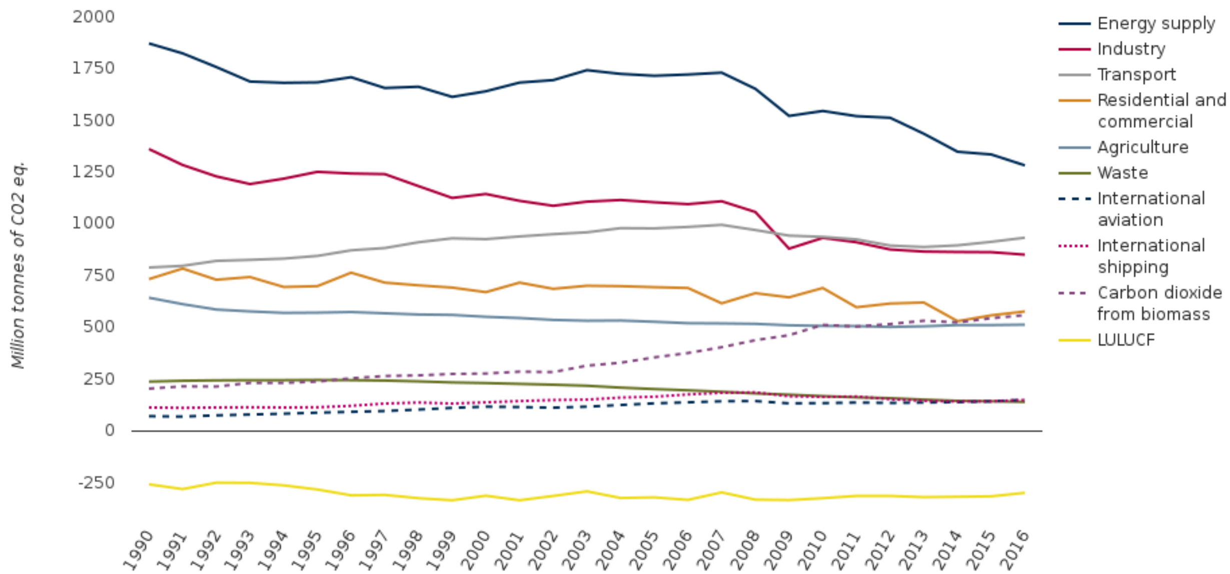
UCL Energy Institute, University College London

London, 2 April 2019

Why look at reducing aviation emissions?

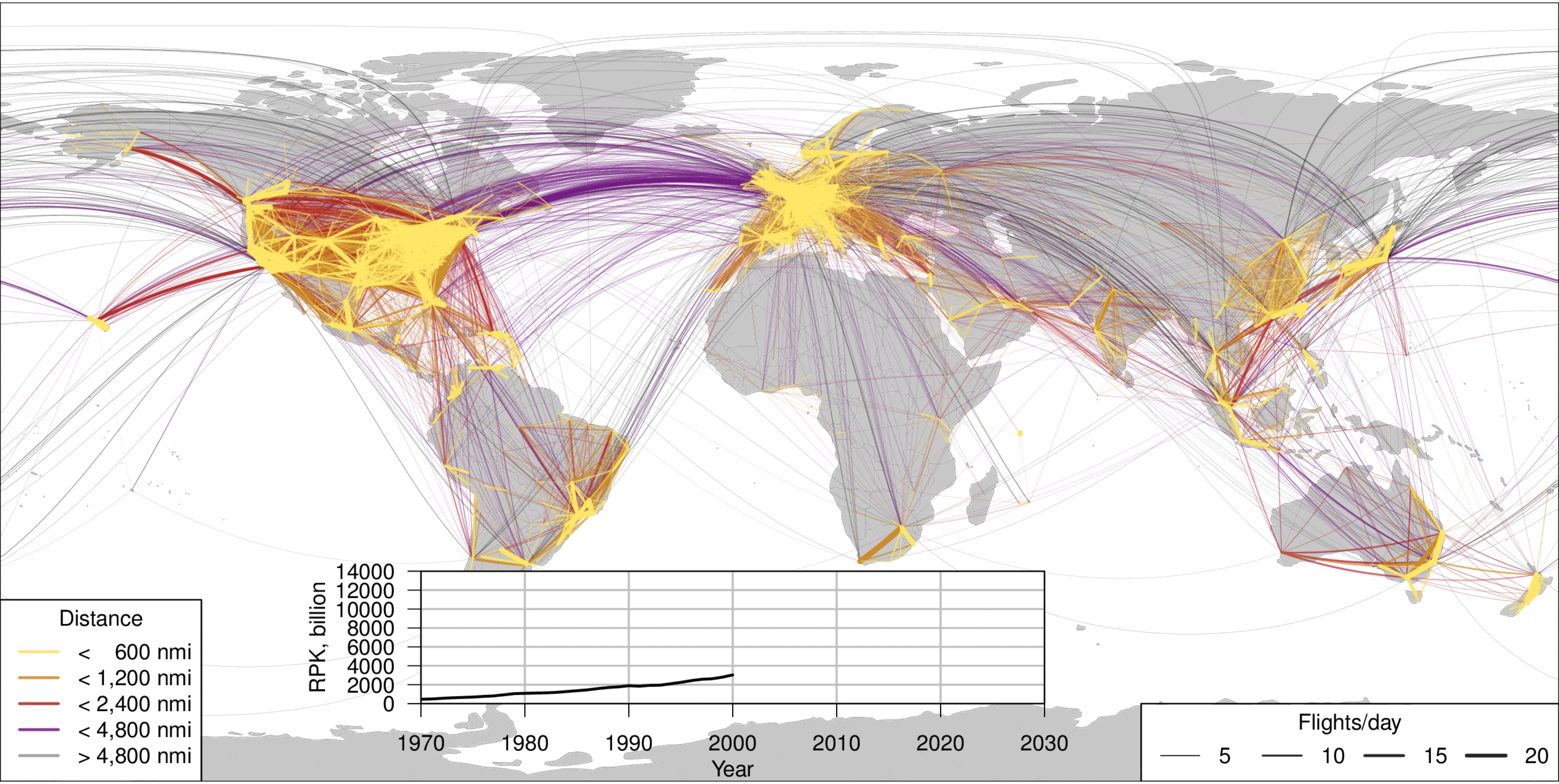
Motivation

- Aviation currently accounts for around 2.7 % of global energy-use related CO_2 emissions
  - Non-CO_2 aviation climate impacts uncertain, roughly equal to CO_2 impacts
  - For the UK, transport is around 30% of total GHG emissions and aviation is around 6.5% (DfT, 2017)
- Projected global aviation demand 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, biofuels etc.
- **If these trends continue, aviation CO_2 will continue to grow**



[EU28 GHG 1990-2016. Source: European Environment Agency]

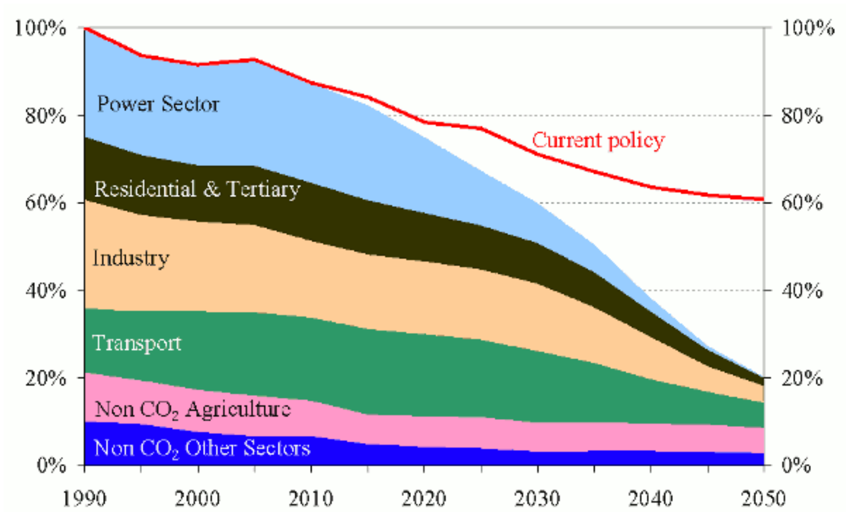
Demand growth 2000-2016



[Data: Sabre, 2017; ICAO, 2018]

International framework

- International shipping/aviation are outside the Paris Agreement
  - For aviation, ICAO's CORSIA scheme applies
  - This requires participating airlines to buy offsets from other sectors for any CO_2 increase above year-2020 levels
  - Intention is to phase out if/when airlines can reduce emissions within-sector
  - If intra-EEA, EU ETS applies
- 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]

Aviation emissions mitigation – some methods

- Operational (e.g. continuous descent approach)
  - Short implementation time, total benefits are relatively limited
- Technological (e.g. open rotor engines)
  - Long timeframes, potentially large benefits
  - In some cases can retrofit existing aircraft (e.g. carbon brakes)
- Economic (e.g. emissions trading)
- Mode shift (e.g. High-speed rail)
  - Limited applicability
- Alternative fuel (e.g. drop-in biofuel)
  - For more radical alternatives also need aircraft design changes

Aviation emissions mitigation - problems

- **BUT:** There are many trade-offs involved
  - E.g. noise vs. GHG vs. local emissions vs. jobs/economic impacts
- A measure which works well on a test flight may not reduce global aviation GHG by the same amount in practice
  - Airlines may choose not to invest if it costs too much, or makes journeys longer/more uncomfortable
  - May not be suitable for all routes, or may conflict with other measures
  - Measures that reduce costs may lead to cheaper tickets and more flying
- 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.

Modelling the global aviation system

Modelling global aviation – UCL ATSlab

- 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
  - Plus work on feasibility of hybrid electric aircraft, carbon leakage, freight, policy assessment, high-speed rail, biofuel, etc.

More information: **www.atslab.org**

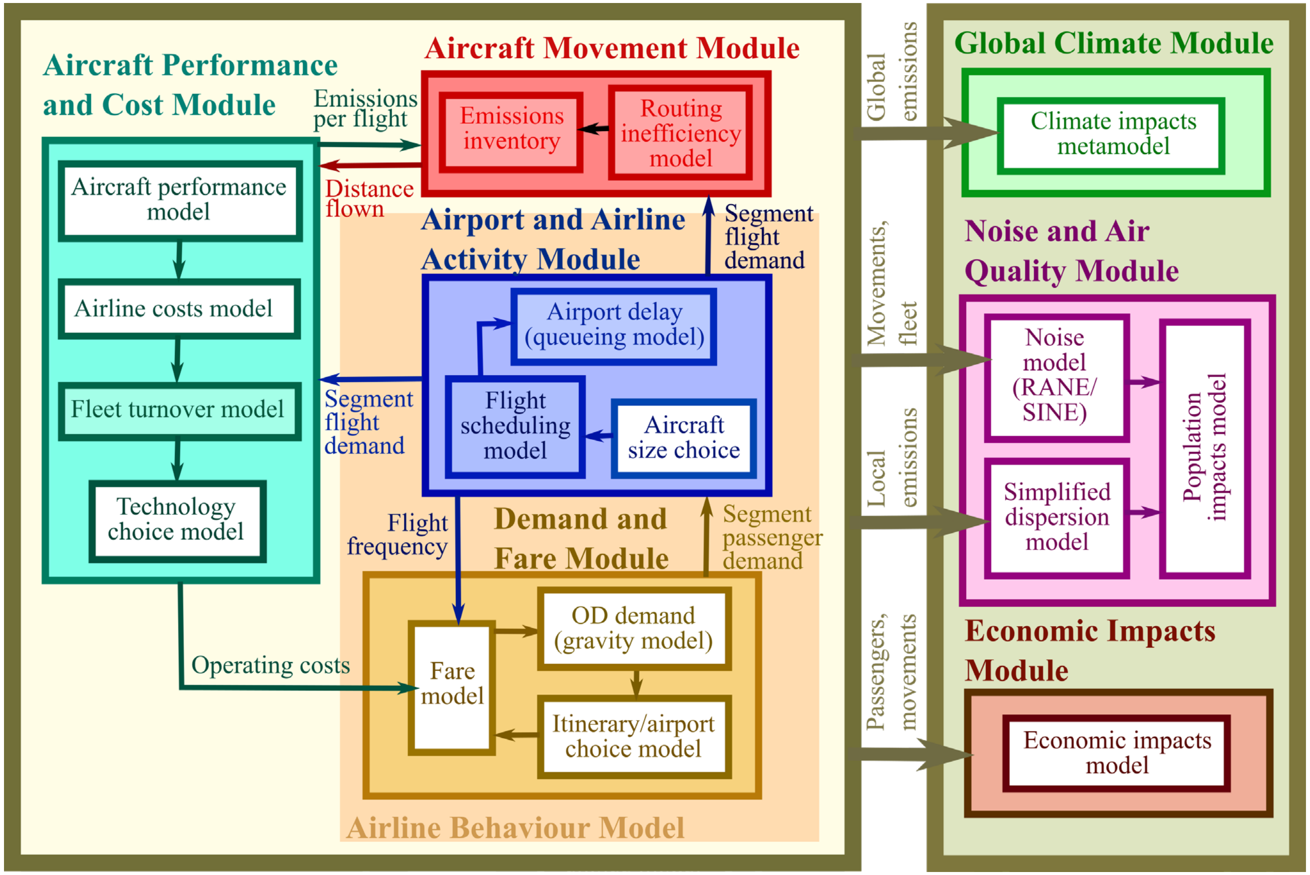
Modelling the global aviation system

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

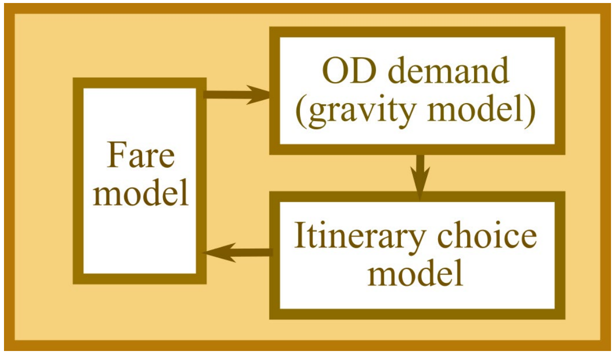
Solve iteratively (AIM2015)

OR

Optimise profit per airline (Airline Behaviour Model)

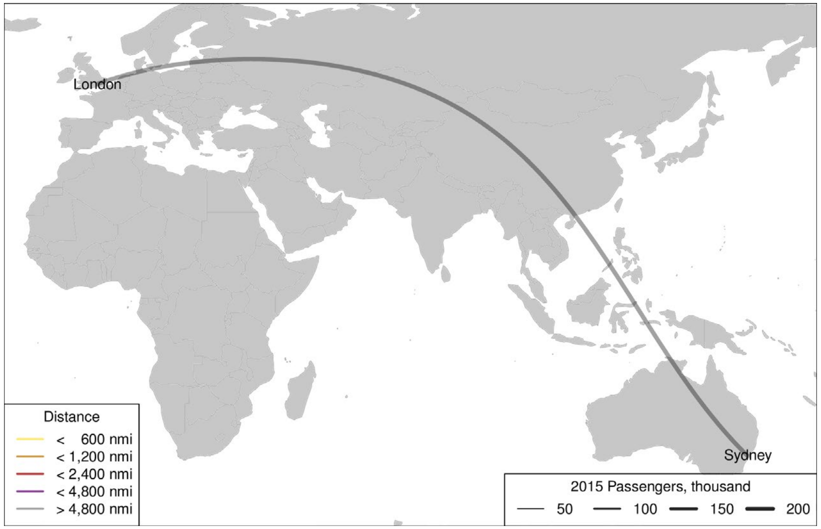


Demand and Fares



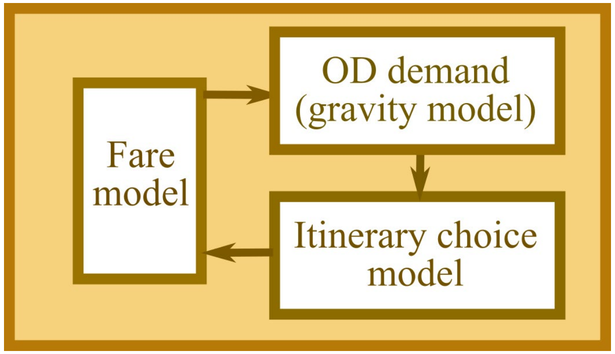
- **Fare** depends on airline costs and competition
- Itinerary-level fare model estimated from global fare data (Wang et al. 2018)

- Total city-city passenger **demand** (e.g. London-Sydney) depends on population, income, fare and other journey characteristics
- Gravity-type model estimated from Sabre (2016) data



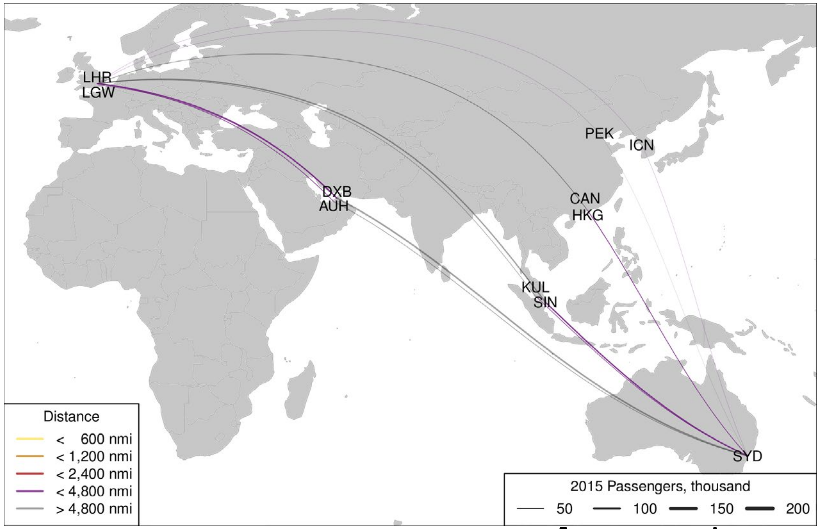
[Data: Sabre, 2016]

Demand and Fares



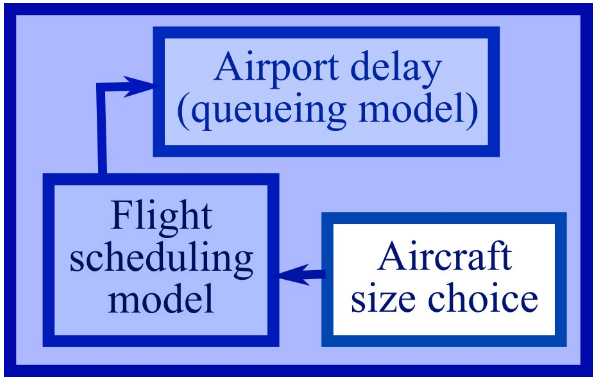
- **Fare** depends on airline costs and competition
- Itinerary-level fare model estimated from global fare data (Wang et al. 2018)

- **Itinerary choice** (e.g. Heathrow-Hong Kong-Sydney or Gatwick-Dubai-Sydney?) depends on fare, frequency, number of flight legs, time etc.
- Estimated using a logit model



[Data: Sabre, 2016]

Airline and Airport Activity Module – simple version



- Aircraft size choice model picks fleet to use based on demand, airport characteristics, etc.
  - Assuming typical segment load factors this gives flight frequency and fleet requirement
- Typical **Delay** depends on demand for flights vs. airport capacity
  - Affects journey time, emissions
- Rapid queueing model for airport delay
  - See Evans (2008)

[Image: Mumbai Airport, Wikimedia commons]

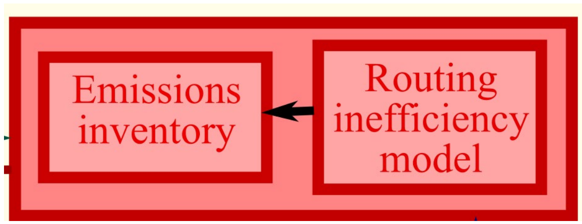
Airline and Airport Activity Module – complex version

- Model individual airlines competing with each other
- Each airline attempts to maximise profit (P)
  - To do this they can change **fares** (F), **flight frequency** (FF) and **which aircraft they use on each route** (a)

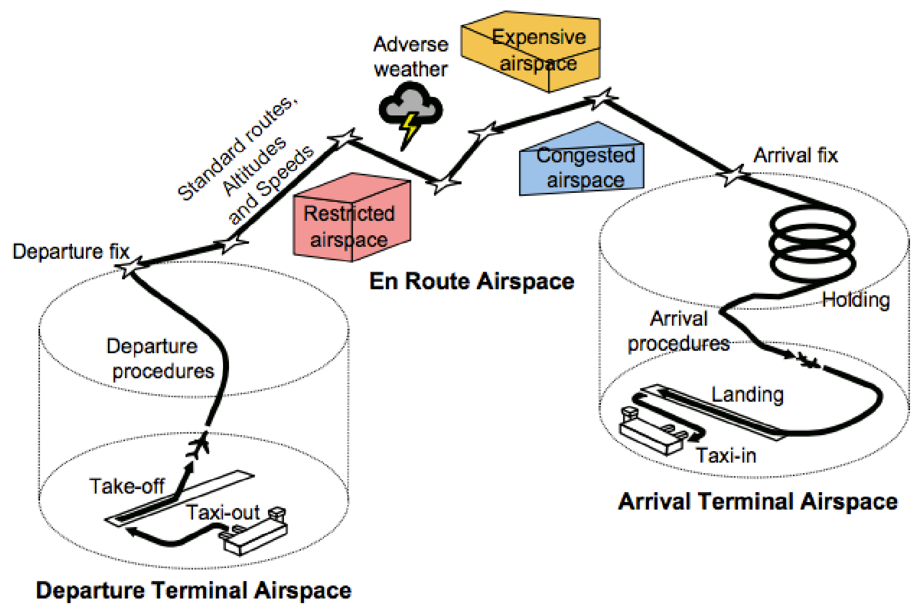
$$P = \underbrace{\sum_{i \epsilon itn} (Itn\ F_i \cdot Itn\ PAX_i)}_{\text{Revenues}} - \underbrace{\sum_{l \epsilon seg} (\sum_{a \epsilon A/C} DOC_{Flight,a,l} \cdot FF_{a,l})}_{\text{Flight-related costs}} - \underbrace{\sum_{l \epsilon seg} (\sum_{a \epsilon A/C} DOC_{PAX,a,l} \cdot PAX_{a,l})}_{\text{PAX-related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

  - Subject to constraints (E.g. available fleet, airport capacity)
- E.g. Doyme et al. (2018)
  - Developed to study airport capacity expansion, but many other uses
  - Examples later

Aircraft Movement Module



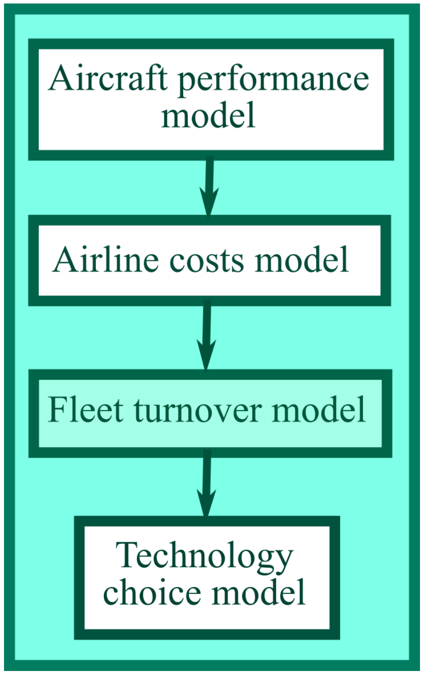
- Flights don’t usually follow the shortest course between origin and destination airport:



[Source: Reynolds, 2008]

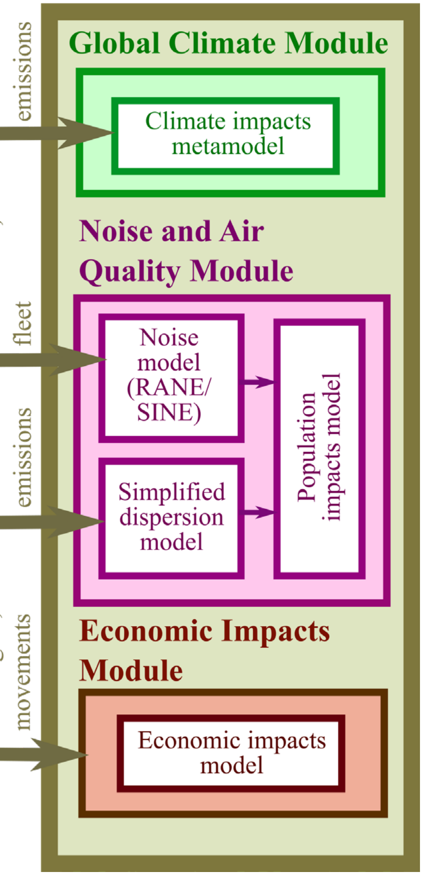
- Can add 5-20 % to distance flown
- Some of this can be reduced (SESAR, NextGen), some not
- See Reynolds (2008)

Aircraft Performance and Cost Module

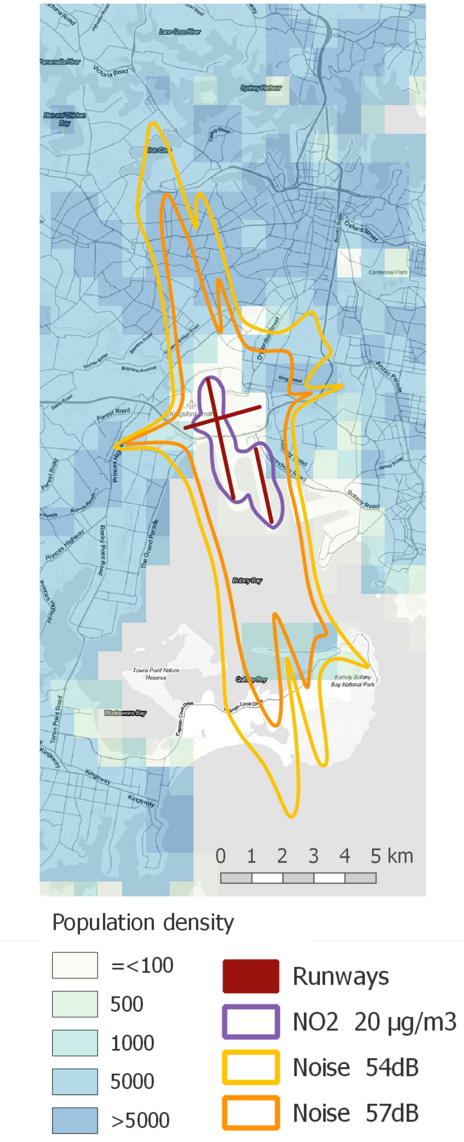


- Performance model
  - Calculates how much fuel aircraft use, and how much CO_2/NOx emitted, by flight stage
  - This affects the cost of using the aircraft, which affects ticket prices
- Fleet turnover model of fleet age, retirement and impact on performance (Dray 2013)
- Technology choice based on Morrell & Dray (2009)
  - Net Present Value assesses uptake of new aircraft models, operational changes, retrofits, given costs

Impacts modules

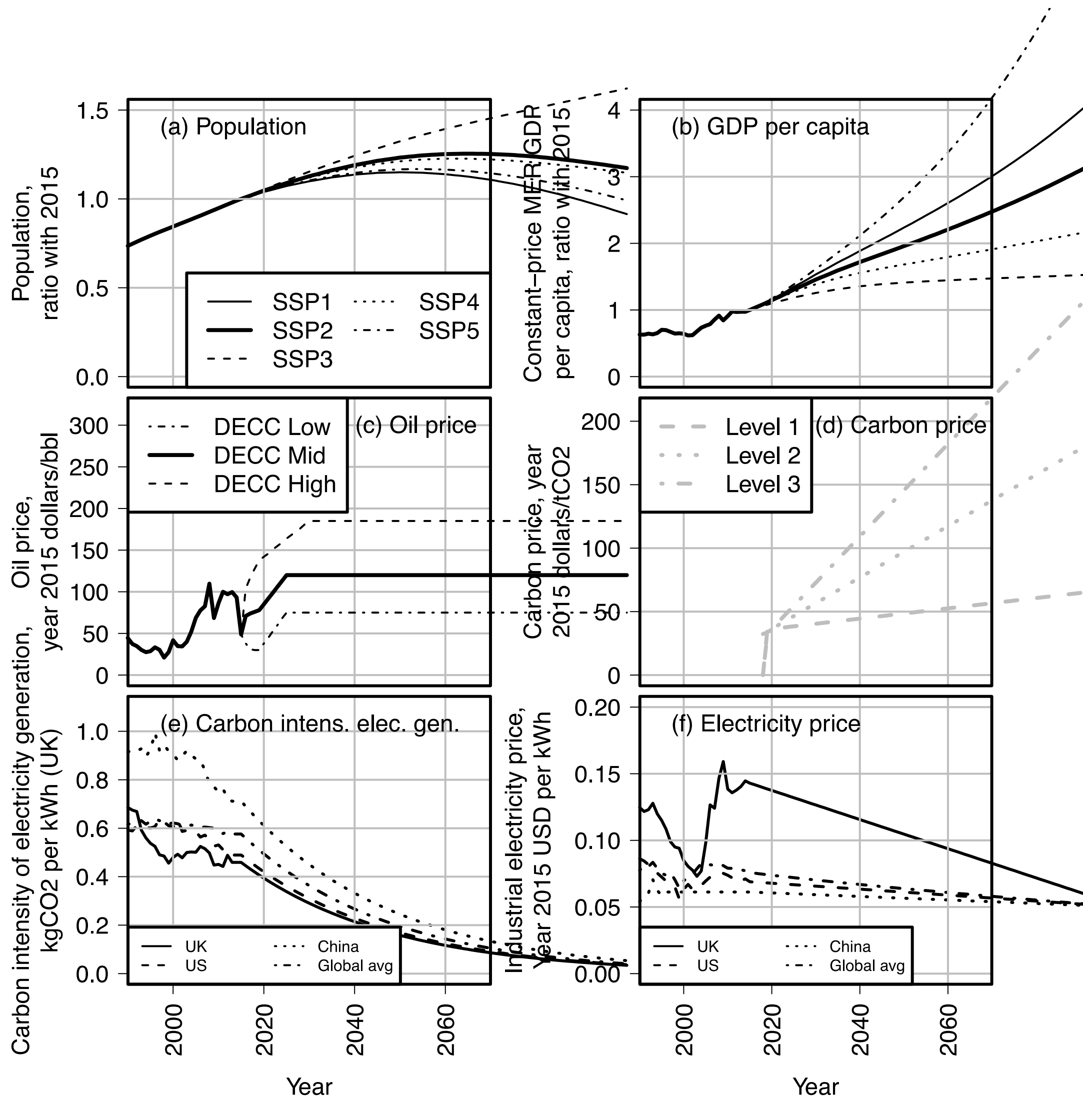


- Climate impacts: metamodel to calculate CO_2e from CO_2/NOx altitude distributions
    - E.g. Krammer et al. (2013)
- Noise: RANE/SINE (Torija et al. 2016,2017)
- Local NOx/NO_2/PM concentrations: RDC (Barrett & Britter, 2009)
- Population impacts: GIS model with gridded population data (Kuleszo)
- Economic impacts: metamodel of airport economic impact studies (Eder et al, forthcoming)



Modelling the future

- Need to assume:
  - Population
  - Income
  - Oil price
  - Carbon prices (+ scope)
  - Carbon intensity of electricity generation
  - Electricity price
  - **Technology characteristics**
- These are all **uncertain**
  - Use different scenarios, e.g. IPCC (SSP1-5)

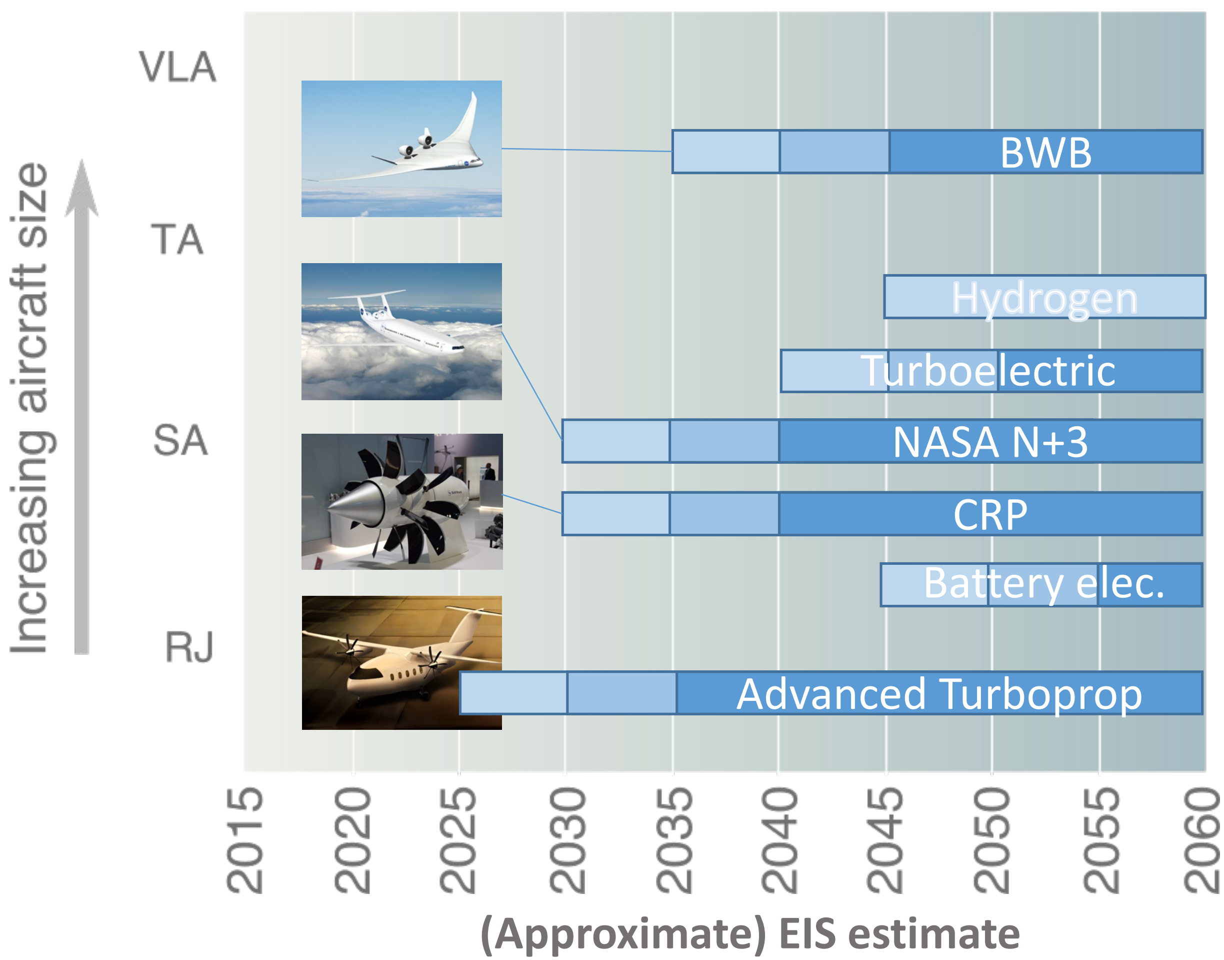


[Example projections. Data: IEA, 2017; IPCC, 2015; DECC, 2015]

Technologies which could reduce aviation emissions

The future?

- Potentially upcoming aircraft technologies include:
  - Contra-rotating propellor engines (CRP)
  - Blended wing body (BWB) aircraft
  - **Battery and/or hybrid electric narrowbody aircraft**
  - Hydrogen fuelled aircraft
  - **Drop-in biofuels**
- Characteristics and timeline uncertain



[Images: NASA; Wikimedia commons]

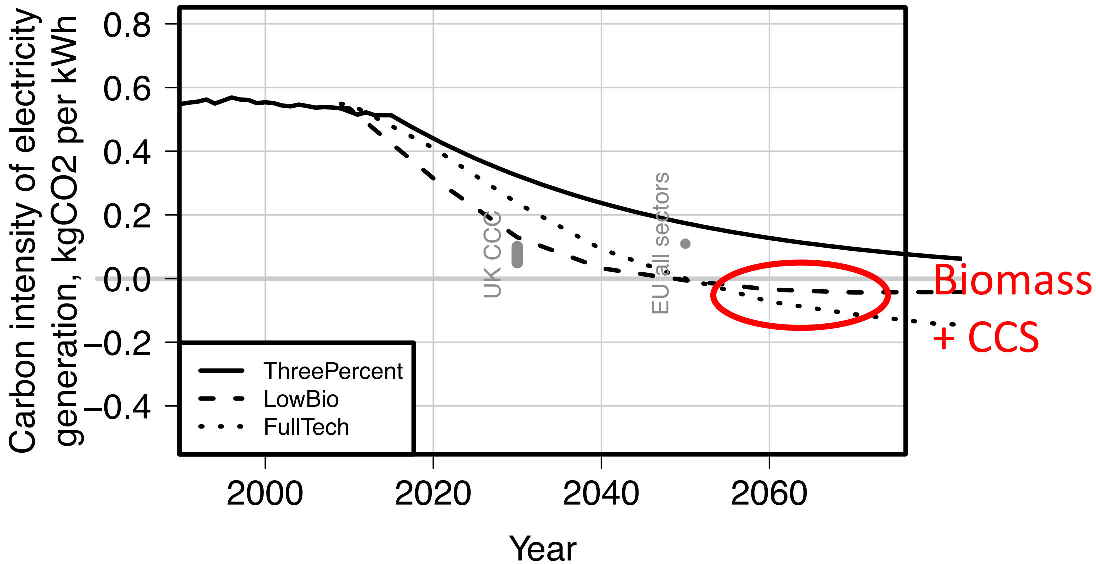
Aviation biofuel

- Drop-in biofuels can be used in current aircraft without modification
  - Already in (limited) use, e.g. AltAir facility at Los Angeles International
- Cellulosic biomass fuels offer 80% reduction in fuel lifecycle CO_2 (e.g. Schäfer et al. 2016)

[Biofuel feedstocks. Source: Idaho National Laboratory]

- However:
  - Current prices well above fossil fuel
  - Scaling up production requires significant infrastructure investment
  - Combustion at altitude (largely) unchanged - contrails, NOx, etc.
  - Still noise, NOx and (reduced) particulate emissions at airports
  - Supply is highly uncertain – depends on other sectors and land use
- In the longer term, liquid hydrogen could be a feasible fuel (but requires aircraft redesign)

Battery electric aircraft



[Data: IIASA EMF27 Scenario database]

- Motivated by projected improvements in electricity carbon intensity
- Multiple aircraft designs in development/testing
    - Hybrid electric designs use jet fuel to generate power for electric propulsors
    - All-electric aircraft (AEA) use only batteries for energy
- Many light/VTOL/air taxi concepts, e.g:
    - Airbus E-Fan, Liaoning Ruixiang RX1E, Uber Elevate etc.
- Fewer narrowbody AEA concepts:
    - 328/328-LBME² (Hepperle 2012); Wright One; Ce-Liner; MIT/SAECA (Gnadt et al., 2019; Schäfer et al., 2019)

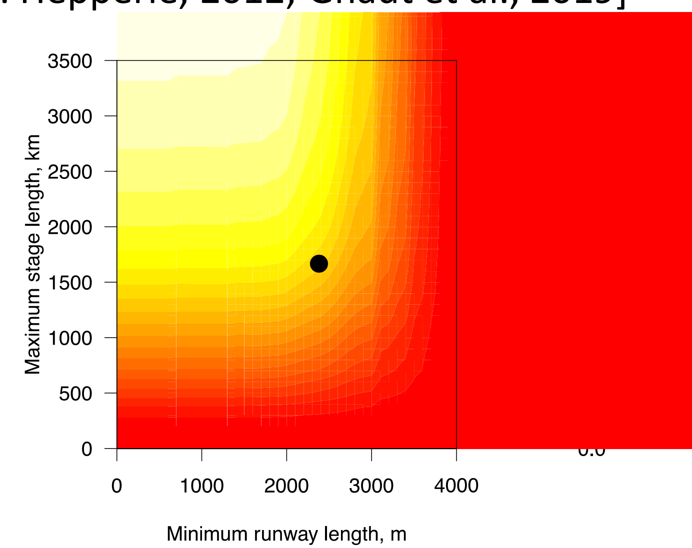
Electric Aircraft - Limitations

- Battery energy density
  - Range/capacity depend on future battery technology improvements
  - Even with these, range is limited (likely < 900 nmi, maybe < 500 nmi)
- 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+ nmi range

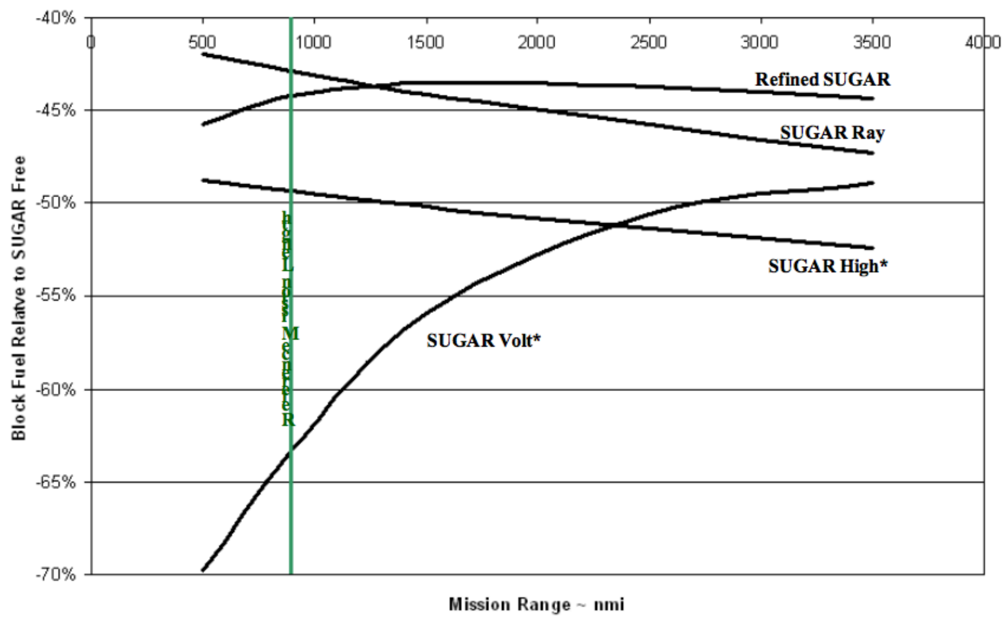
[Data: Hepperle, 2012; Gnadt et al., 2019]



[Data: Sabre, year 2015 schedules]

Hybrid electric aircraft

- Uses conventional jet fuel + battery
  - The fuel can be used to generate electricity to power electric propulsors, reducing fuel use per flight
  - This helps with range constraints, but overall CO_2 benefits are less than with a fully battery-electric aircraft
- E.g. NASA/Boeing SUGARvolt design
- Up to 70% fuel burn reduction (from year-2008 tech) at short range
- Smaller benefits at long range



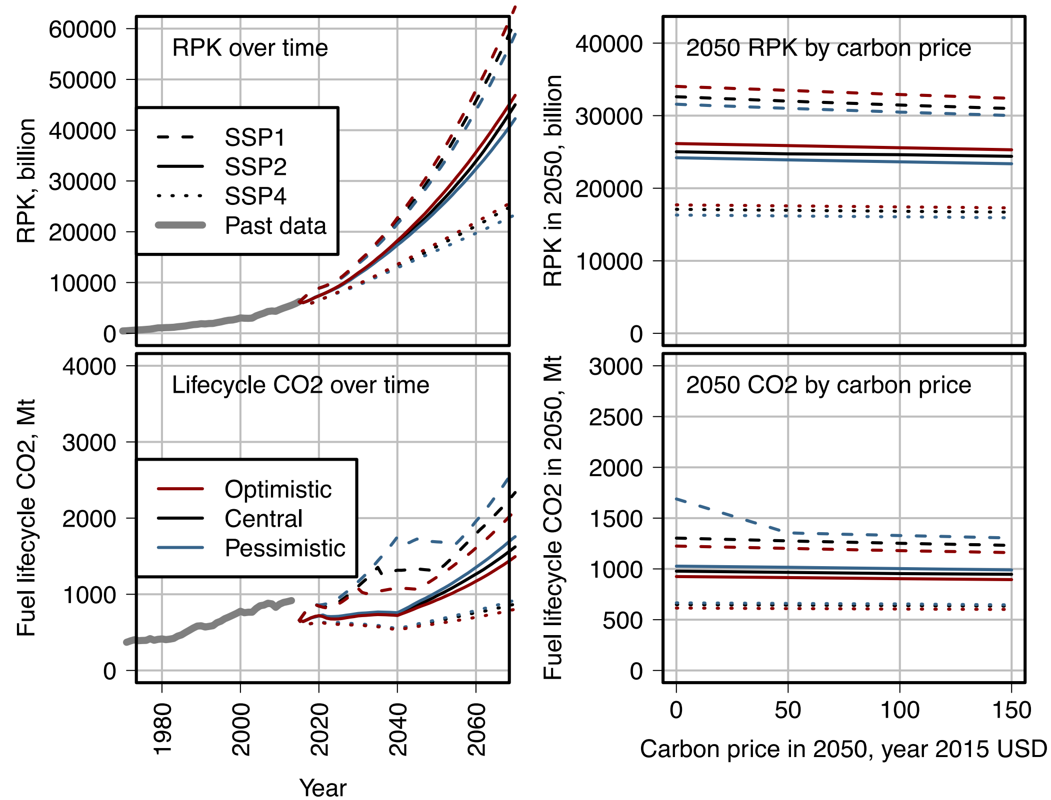
[Source: NASA; Bradley & Dromey 2015]

Modelling how (and whether) these technologies could affect global emissions

Conventional tech + BWB/CRP/Biofuel

- Dray et al. (2018)
  - Technologies only adopted if cost-effective
  - Cost curve model for biofuel
  - Range of socioeconomic/ technological scenarios
- RPK growth of 3.0 – 5.5%/year 2015-2035 by scenario
- Year-2050 fuel lifecycle CO_2 varies between 620 and 1690 Mt
  - Without biofuels, 1630 – 3400 Mt
- 1.9-3.0 %/year reduction in lifecycle fuel/RPK to 2050
  - Without biofuels, 0.8 – 1.6 %/year

With biofuels

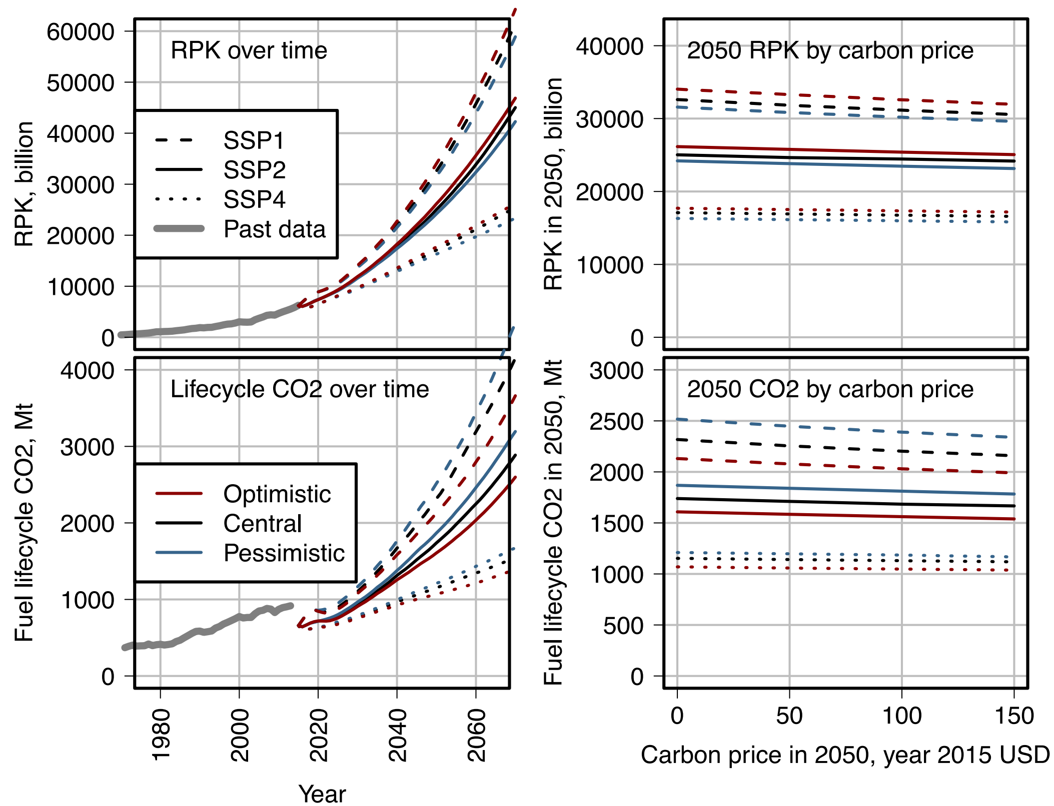


[Past data: ICAO, 2016; IEA, 2017; note past CO_2 includes unscheduled/freight/military flights]

Conventional tech + BWB/CRP/Biofuel

- Dray et al. (2018)
  - Technologies only adopted if cost-effective
  - Cost curve model for biofuel
  - Range of socioeconomic/ technological scenarios
- RPK growth of 3.0 – 5.5%/year 2015-2035 by scenario
- Year-2050 fuel lifecycle CO_2 varies between 620 and 1690 Mt
  - Without biofuels, 1630 – 3400 Mt
- 1.9-3.0 %/year reduction in lifecycle fuel/RPK to 2050
  - Without biofuels, 0.8 – 1.6 %/year

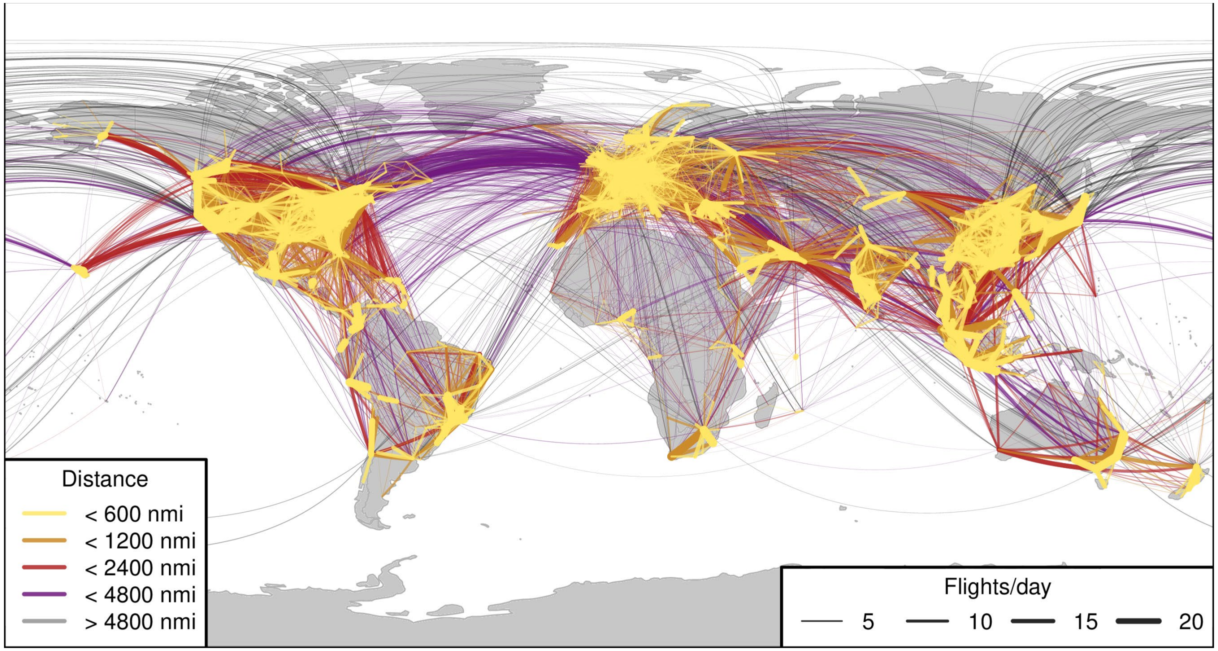
Without biofuels

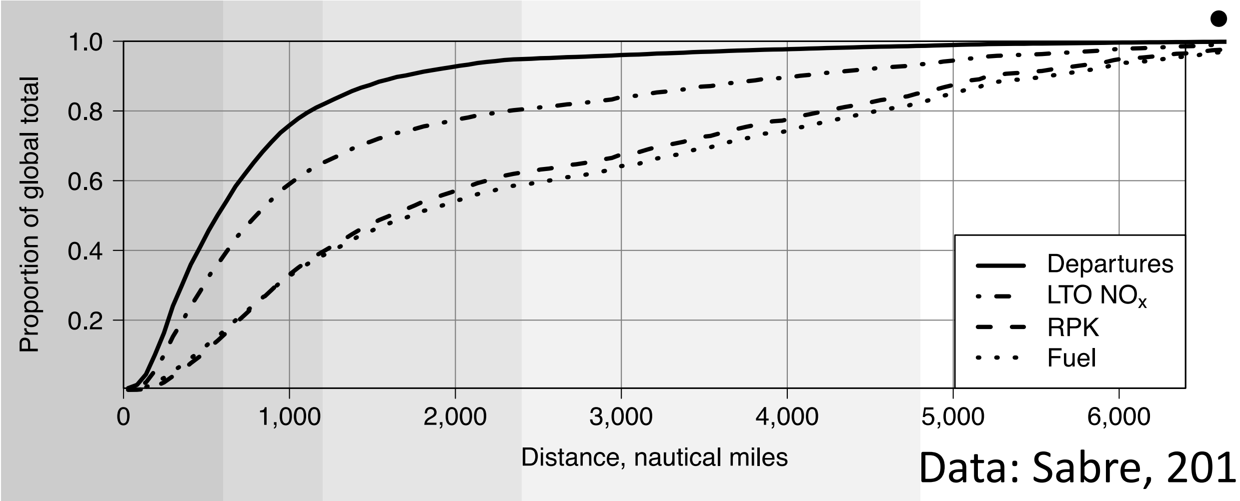


[Past data: ICAO, 2016; IEA, 2017; note past CO_2 includes unscheduled/freight/military flights]

Battery Electric Aircraft

- Schäfer et al. (2019)
- Range dependence is vital
- In the most constrained cases only a very local network is possible





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

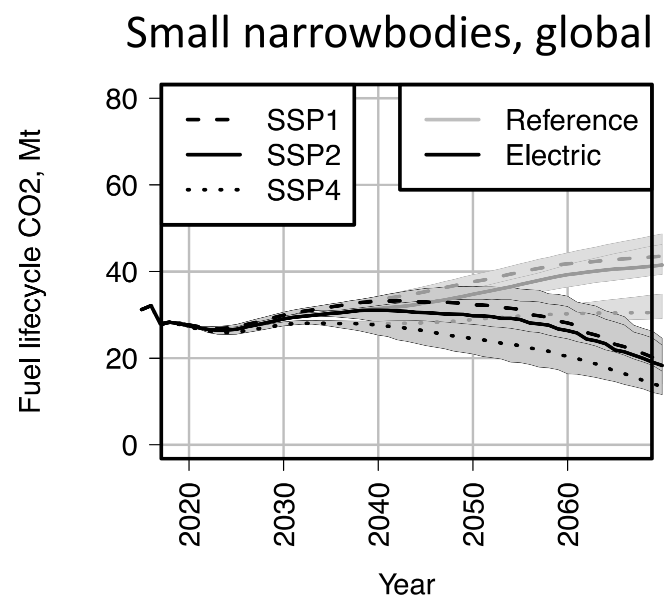
Data: Sabre, 2017 (from 2015 global schedules)]

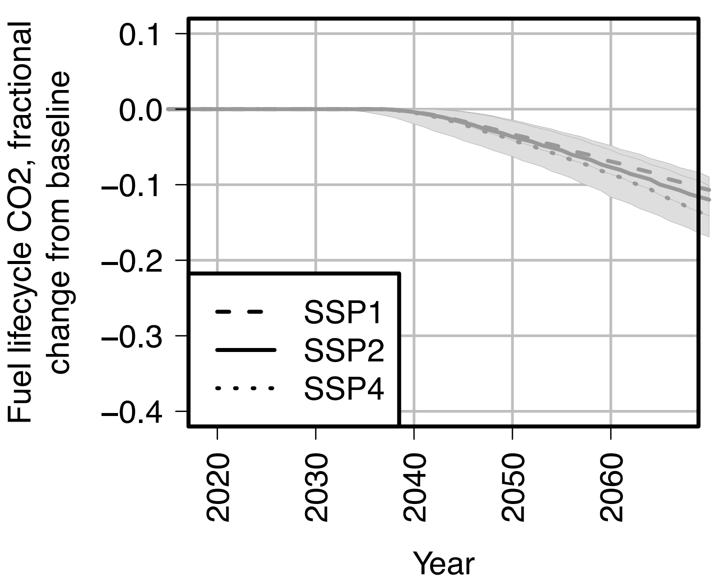
Air Transportation Systems Lab

UCL

Battery electric aircraft

- Large impact on compatible route CO_2
- BUT compatible routes account for a small fraction of global CO_2
- End result may be only ~ 10-15% global CO_2 reduction from non-electric baseline





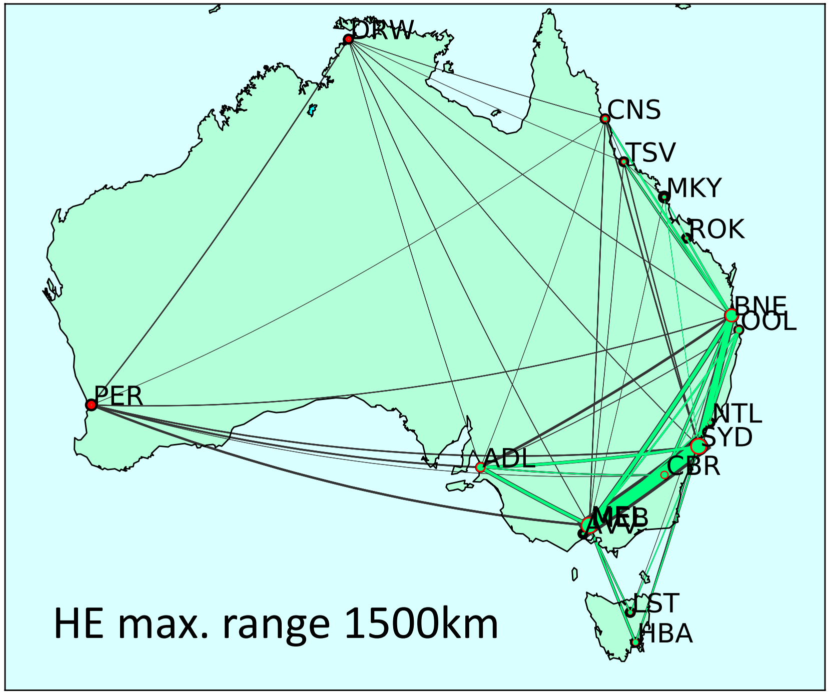
- Still may be important as part of a basket of future measures
- Contrails, local NOx/PM and noise will decrease

- Extra electricity demand relatively small
  - E.g. Electrifying all flights under 600 nmi would add less than 2% to global demand

Hybrid electric aircraft

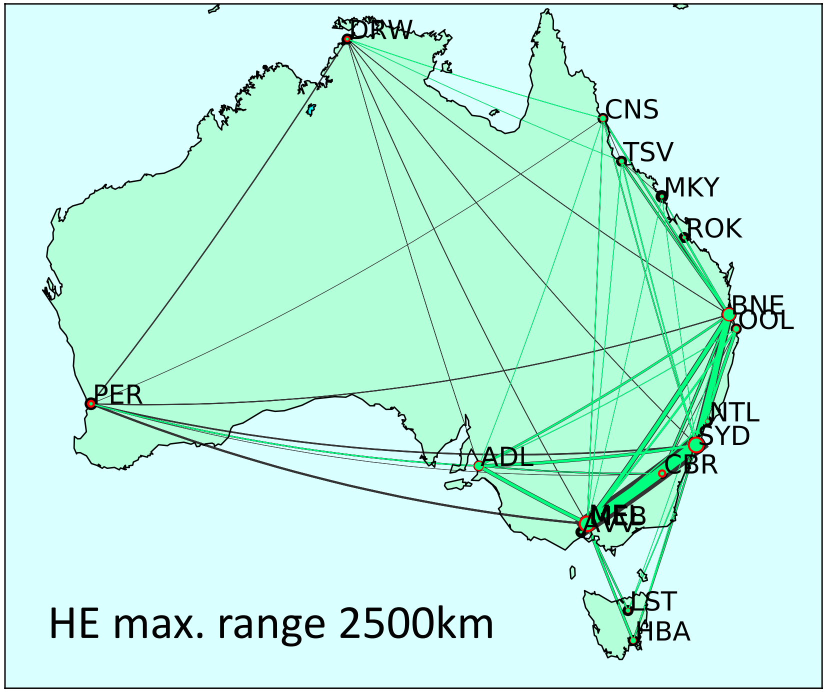
- Doyme et al., in preparation
- Using the full airline behaviour model to simulate hybrid electric aircraft adoption by competing airlines
  - E.g. What characteristics would the aircraft need to be cost-competitive at different fuel prices?

- Test case using the 2035 Australian domestic market
  - Identifies feasible fuel price, range, capacity conditions for adoption
  - Up to 20% reduction in jet fuel use compared to case without hybrid electric aircraft



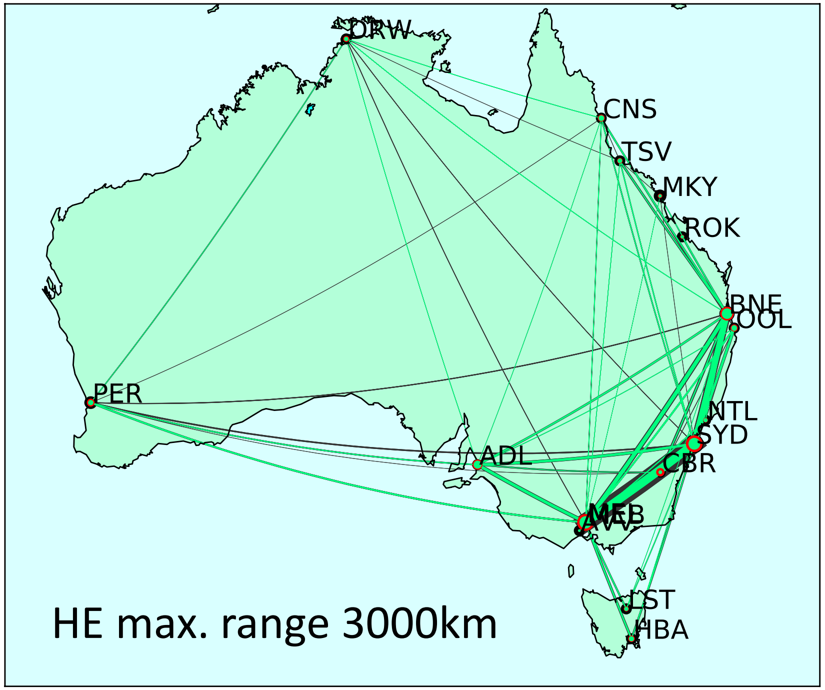
Hybrid electric aircraft

- Doyme et al., in preparation
- Using the full airline behaviour model to simulate hybrid electric aircraft adoption by competing airlines
  - E.g. What characteristics would the aircraft need to be cost-competitive at different fuel prices?
- Test case using the 2035 Australian domestic market
  - Identifies feasible fuel price, range, capacity conditions for adoption
  - Up to 20% reduction in jet fuel use compared to case without hybrid electric aircraft



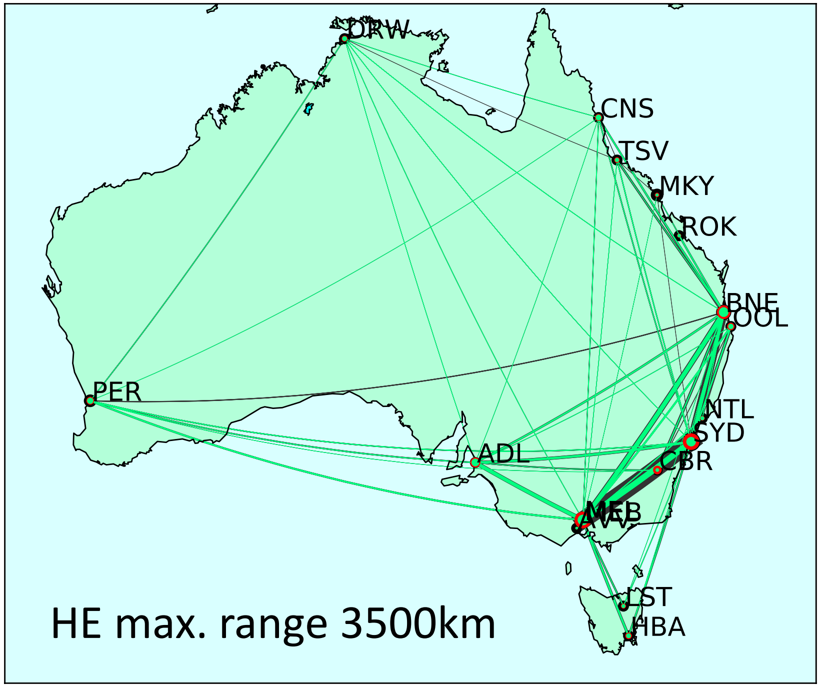
Hybrid electric aircraft

- Doyme et al., in preparation
- Using the full airline behaviour model to simulate hybrid electric aircraft adoption by competing airlines
    - E.g. What characteristics would the aircraft need to be cost-competitive at different fuel prices?
- Test case using the 2035 Australian domestic market
    - Identifies feasible fuel price, range, capacity conditions for adoption
    - Up to 20% reduction in jet fuel use compared to case without hybrid electric aircraft



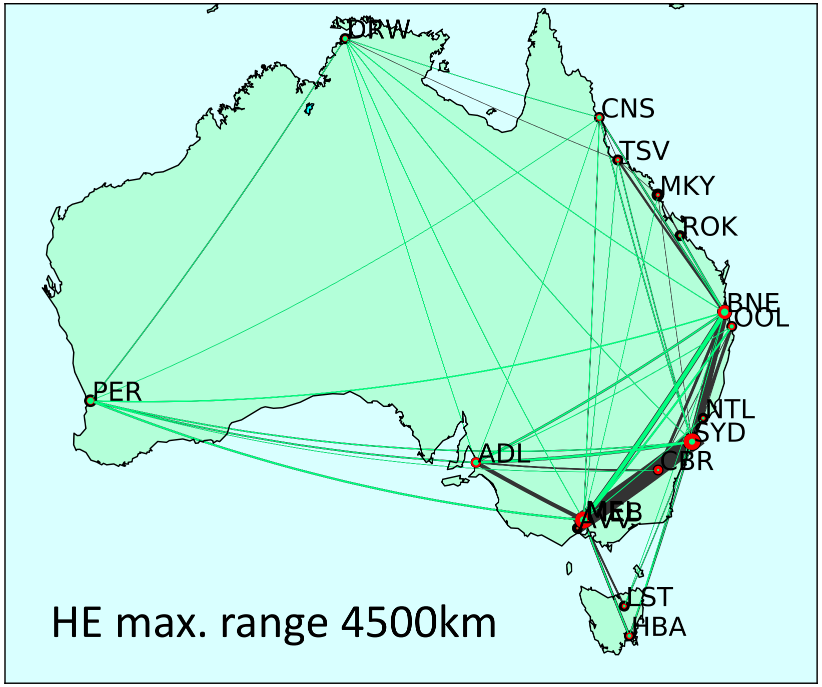
Hybrid electric aircraft

- Doyme et al., in preparation
- Using the full airline behaviour model to simulate hybrid electric aircraft adoption by competing airlines
  - E.g. What characteristics would the aircraft need to be cost-competitive at different fuel prices?
- Test case using the 2035 Australian domestic market
  - Identifies feasible fuel price, range, capacity conditions for adoption
  - Up to 20% reduction in jet fuel use compared to case without hybrid electric aircraft



Hybrid electric aircraft

- Doyme et al., in preparation
- Using the full airline behaviour model to simulate hybrid electric aircraft adoption by competing airlines
  - E.g. What characteristics would the aircraft need to be cost-competitive at different fuel prices?
- Test case using the 2035 Australian domestic market
  - Identifies feasible fuel price, range, capacity conditions for adoption
  - Up to 20% reduction in jet fuel use compared to case without hybrid electric aircraft



So how low can we go?

- For an **individual flight**: 80+% reduction in fuel lifecycle CO_2
- For **global aviation**
  - **Stabilising** emissions within-sector to 2060 is possible if:
    - GDP growth is on the low end of what is projected
    - Biomass supply is enough to substitute around 50% of fossil aviation fuel
    - Future fossil fuel prices (including carbon price) are above present levels
    - Current projected improvements in operations and technologies are realised
  - **Reducing** emissions from current levels is possible if, additionally:
    - Biomass supply is enough to substitute most or all long-haul flight fuel
    - Short-haul flights are either electrified or use (more) biofuels

AIM/ACCLAIM team and collaborators

Prof. Steven R.H. Barrett (MIT)
Dr. Lynnette Dray (UCL)
Dr. Khan Doyme (UCL)
Mr. Raphael Eder (UCL)
Dr. Roger Gardner (U. Southampton)
Mr. Albert Gnadt (MIT)
Dr. Chez Hall (U. Cambridge)
Dr. Joanna Kuleszo (UCL)
Mr. Weibo Li (UCL)
Dr. Antonio Martinez (U. Southampton)
Prof. Andreas W. Schäfer (UCL)
Prof. Rod Self (U. Southampton)
Dr. Aidan O'Sullivan (UCL)
Mr. Bojun Wang (UCL)

For more information:
www.atslab.org