# Modelling the impact of small hydrogen aircraft characteristics on potential UK domestic uptake

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# Introduction

- Aviation accounts for around 3.5% of anthropogenic effective radiative forcing (Lee et al. 2020)
  - The sector's current increasing emissions trajectory is not compatible with Paris agreement goals…
  - …but putting the sector on a net zero aligned trajectory requires radical changes:

$$\text{Climate impact } (CO_{2eq}) = \underbrace{\frac{CO_{2eq}}{E}}_{\text{Fuel Composition}} \cdot \underbrace{\frac{E}{RTK}}_{\text{Energy Intensity}} \cdot \underbrace{RTK}_{\text{Air Transport Demand}} - \underbrace{Offsets}_{\text{CORSIA, DAC, ETS allowances…}}$$

**$CO_{2eq}$ includes:**

- **$CO_2$ from aircraft engines**
- **Lifecycle $CO_2$ from fuel production**
- **Non-$CO_2$ from aircraft engines (Contrails, NOx, AIC…)**
- **Lifecycle non-$CO_2$ from fuel production ($CH_4$, $N_2O$, …)**

- **Energy intensity:** -2.7%/year 1980-2018, but slower rates (<2%/year) projected in future
- **RTK:** +5.5%/year 1980-2018, 2.3-4.1%/year projected 2019-2050

*Increase in total climate impact if other factors do not change*

- **Non-$CO_2$:** requires **change in fuel type** or operations for significant change
- **Fuel Composition:** requires **move away from fossil kerosene** for significant change

[Data: IEA, 2019; ICAO, 2019; Dray & Schäfer 2021]

# Decarbonising aviation with hydrogen

- Deep decarbonisation within the aviation sector (i.e., excluding offsets) requires demand reduction or technology change
  - Either rapid increase in drop-in alternative fuels…
    - Biofuels (high TRL, likely low supply) or Power-to-Liquids (low TRL, currently high cost)
  - …or changing both aircraft and fuel (hydrogen, electricity)
    - Hydrogen long-haul aircraft are feasible in 2050, electric are not

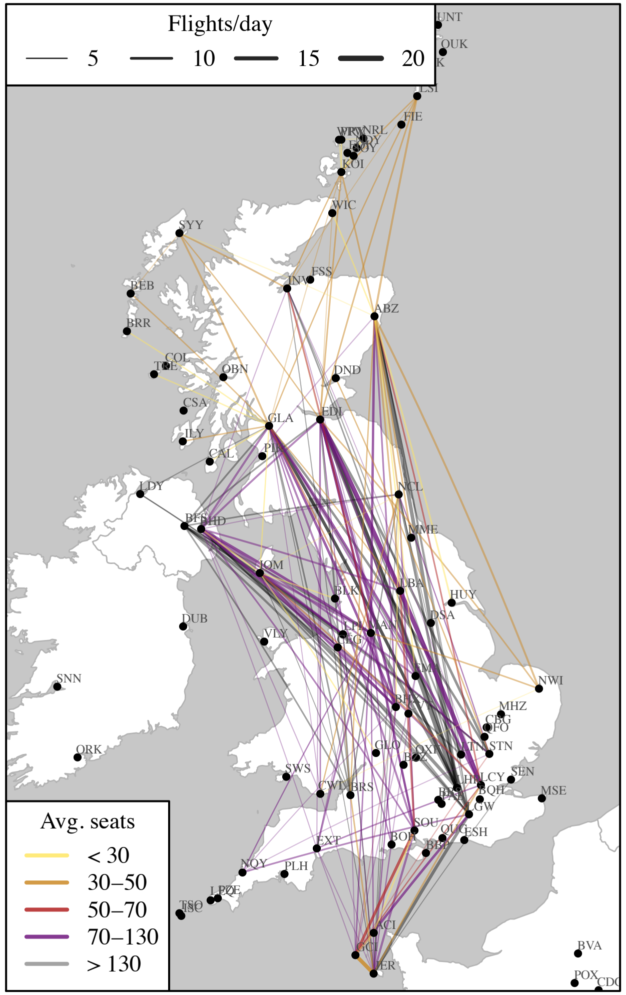
- Hydrogen aircraft are technically feasible, but many uncertainties about their introduction:
  - Future Jet A and hydrogen prices are uncertain
  - Maintenance and capital costs are uncertain
  - Infrastructure and fleets will need to change
  - Early hydrogen aircraft are likely to have different operating characteristics to conventional designs (size, range, …)
  - Under what circumstances will they be operationally feasible to use for airlines?
- To investigate we use the UCL **Airline Behaviour Model**

[Image sources: NASA, 2018; Airbus, 2020; Wikimedia Commons]

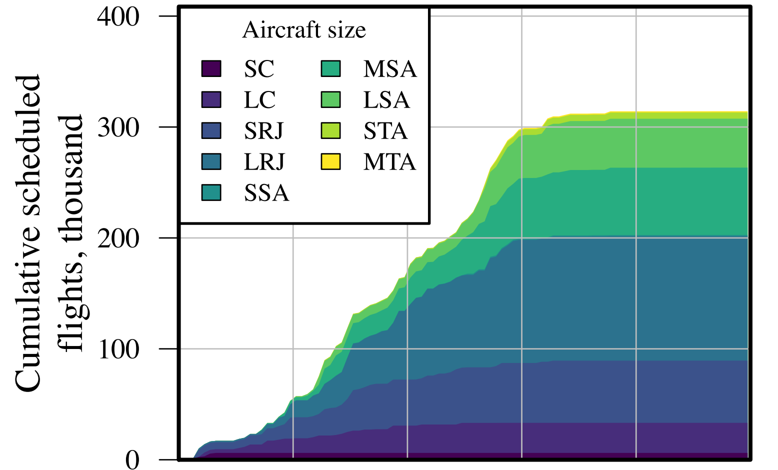
# The UK domestic aviation system – a test case for hydrogen aircraft?

- There is a proposed net zero target for **2040** for UK domestic flights (DfT, 2021)
- Limited emissions impact (1.5 $MtCO_2$ in 2015, <0.3% of global $CO_2$)…
- …but short distances and 2040 emissions target make the UK a promising environment for early hydrogen aircraft
    - Also aligns with UK hydrogen strategy (5GW green hydrogen production capacity target by 2030)
- The UK is also a useful test environment due to the mix of carrier and route types:
    - Network carriers (e.g. BA/OneWorld), often on busy routes from constrained airports, using a mix of aircraft sizes
    - LCCs (e.g. Easyjet), often on busy routes to/from secondary airports, using mid/large-size narrowbodies
    - Regional carriers (e.g. LoganAir), often on minor and PSO routes
    - Often low profitability, with recent high-profile airline bankruptcies

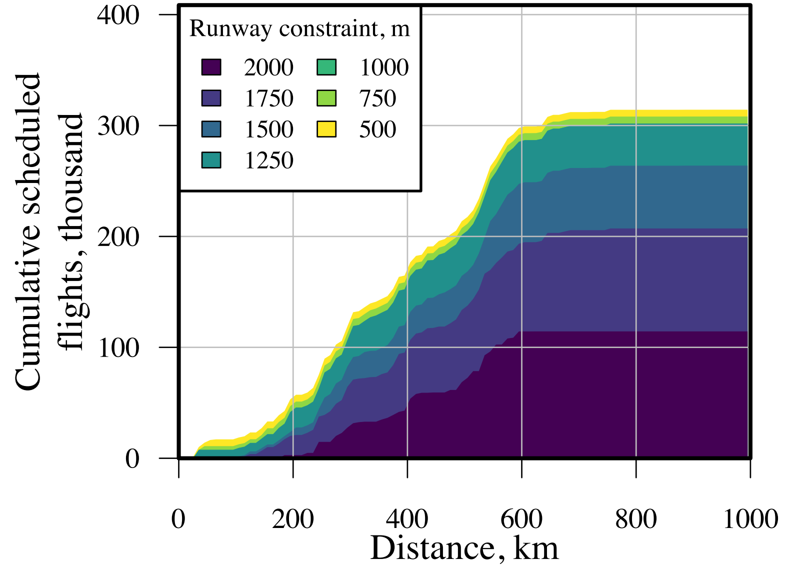
(a) Network



(b) Cumulative flights by aircraft size



(c) Cumulative flights by runway constrain



# Project NAPKIN and the UCL Airline Behaviour Model

- The Airline Behaviour Model (ABM) is an optimisation model which simulates the behaviour of competing airlines as they seek to maximise profits across their networks (Doyme et al. 2019)
  - Previously adapted for use in Australia (Doyme et al. 2019) and North America (Doyme et al. 2022)
  - Also used to investigate capacity constraints, scarcity rents and cost pass-through at airports (Dray et al. 2020)
- This study was carried out as part of Project NAPKIN (New Aviation Propulsion Knowledge and Innovation Network)
  - 18-month UK Future Flight Challenge-funded project with a consortium of airports (Heathrow, London City, Highlands and Islands), manufacturers (Rolls-Royce, GKN, Cranfield Aerospace Sciences) and universities (UCL, Southampton, Cranfield)
  - Modelling the transition to a UK zero-carbon aviation system using a ‘whole-systems’ approach – Aircraft, Airlines, Airports, Airspace, Air Passengers
  - For NAPKIN, we adapted the ABM to a UK context to assess the market feasibility of specific hydrogen aircraft designs
  - The model runs shown here assess hypothetical hydrogen aircraft rather than the specific manufacturer-led designs used in the NAPKIN final report, but aircraft characteristics and trade-offs are informed by NAPKIN outcomes
  - **Final report out in September** also including aircraft design, safety, infrastructure and noise analysis

**NAPKIN partners:**

# UCL Airline behaviour model - methodology

**Each airline is a player in an n-player noncooperative game. They attempt to maximise profit by adjusting the decision variables of airfares, flight frequency and choice of aircraft on routes within their network:**

$$P_A = \underset{\text{Revenue}}{\boxed{\sum_{i\in \mathrm{ITN}_A} fare_i.pax_i + arev_A.pax_A}} - \underset{\text{Flight related costs}}{\boxed{\sum_{j\in \mathrm{SEG}_A} \sum_{a\in \mathrm{CRFT}_j} opcost_{a,j}.freq_{a,j}}} - \underset{\text{Passenger related costs}}{\boxed{\sum_{j\in \mathrm{SEG}_A} \sum_{a\in \mathrm{CRFT}_j} paxcost_{a,j}.pax_{a,j}}}$$

**Passenger numbers are limited by each itinerary's market share of overall air travel demand between two locations:**

$$pax_i \leq \boxed{\mathrm{MS}_i}.\boxed{\mathrm{D}_i}$$

**Itinerary market share given by a (MNL) choice model:**

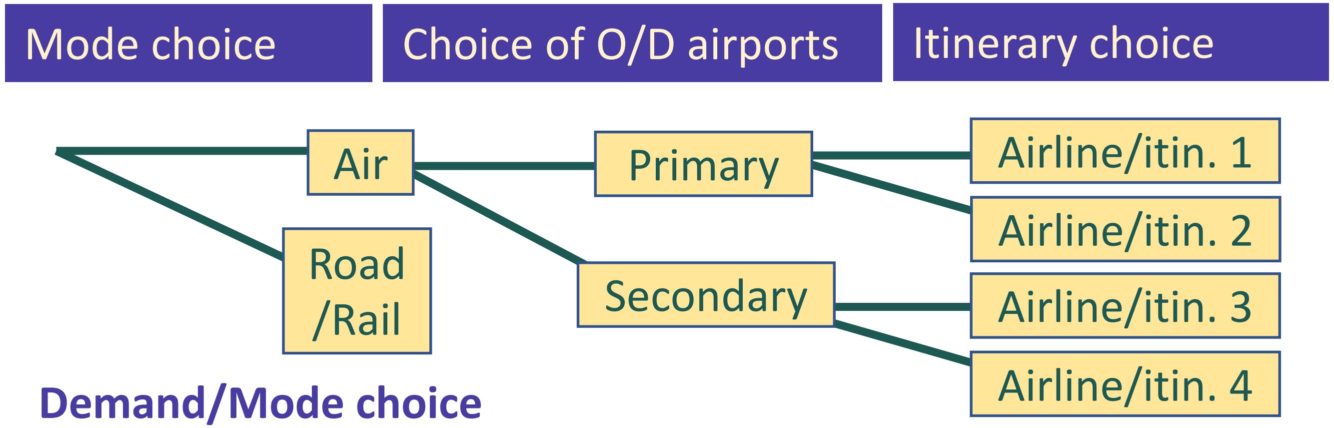
$$\mathrm{MS}_i = \frac{e^{U_i}}{\sum_{j\in \mathrm{ITN}_{o_i d_i}} e^{U_j}}$$

**Overall city-pair air travel demand, given by a gravity model.**

**Constraints also include fleet, the number of seats available on each aircraft type, airport capacity and Public Service Obligations (PSOs).**

# Airline Behaviour Model adaptation and validation for the UK

- For UK domestic flights, mode/airport choice is more complex than in Doyme et al. (2019)
- We use a nested logit model to capture this, based on Doyme et al. (2022) and Jamin et al. (2004)
- Estimated using UK+European data (Sabre 2017) – $R^2 = 0.7$



## Demand/Mode choice

$$D_{o_i d_i} = \alpha_1 Min\left(P_{o_i}, P_{d_i}\right)^{\alpha_2} Max\left(P_{o_i}, P_{d_i}\right)^{\alpha_3} \left(I_{o_i} I_{d_i}\right)^{\alpha_4} e^{\alpha_5 FracLH_{o_i d_i}} e^{\alpha_6 Dom_{o_i d_i}} \times e^{\alpha_7 CL_{o_i d_i}} e^{\alpha_8 North_{o_i d_i}} e^{\alpha_9 Spec_{o_i d_i}} e^{\alpha_{10} Visa_{o_i d_i}} e^{\alpha_{11} L_{o_i d_i}} \times \frac{e^{\alpha_{12} L^{air}_{o_i d_i}}}{e^{\alpha_{12} L^{air}_{o_i d_i}} + e^{U^{ground}_{o_i d_i}}},$$

where $L_{o_i d_i} = \log\left(e^{\alpha_{12} L^{air}_{o_i d_i}} + e^{U^{ground}_{o_i d_i}}\right)$ and $U_{ground} = \alpha_{13} + \alpha_{14} Min\left(t_{drive,o_i d_i}, t_{rail,o_i d_i}\right) + \alpha_{15} SD_{o_i d_i}$

## Airport/itinerary choice

$$MS_{A^o_k A^d_k} = e^{V_k} \Big/ \sum_{A^o \in Apts_{o_m},\, A^d \in Apts_{d_m}} e^{V_m}$$

where $V_k = \beta_1 L_{A^o_k A^d_k} + C_{A^o} + C_{A^d}$ and $L_{A^o A^d} = \log\left(\sum_{j \in ITNS_{A^o_i A^d_i}} e^{U_j}\right)$

$$MS_i = e^{U_i} \Big/ \sum_{j \in ITNS_{A^o_i A^d_i}} e^{U_j}$$ where $U_i = \gamma_1 Fare_i + \gamma_2 Time_i + \gamma_3 \log(Freq_i / Freq_{od}) + M_A$

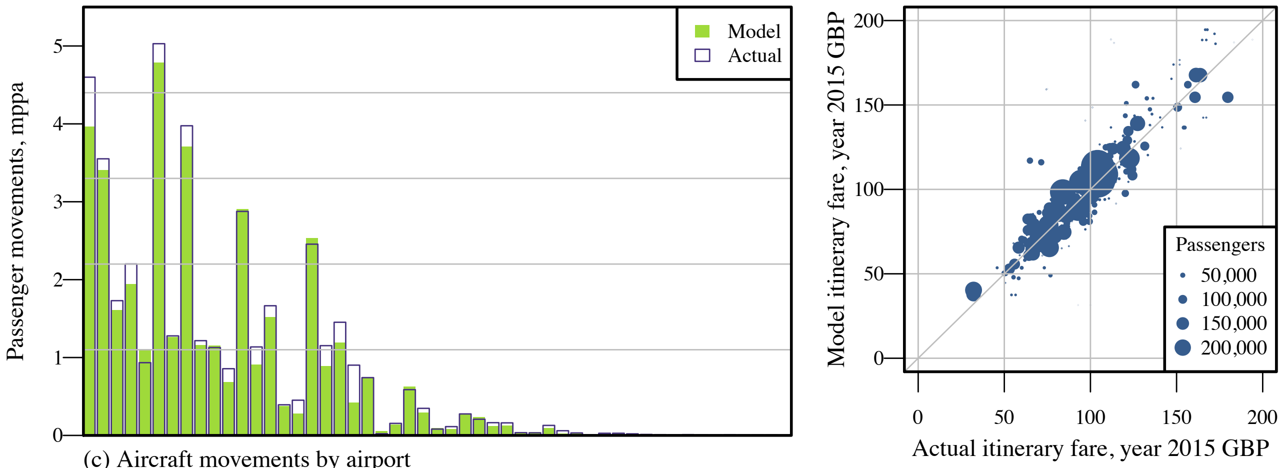
| Itinerary and Airport Choice | | Demand | |
|---|---|---|---|
| **Parameter** | Estimate (standard error) | Parameter | Estimate (standard error) |
| **$\gamma_1$ (Fare)** | -0.0040 (0.00008) | $\alpha_1$ (Intercept) | -15.9 (0.34) |
| **$\gamma_2$ (Time)** | -0.0043 (0.00005) | $\alpha_2$ (Smaller population) | 0.40 (0.006) |
| **$\gamma_3$ (Frequency)** | 0.862 (0.006) | $\alpha_3$ (Larger population) | 0.78 (0.012) |
| **$\gamma_4$ (Number of stops)** | -0.386 (0.0024) | $\alpha_4$ (Income*) | 0.48 (0.01) |
| **$M_A$ (Airline) – BM†** | -0.166 (0.165) | $\alpha_5$ (FracLH) | 1.26 (0.05) |
| **$M_A$ (Airline) – GR** | -0.197 (0.263) | $\alpha_6$ (Domestic) | 0.67 (0.02) |
| **$M_A$ (Airline) – ONEWORLD** | 0.060 (0.040) | $\alpha_7$ (Common language) | 0.61 (0.02) |
| **$M_A$ (Airline) – T3** | -0.480 (0.20) | $\alpha_8$ (Far North) | 1.42 (0.02) |
| **$M_A$ (Airline) – U2** | -0.58 (0.005) | $\alpha_9$ (Tourist destination) | 0.57 (0.01) |
| **$M_A$ (Airline) – Virgin** | -0.46 (0.33) | $\alpha_{10}$ (Visa required) | -1.84 (1.14) |
| **$M_A$ (Airline) - FR** | -0.583 (0.050) | $\alpha_{11}$ (Mode choice logsum) | 0.27 (0.01) |
| **$M_A$ (Airline) – other** | 0.02 (0.04) | $\alpha_{12}$ (Itinerary choice logsum) | 2.80 (0.11) |
| **$\beta_1$ (Airport choice logsum)** | 1.393 (0.004) | $\alpha_{13}$ (Ground transport utility intercept) | 1.63 (0.19) |
| | | $\alpha_{14}$ (Ground transport time) | -0.02 (0.0006) |
| | | $\alpha_{15}$ (Short ground transport distance) | 1.82 (0.14) |

# Airline Behaviour Model adaptation and validation for the UK

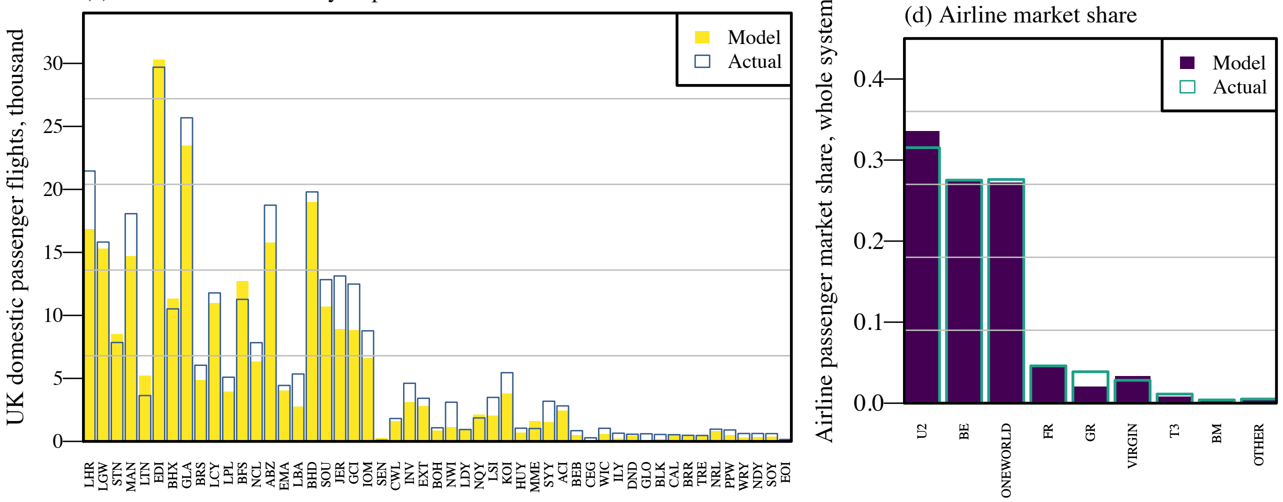
- We use a 2015 base year
- Baseline fares, routing, numbers of passengers and numbers of flights are compared with Sabre booking data (Sabre, 2017)
- Some other UK-specific model adaptations are added:
  - 9- and 19-seater aircraft, including aviation gasoline use
  - PSO routes and other routes with minimum frequency requirements
  - Air Passenger Duty (APD) route eligibility
  - Adding in international transfer passengers on specific routes (e.g. Manchester-London)
- Airline operating cost estimation is derived from work commissioned by the CCC and DfT (ATA & Ellondee, 2018)
  - The NAPKIN advisory board includes multiple airlines who were able to provide additional data/validation

(a) Passenger movements by airport

(b) Fares



(c) Aircraft movements by airport


(d) Airline market share

# Model run setup

- We use the validated UK Airline Behaviour Model to simulate what the future UK domestic aviation system might look like with hydrogen aircraft availability
- The runs presented here all use a similar setup:
  - Start with the validated baseline, make changes and see how the system responds:
    - Domestic APD decrease (as announced in UK Autumn Budget 2021)
    - Airlines have the option of investing in new aircraft:
      - **Conventional aircraft** (of the same sizes as they already have in their fleets), *or*
      - **Hydrogen aircraft** of similar size to those in an airline's existing fleet
    - Assess how uptake and other system outcomes vary as aircraft or system parameters are changed:
      - Aircraft characteristics: range, capacity, runway length required **(step 1)**
      - Jet A/carbon price, hydrogen price, APD on hydrogen aircraft passengers **(step 2)**
- We keep other baseline demand drivers constant for now, reflecting uncertainty in how domestic demand may develop – however it is possible to change these
- Similarly, although we use existing airports, airlines, networks, and airport capacity, it is possible to look at the impact of changing these (e.g. Doyme et al. 2022, Dray et al. 2020)

# Modelling how aircraft characteristics affect uptake

Early hydrogen aircraft are likely to differ from conventional designs in several ways:

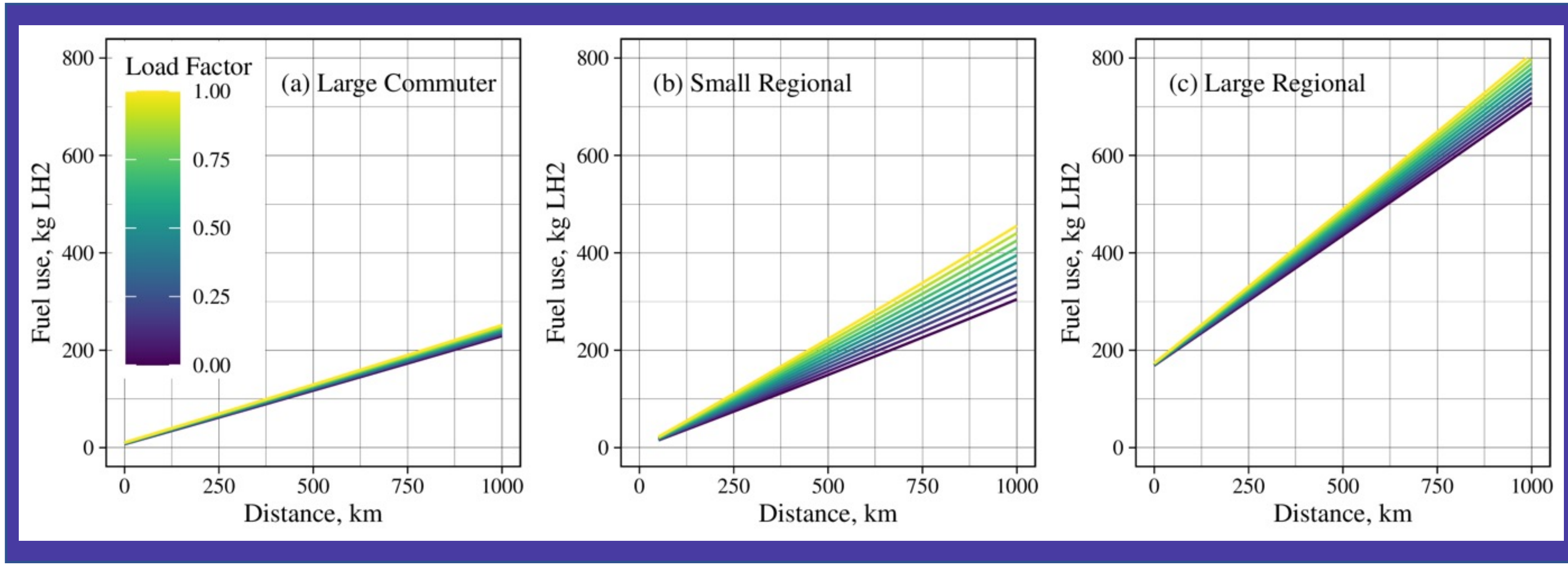
- **Size:** likely to be small aircraft (e.g., Project Fresson 2023 7-seater)
- **Range:** may have shorter ranges than conventional equivalents, depending on how much fuel they are able to carry
- **Runway length:** might require longer runways to take off and land
- **Number of seats:** accommodating hydrogen tanks may take space that could be used for seating/luggage.

- These factors trade off with each other and with operating cost.
  - **Step 1:** we investigate which of these design compromises have the largest impact on uptake for individual aircraft size classes, for a single set of operating cost assumptions.
  - **Step 2:** we investigate how different designs compete against each other and conventional aircraft at different cost assumptions, accounting for potential design compromises

# Step 1: how do aircraft characteristics affect uptake?

- For this analysis we assume hypothetical hydrogen aircraft :
  - Large Commuter (LC) - based on 19-seat Twin Otter
  - Small Regional (SR) – based on 78-seat ATR-72
  - Large Regional (LR) – based on 100-seat E190

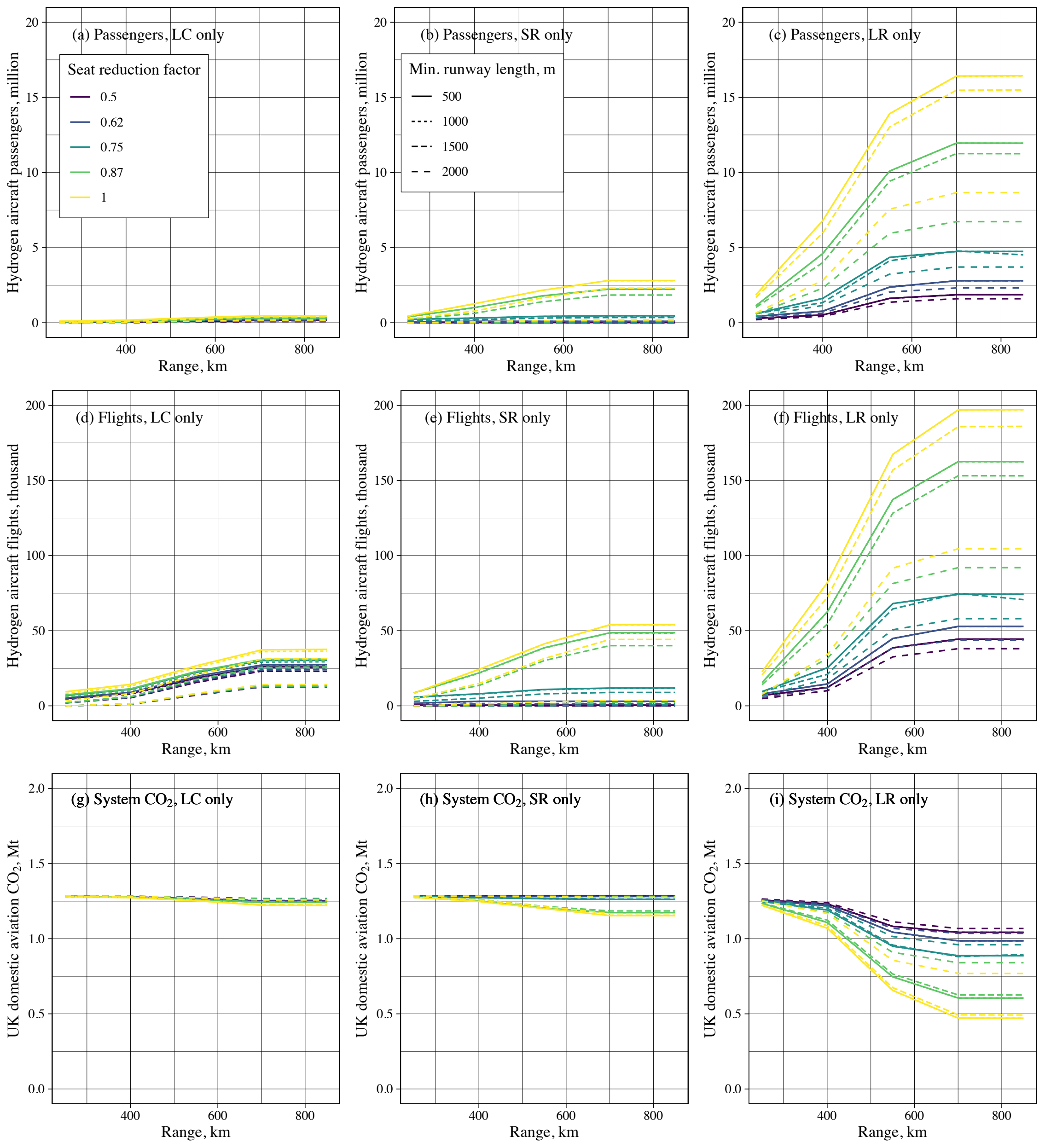
| Size class | Typical Seats | Ref. aircraft | Assumed ref. aircraft range, km | Assumed ref. aircraft min. runway length, m | Alternative aircraft |
|---|---|---|---|---|---|
| **Small Commuter (SC)** | 9 | B-N Islander | 900 | 427 | LH2 Large Commuter (LC) |
| **Large Commuter (LC)** | 19 | DHC Twin Otter† | 1,480 | 366 | |
| **Small Regional (SR)** | 70 | ATR-72 | 3,300 | 1,300 | LH2 Small Regional (SR) |
| **Large Regional (LR)** | 100 | Embraer 190 | 3,510 | 1,450 | LH2 Large Regional (LR) |
| **Small Single Aisle (SSA)** | 124 | Airbus A319 | 4,000 | 1,700 | N/A |
| **Med. Single Aisle (MSA)** | 150 | Airbus A320 | 4,500 | 1,700 | |
| **Large Single Aisle (LSA)** | 175 | Boeing 737-800 | 5,500 | 1,700 | |



- Wide range of literature estimates of LH2 aircraft performance
  - Can be more-less energy efficient than conventional aircraft
- We assume equal performance on an energy basis
- Variation in performance is assumed to have similar impact to variation in fuel price (explored later)

# Step 1: how do aircraft characteristics affect uptake?

- We set Jet A + carbon price at around \$1.7/kg and hydrogen price on an energy basis just below this
- Other operating costs set equal to the conventional reference
- For each set of runs, airlines have the option of extra conventional fleet or a single hydrogen design, with different:
  - Size class (LC only, SR only, LR only)
  - Maximum range (250-850 km)
  - Minimum required runway length (500 – 2,000m)
  - Number of seats (between 50 and 100% of the conventional reference)
- These ranges are set by UK domestic characteristics (few routes > 850km) and literature assessments of early hydrogen designs (e.g. McKinsey, 2020; Project Fresson; NAPKIN)
- We can then explore how different design characteristics which trade off against each other may affect uptake

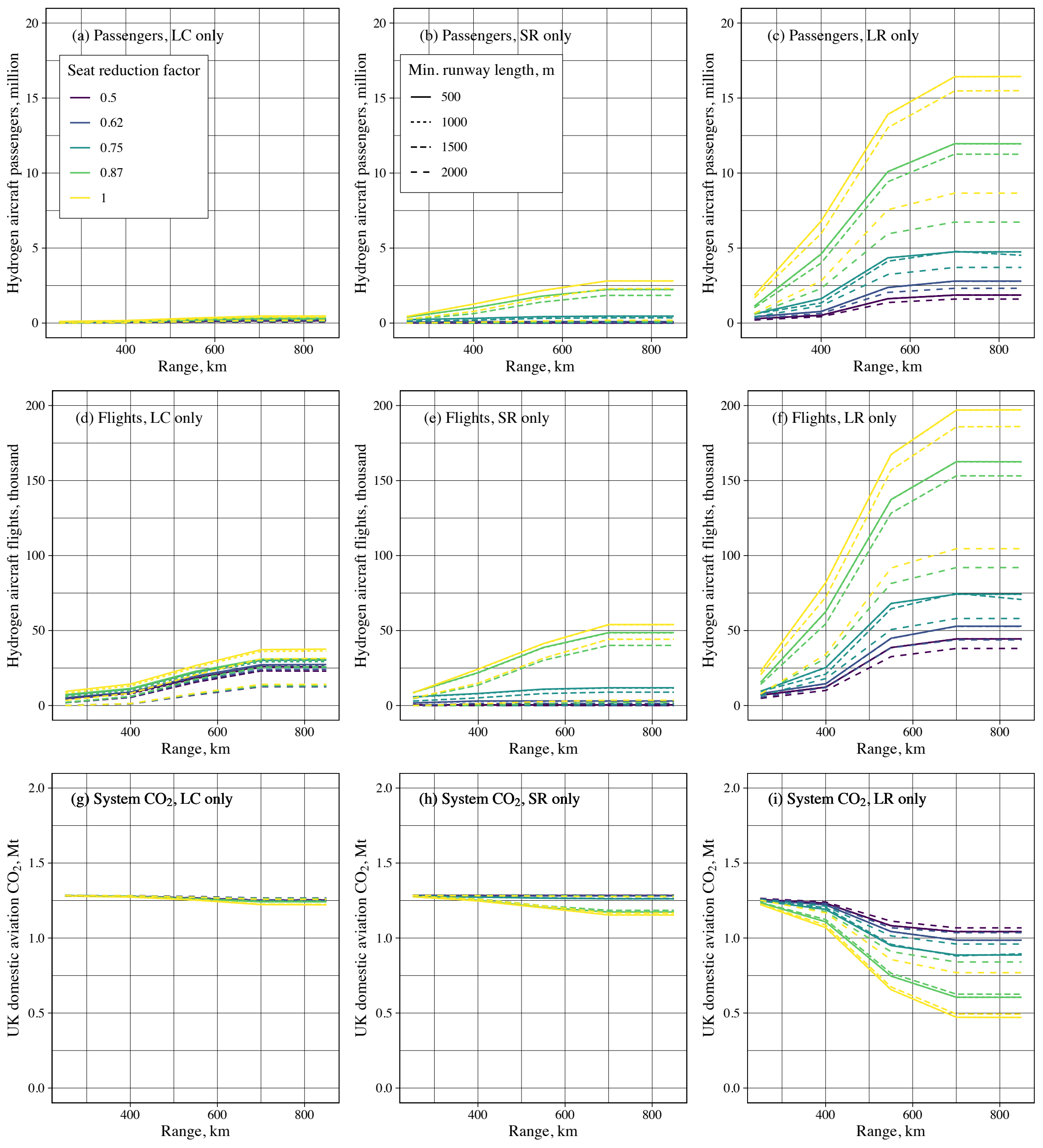


[Note: CO$_2$ reductions assume 100% fossil kerosene in conventional aircraft]

# Step 1: how do aircraft characteristics affect uptake?

Conclusions:

- **Large Commuter (LC) aircraft**
  - Limited impact on UK domestic $CO_2$ – niche market (e.g. PSO routes)
  - Need short runway capability; can potentially compromise on range
- **Small Regional (SR) aircraft**
  - Can compromise on seats but large reductions (<85% of conventional equivalent) see big drop in uptake
  - Slower cruise speed (based on turboprop design) also affects substitution potential for larger aircraft
  - Much less requirement for short runway capability
- **Large Regional (LR) aircraft**
  - Uptake potential (and $CO_2$ reduction potential) much larger than for LC, SR
  - Similar response to changes in range, size, runway length as SR aircraft – but longer range is more important



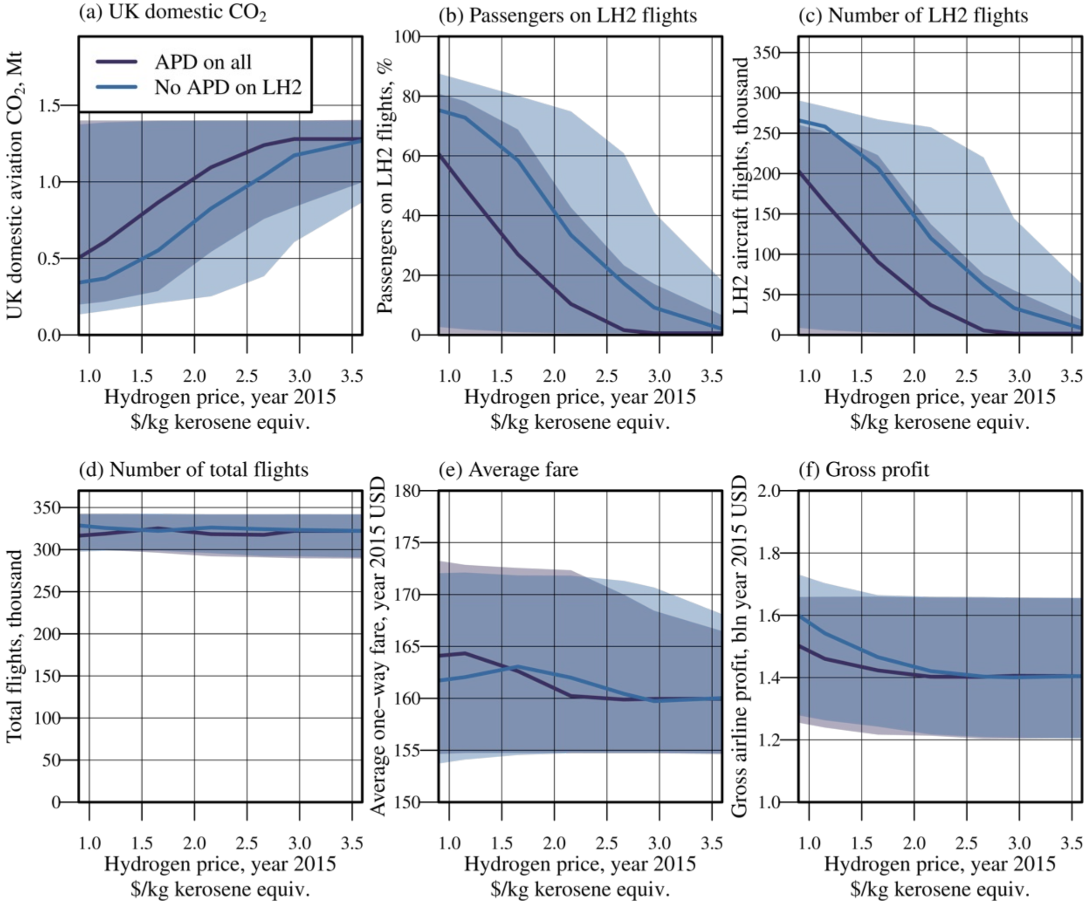
[Note: CO2 reductions assume 100% fossil kerosene in conventional aircraft]

# Step 2: how does policy and operating cost affect uptake?

- Using analysis from Step 1 (informed by NAPKIN designs) we assume:
  - LC aircraft have reduced range (400km) but are short runway capable (500m)
  - SR and LR aircraft require longer runways (1500m) and have seat capacity at 85% of the conventional reference
- For step 2, we make all three size classes of LH2 aircraft available to airlines
  - These designs compete against each other as well as against conventional aircraft
  - We assess uptake over different **cost** and **policy** inputs based on what might be feasible over the period to 2040:
    - **LH2 aircraft capital and maintenance costs**: between 100-160% of conventional aircraft costs (McKinsey et al., 2020)
    - **LH2 prices:** \$2.5-10/kg$H_2$ (\$0.9-3.6/kg kerosene equivalent; IRENA, 2020; Dray et al., 2022)
    - **Effective Jet A prices:** \$0.7-2.7/kg including UK ETS carbon price (EIA, 2021; BEIS, 2021)
    - **Air Passenger Duty**: hydrogen aircraft exempt, or hydrogen aircraft included (HMRC, 2021)
    - **Aviation Gasoline price:** \$3.4/kg used throughout (NAPKIN)
  - These model runs examine what cost-effective operations and emissions might look like once airlines have had time to turn over their UK domestic fleet
  - Note that costs and design limitations also trade off against each other (e.g., retrofits vs. clean sheet designs) – not modelled here, but see NAPKIN final report

# Step 2: how does policy and operating cost affect uptake?

- System-level outcomes depend strongly on fuel prices
  - At high Jet A/low LH2 prices, <100 seat LH2 aircraft can address **almost all UK domestic $CO_2$** (90% of flights)


(a) UK domestic $CO_2$

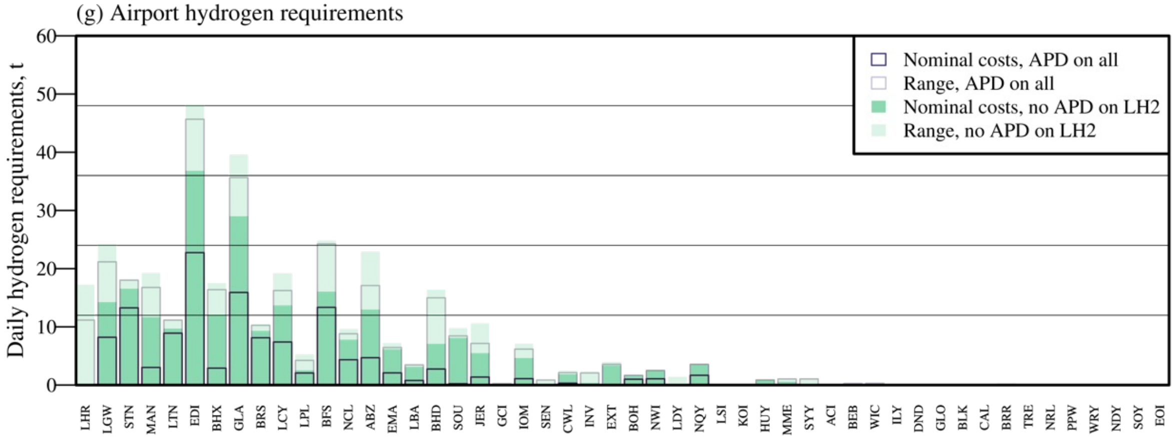
(b) Passengers on LH2 flights

(c) Number of LH2 flights

(d) Number of total flights

(e) Average fare

(f) Gross profit

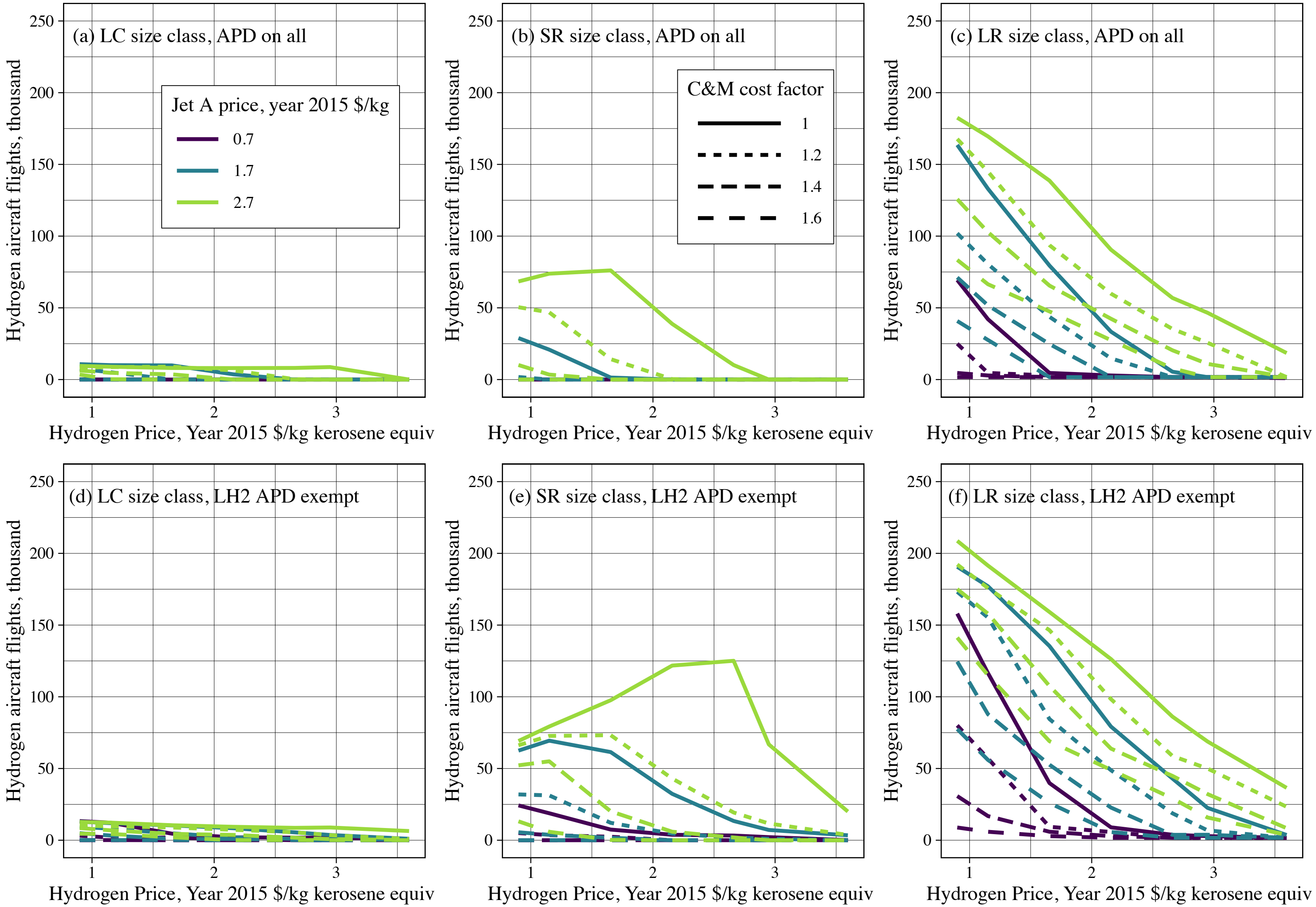

(g) Airport hydrogen requirements

[Nominal costs: $1.7/kg Jet A; $1.65/kg kerosene equiv. LH2]

- The bulk of emissions reductions come from the LR size class
  - It's likely that a 150-seater hydrogen aircraft (outside the scope of NAPKIN) would compete with the LR aircraft and also see strong uptake if available
  - One key uncertainty here is whether LCCs would consider an 85-seater aircraft if a 150-seater is in development (see NAPKIN final report)
- One key limitation for small hydrogen aircraft is capacity constraints (e.g., at Heathrow)
- About 150 LH2 aircraft are implied at high Jet A/low LH2 prices (110 at size LR)

# Step 2: how does policy and operating cost affect uptake?

- Operating cost assumptions affect different size aircraft differently:
- Large commuter – **non-fuel** costs have a large impact on uptake
- Small Regional – fuel and non-fuel costs important, ‘niche’ adoption conditions
- Large Regional – **fuel costs** and **APD** have largest impact



# Step 2: how does policy and operating cost affect uptake? Large Commuter

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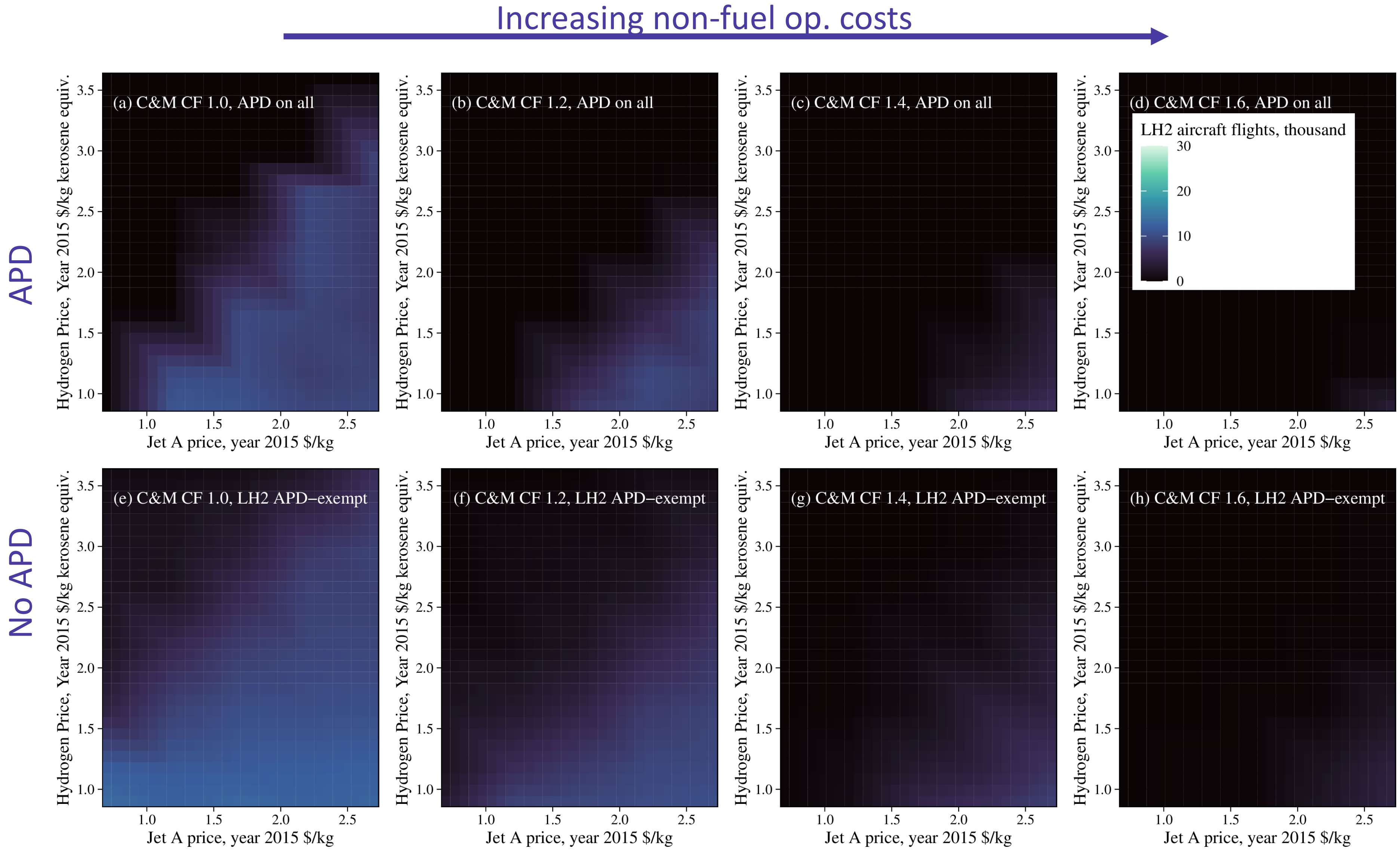

# Step 2: how does policy and operating cost affect uptake? Small Regional

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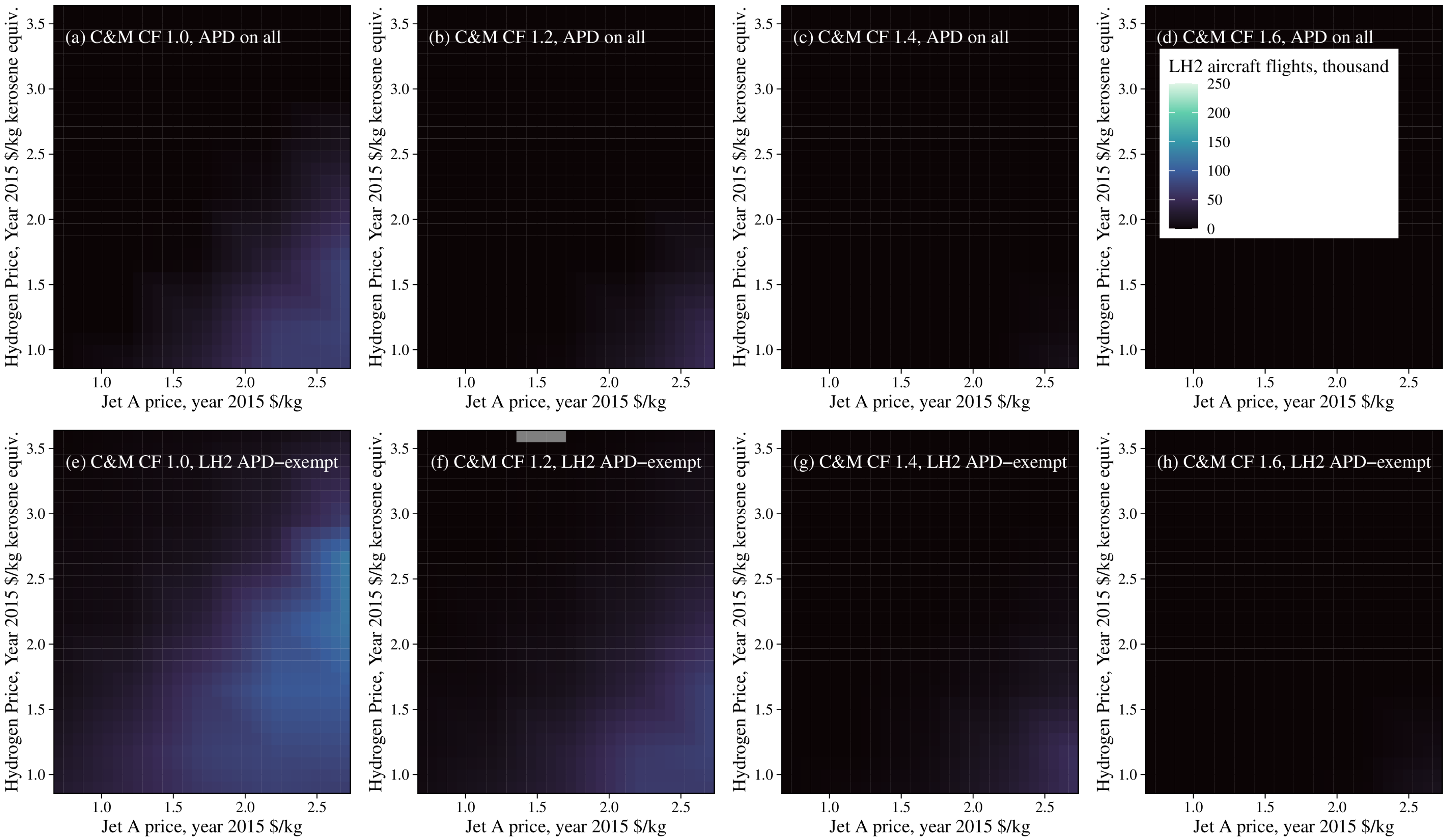
Increasing non-fuel op. costs

APD

No APD



# Step 2: how does policy and operating cost affect uptake? Large Regional

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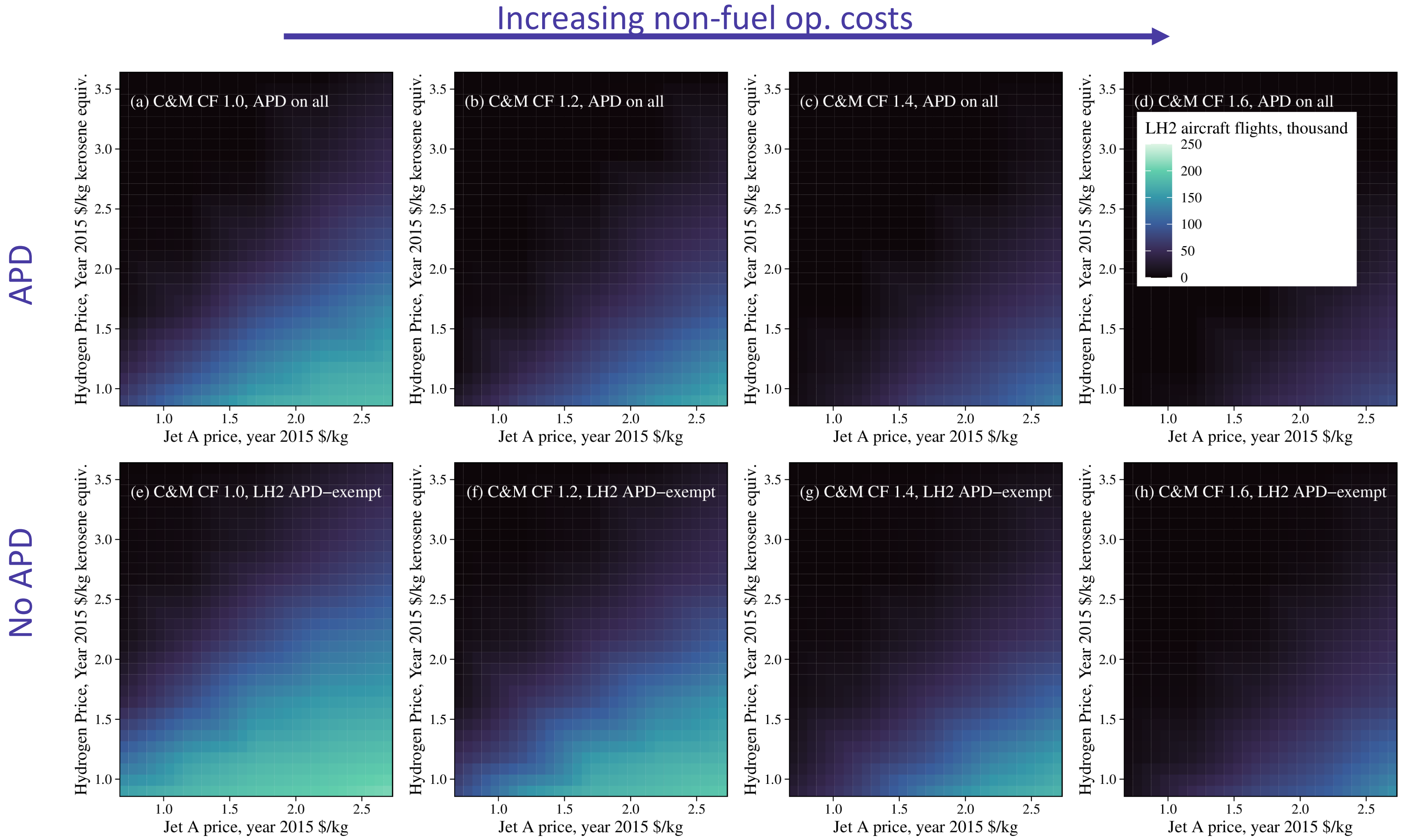
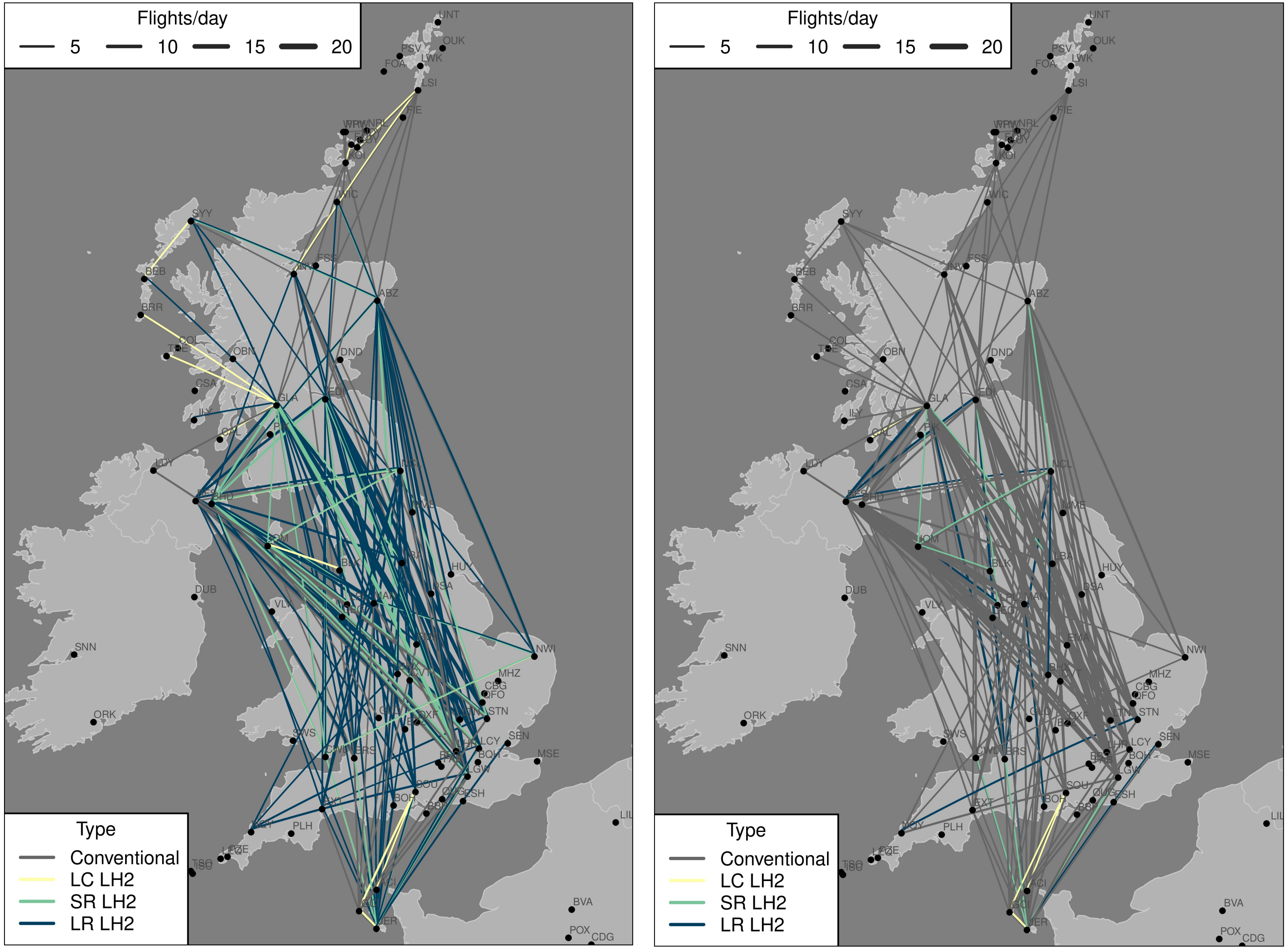


# Networks

- We can also look at **where** these aircraft are projected to be used
  - Allows assessment of the airports and airlines that should be targeting early infrastructure
  - LC-size aircraft: routes to/from/within remote regions (often PSO)
    - Because conventional aircraft on these routes often use aviation gasoline, LH2 aircraft can be competitive here at high LH2 cost → **promising early use case**
  - SR-size aircraft: routes to/from regional airports
  - LR-size aircraft: routes to/from regional airports, trunk routes (at low LH2 cost, high Jet A cost)
- Most routes that are currently not projected to see uptake at low LH2 cost, high Jet A cost could be addressed with adjustments to operating characteristics (e.g., they require longer range + short runway)

**Fossil Jet A (inc. carbon) = $1.7/kg, C&M cost factor 1.0, no APD on LH2 aircraft and:**



**LH2 = $2.5/kg** **LH2 = $8.5/kg**

# Conclusions

- The UK 2040 domestic net zero aviation target **can** likely be cost-effectively achieved with <100 seat hydrogen aircraft
  - We project several **policy-related factors** which can make this transition more feasible:
    - At least 2 LH2 aircraft sizes available (e.g., 19-seat STOL + 85-seat regional)
    - No Air Passenger Duty on LH2 flights
    - Green hydrogen prices meet EU/US targets
    - UK ETS carbon prices remain on the mid/upper end of projections
  - We project **different design priorities** for different sizes of LH2 aircraft:
    - For commuter-sized aircraft, STOL capability and limiting increases in capital/maintenance cost is key
    - For large regional-sized aircraft, performance/fuel costs and other per-passenger costs become more important
    - There may be less of a market case for small regional aircraft, unless both hydrogen and jet A prices are high
  - These outcomes can also be supported by SAF use in the remaining kerosene fleet, and by clear signalling on UK policy to reduce uncertainty for airline/airport investors
  - Further research is needed including larger designs and larger areas to determine if similar outcomes can be achieved globally

## More information

**UCL aviation modelling:** www.atslab.org

**Project NAPKIN:** https://www.heathrow.com/company/about-heathrow/future-flight-challenge/napkin – final report released in September