Technical Report – UK Domestic Market Modelling – Methodology and Additional Outcomes

PROJECT NAPKIN

Contents

1. UK Domestic Market Modelling - Methodology and Additional Outcomes

This technical report covers the methodology and assumptions used for the market predictions in the main report and gives additional outcomes and sensitivity tests.

1.1 How airline behaviour is modelled

One test of whether a new technology can be successful in a competitive aviation market is whether airlines can increase their profits by using the technology. Given the relatively low profit margins of typical airlines[1], technologies that increase operating costs over those of conventional alternatives without corresponding increases in revenues are unlikely to be successful. Airline gross profits are the sum of fare, PSO and ancillary[2] revenues across all the direct and indirect flight itineraries they offer, minus the sum of operating costs (including fuel, maintenance and capital costs) across all the flight legs they operate. For an airline *A* offering a set of passenger itineraries N_A on flight segments SEG_A, profits can be modelled as:

$$P_A = \sum_{i \in ITN_A} fare_i \cdot pax_i + arev_A \cdot pax_A - \sum_{j \in SEG_A} \sum_{a \in AC_j} opcost_{a,j} \cdot freq_{a,j} - \sum_{j \in SEG_A} \sum_{a \in AC_j} paxcost_{a,j} \cdot pax_{a,j},$$

consisting of passenger fare revenue ($fare_i$ * pax_i) for each itinerary *i* plus per-passenger average ancillary revenues $arev_A$ (including PSO subsidy where appropriate), minus per-flight costs ($opcost_{a,j}$) and per-passenger costs ($paxcost_{a,j}$) for each flight segment flown *j* with aircraft type *a* at frequency $freq_{a,j}$. This function can be used as input to an optimiser[3] to work out the maximum-profit combination of itinerary fares, leg flight frequency, and fleet deployment for an airline across its network. Constraints applying to this optimization include that the airline cannot schedule more flights than it has available aircraft for, and that flights at each airport cannot exceed the number of flight slots available.

In changing their fleet or operations to try and maximise profit, however, individual airlines also need to respond to the acts of competitors and to passenger preferences. For example, an airline which adopted a new aircraft design with high costs and increased its fares to compensate for this could lose market share to a competitor using conventional technology and maintaining existing fares. An airline adapting its network to use smaller hydrogen aircraft rather than larger conventional aircraft, and increasing flight frequency to accommodate this, might see an increase in demand and market share due to the increased convenience of travelling by air on this route. For short-haul routes, this could potentially include a shift from ground transport modes to air. And airlines offering a zero-emissions flight option could also

[1] See e.g. ICAO, 2020, Presentation of 2020 Air Transport statistical results. https://www.icao.int/annual-report-2020/Pages/the-world-of-air-transport-in-2020-statistical-results.aspx.

[2] Ancillary revenues are non-fare sources of airline income such as sandwich sales, priority boarding, website advertising or insurance tie-ins.

[3] In this case, IBM CPLEX (IBM (2017): IBM ILOG CPLEX 12.7 User's Manual, IBM ILOG CPLEX Division, Incline Village, NV.)

see increased demand from passengers who are normally unwilling to fly due to the environmental impacts. The factors affecting these choices will vary from region to region depending on what ground transport is available, public attitudes to flying and to new technologies, and regional policy and operating costs.

To simulate these interactions in the UK domestic market, the UCL Airline Behaviour Model (ABM)[4] is used. This is an optimisation model which simulates the actions taken by multiple profit-optimising airlines across competing networks. Given information about regional operating costs, airline business models, airport capacity, and available fleets, the ABM projects profit-optimal flight frequency, aircraft type utilisation, and fares for each competing airline, with airlines responding in turn to the fare, frequency and type utilisation decisions of their competitors, and passengers responding to ticket prices and available itinerary characteristics, until an equilibrium solution is reached. A detailed discussion of the model's methodology and assumptions, and sample model validation results, is given in Doyme et al. (2019)[5].

For NAPKIN, this model has been adapted for a UK domestic context. The UK domestic aviation market is a complex market with competition both between airlines and between air and other modes. As such, two separate adaptations of the ABM were made. The first is a straightforward adaptation of the existing model format, which models passenger demand on an origin city-destination basis, to a UK context, including UK domestic networks, airlines, airports and operating costs ('city-city model'). This model is used for the majority of the projections shown in this report. The second is a more experimental adaptation of the model to simulate complex passenger choices between modes given different technology availability, informed by NAPKIN passenger survey outcomes and modelled on a region-region basis ('region-region model'). This model, which has a significantly longer run time, is used for sensitivity tests. Both adaptations are described separately below.

1.1.1 Adaptation to UK costs and networks

To adapt the ABM to a UK domestic context, UK-specific airlines, networks, costs and passenger characteristics need to be included. Because UK domestic passengers may place different priorities on fare, journey time and flight frequency to passengers in other world regions, models also need to be estimated for passenger demand and itinerary choice from UK domestic data on passenger choices.

This process starts with model adaptation and calibration to match operations and passenger movements in a given base year. This process uses a 2015 base year and validation outcomes can be compared with baseline flight frequency, passenger movements and fares derived from

[4] Doyme, K., Dray, L., O'Sullivan, A., & Schäfer, A. (2019). Simulating Airline Behavior: Application for the Australian Domestic Market. Transportation Research Record, 2673(2), 104–112; Dray, L., Doyme, K. and Schäfer A.W., 2020. Airline Profit Maximisation, Cost Pass-through, and Scarcity Rents in Capacity-constrained Aviation Systems. Journal of Transport Economics and Policy, 54(4), 244-266.

[5] Doyme, K., Dray, L., O'Sullivan, A., & Schäfer, A. (2019). Simulating Airline Behavior: Application for the Australian Domestic Market. Transportation Research Record, 2673(2), 104–112.

global booking database data[6]. Figure 1 shows the baseline UK domestic network, including the distribution of flights by distance, aircraft size and runway length[7]. UK domestic flights are a mixture of busy, competitive trunk routes operated with single-aisle aircraft (e.g., London-Edinburgh); provincial routes with lower frequency and smaller aircraft (e.g., London-Newquay) and small aircraft flights to, from and between remote/island regions (e.g., Glasgow-Barra), many of which are subject to Public Service Obligation (PSO) subsidy contingent on a minimum flight frequency and would not be commercially feasible otherwise[8]. Between 2008 and 2018, UK domestic air transport movements decreased by almost a third, whilst international movements grew by 7%[9], a trend which is in line with decreases in domestic aviation in many other European countries. However, UK government projections anticipate growth in domestic aviation demand to 2050[10]. From 2023, Air Passenger Duty (APD) on non-exempt domestic itineraries is planned to decrease from £13 per passenger to £6.50 per passenger[11], a move which is likely to decrease ticket prices and boost demand.

[6] Sabre, 2017. Market Intelligence Database. https://www.sabreairlinesolutions.com/images/uploads/AirVision-Market-Intelligence_GDD_Profile_Sabre.pdf.

[7] Airports are identified by their 3-letter IATA code (https://www.iata.org/en/publications/directories/code-search/). Aircraft size classes shown are Small Commuter (SC; e.g. 9-seaters), Large Commuter (LC; e.g. 19-seaters), Small Regional (SR; e.g. ATR-42), Large Regional (LR; e.g. Embraer E190), Small Single Aisle (SSA; e.g. Airbus A319), Medium Single Aisle (MSA; e.g. Airbus A320), Large Single Aisle (LSA; e.g. Airbus A321), Small Twin Aisle (STA; e.g. Boeing 787) and Medium Twin Aisle (MTA; e.g. A330). Although there is some use of twin-aisle aircraft on UK domestic routes it is typically associated with onward flights to international destinations.

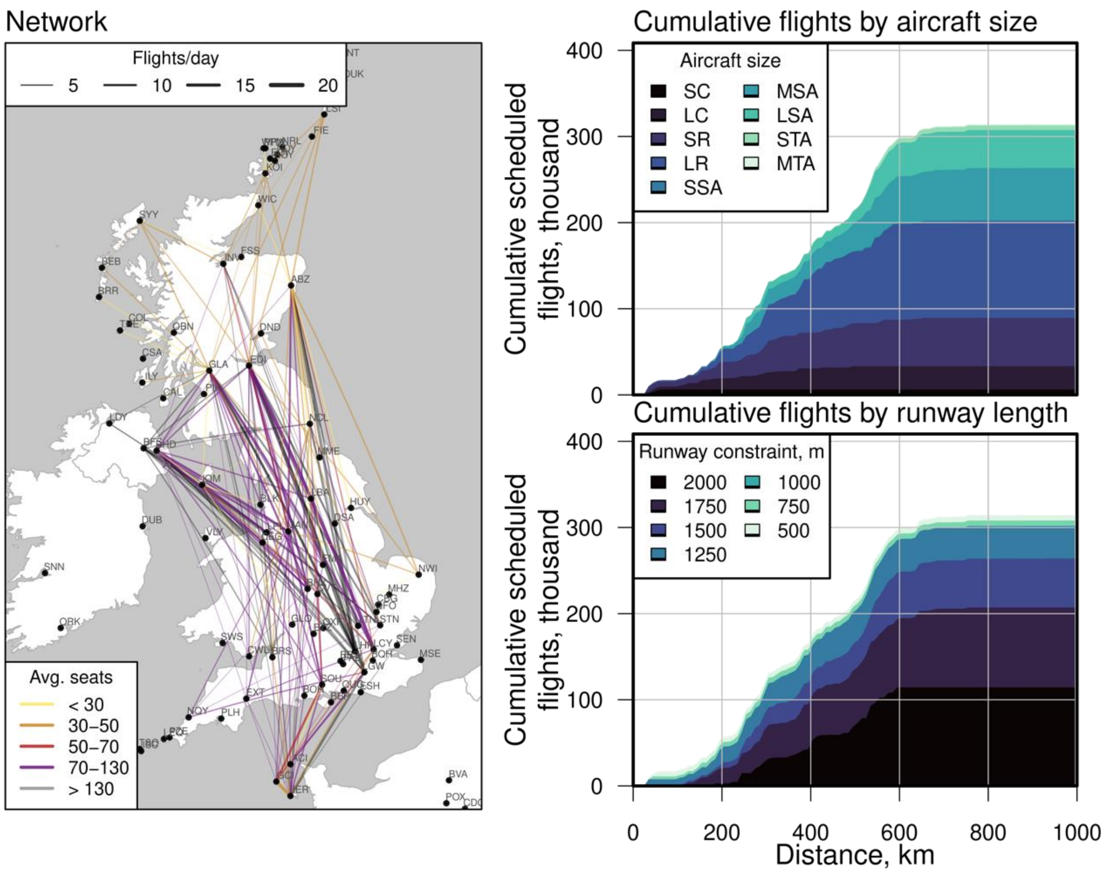
[8] Budd, L. & Ison, S., 2019. The UK domestic air transport system: how and why is it changing? https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/777681/fom_domestic_aviation.pdf.

[9] CAA, 2022. UK airport data. https://www.caa.co.uk/data-and-analysis/uk-aviation-market/airports/uk-airport-data/

[10] DfT, 2017. UK aviation forecasts 2017. https://www.gov.uk/government/publications/uk-aviation-forecasts-2017.

[11] HM Treasury, 2021. Autumn budget and spending review 2021: documents. https://www.gov.uk/government/publications/autumn-budget-and-spending-review-2021-documents. Note that direct flights departing from Northern Ireland or the Scottish Highlands and Islands region are exempt from APD.

Figure 1: The baseline UK domestic flight network modelled, including distribution of baseline flights by aircraft size, distance and shortest runway used on a given flight leg.



Most flights shown in Figure 1 are performed by regional jet or single-aisle sized aircraft using Jet A but, as discussed in the main report, PSO-type flights are often performed with commuter-sized (9- or 19-seater) aircraft using either Jet A or aviation gasoline. Because of the short distances involved and the high price of aviation gasoline, PSO routes may become cost-effective for hydrogen aircraft operation before other routes[12]. PSO-type flights are also more likely to be under 300 km and to involve short runways (<1,000m) at one or both airports. Table 1 shows the UK PSO routes modelled in this study (excluding routes not included in schedule data), including minimum frequency requirements, from EC (2019)[13]. Additionally, some routes in 2015 had minimum frequency requirements as operating license conditions (for example, in the Channel Islands). Imposing a minimum frequency requirement incentivises airlines to use aircraft with low per-flight costs over those with low per-passenger costs, i.e., smaller aircraft.

[12] ELICA, 2020. Economic Feasibility Study for a 19 PAX Hybrid-Electric Commuter Aircraft. https://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/innovation/elica-d2-1-economic-feasibility-study-for-a-19-pax-hybrid-electric-commuter-aircraft.pdf

[13] EC, 2019. List of Public Service Operations. https://ec.europa.eu/transport/sites/transport/files/pso_inventory_table.pdf.

Table 1. UK PSO routes modelled in 2015

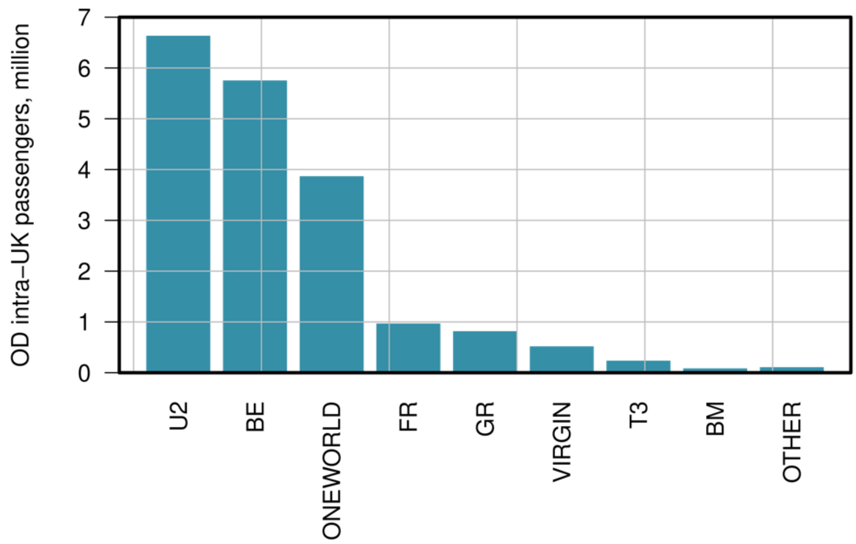
Origin	Destination	Minimum annual seat requirement	Frequency requirement per week (return)	PSO passengers, 2018	Load factor, 2018	Compensation/ passenger, 2018
Cardiff (CWL)	Anglesey (VLY)	17,860	10	14,584	81.66	£103.63 (€114.28)
Glasgow (GLA)	Barra (BRR)	18,872	13	14,437	76.50	£111.36 (€122.81)
Glasgow (GLA)	Campbeltown (CAL)	17,312	10-11	8,763	50.62	£135.02 (€148.90)
Glasgow (GLA)	Tiree (TRE)	20,460	13	11,190	54.69	£146.37 (€161.41)
Kirkwall (KOI)	North Ronaldsay (NRL)	Shared flight requirement	16-20	6,106	-	£53.20 (€58.67)
Kirkwall (KOI)	Papa Westray (PPW)		15-17	5,461		£53.20 (€58.67)
Kirkwall (KOI)	Eday (EOI)		3	392		£53.20 (€58.67)
Kirkwall (KOI)	Sanday (NDY)		11+1	3,074		£53.20 (€58.67)
Kirkwall (KOI)	Stronsay (SOY)		11+1	2,361		£53.20 (€58.67)
Kirkwall (KOI)	Westray (WRY)		11+1	2,561		£53.20 (€58.67)
Stornoway (SYY)	Benbecula (BEB)	28,288	8	8,542	39.3	£41.97 (€46.28)
Newquay (NQY)	Heathrow (LHR)	231,516	19	173,446	74.92	£3.71 (€4.09)
Dundee (DND)	Stansted (STN)	35,216	11	20,534	58.31	£87.98 (€97.02)
City of Derry (LDY)	Stansted (STN)	51,100	13	47,375	92.71	£44.52 (€49.10)

UK Airport capacities are based on slot declarations where available and runway layout otherwise (as in e.g. Dray, 2020[14]) and are adjusted to reflect capacity available for domestic

[14] Dray, L., 2020. 'An Empirical Analysis of Airport Capacity Expansion', Journal of Air Transport Management, 87, 101850.

flights and externally-imposed capacity limits (e.g. at Belfast City Airport[15]). Airline fleets by aircraft size class available for domestic routes are assessed based on historical operations and rates of utilization (e.g., FlightGlobal, 2016)[16]. Airlines are grouped based on whether they are competing or collaborating. As discussed in Doyme et al. (2019)[17], airlines which work together can be treated as a single entity for the purposes of competition modelling. In 2015, the majority of UK scheduled domestic passengers travelled with airlines in or associated with the OneWorld Alliance (i.e., British Airways), Flybe (BE), Easyjet (U2) and, to a lesser extent, Ryanair (FR). The number of scheduled passengers using each airline/alliance in 2015 is shown in Figure 2. Other airlines shown are Aurigny Air Services (GR, the flag carrier of Jersey), Virgin, Air Kilroe/Eastern Airways (T3), and Airline Investments Limited airlines (British Midland Regional and LoganAir; BM). Of these airlines, British Midland Regional, Thomas Cook and Flybe have all ceased operations since 2015, as have several smaller airlines grouped into the 'Other' category. As such, the airline set represents a broadly typical mix of network, low-cost and regional carriers for the UK domestic market, rather than a definitive list of airlines that are expected to be operating in future years.

Figure 2: Passengers travelling on UK domestic flights in 2015, by airline/alliance.



UK-specific operating costs for regional and commuter-sized aircraft are directly derived from NAPKIN project estimates (detailed in the accompanying NAPKIN technical report on operating costs). For larger aircraft, airline operating costs are derived from analysis of detailed

[15] DfI, 2019. George Best Belfast City Airport Planning Agreement Modification Process. https://www.infrastructure-ni.gov.uk/articles/gb-bca-planning-agreement-process.

[16] FlightGlobal, 2016. Ascend Online Fleet Database. http://www.ascendworldwide.com/what- we-do/ascend-data/aircraft-airline-data/ascend-online-fleets.html.

[17] Doyme, K., Dray, L., O'Sullivan, A., & Schäfer, A. (2019). Simulating Airline Behavior: Application for the Australian Domestic Market. Transportation Research Record, 2673(2), 104–112.

rating cost data by aircraft size[18] and are adapted for UK-specific conditions[19]. Route-level enroute and landing costs are derived from RDC (2017)[20]. Year-2015 APD rates are used when validating the model, in line with the 2015 base year for the validation data. However, for future years cuts in domestic APD are assumed as described above. Because APD is applied per passenger, reducing APD has a stronger cost-reducing effect on aircraft with a larger number of passengers. In practice, this means that the APD change has a larger impact on UK domestic flights with narrowbody-size aircraft than on those with regional- or commuter-size aircraft. Because only regional- and commuter-sized hydrogen aircraft are considered in NAPKIN, this has the potential to act against their adoption.

1.1.2 Demand modelling and validation – city-city model

Passenger demand and market share response to airline changes in fare, frequency and other itinerary characteristics is a key component of the ABM. Models for passenger response in a UK context are estimated using global booking database data for 2015 on passenger movements, fares and itinerary choice[21]. For the city-city model, regional catchment areas are modelled on a metropolitan area-type basis, with groups of competing airports assigned to cities, islands or other non-overlapping regions containing at least one airport (e.g. London; Inverness; Jersey). UK passenger choices are relatively complex, with a wide range of competing airports available and significant competition from ground transportation. As such, a nested logit functional form, adapted from existing models for North American air passenger demand and market share, is used (Doyme et al. 2023[22]; Jamin et al., 2004[23]). Mode choice, choice of origin and destination airport, and choice of itinerary for a given airport-pair are considered as sequential choices. To increase the size of the estimation dataset, data across all European routes is used for estimation. However, similar parameter estimates (with higher standard error) are obtained for relevant variables when using just UK data. For an itinerary *i* between airports A^o and A^d the itinerary market share MS_i is modelled as:

$$MS_i = e^{U_i} \Big/ \sum_{j \in ITNS_{A_i^o A_i^d}} e^{U_j},$$

where

$$U_i = \gamma_1 Fare_i + \gamma_2 Time_i + \gamma_3 \log(Freq_i / Freq_{od}) + M_A$$

[18] BTS (2019). 'Form 41 Financial Data', https://www.transtats.bts.gov/Tables.asp?DB_ID=135.
[19] ATA and Ellondee, 2018. Understanding the potential and costs for reducing UK aviation emissions. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/785685/ata-potential-and-costs-reducting-emissions.pdf.
[20] RDC, 2017. RDC Aviation airport and enroute charges databases. http://www.rdcaviation.com/.
[21] Sabre, 2017. Market Intelligence Database. https://www.sabreairlinesolutions.com/images/uploads/AirVision-Market-Intelligence_GDD_Profile_Sabre.pdf.
[22] Doyme, K., Dray, L. & Schäfer, A., 2023. Airline Behaviour Modelling in North America. Transportation Research Board, under review.
[23] Jamin, S., Schäfer, A., Ben-Akiva, M. & Waitz, I., 2004. Aviation emissions and abatement policies in the United States: a city-pair analysis. Transportation Research Part D, 9(4), 295-317.

and *Freq* is the effective flight frequency of itinerary *i*, $Freq_i = afreq_i^{(1-\gamma_4 S_i)}$; $afreq_i$ is the actual frequency (defined as the smaller of the two leg frequencies for stopping flights), S_i is 1 for stopping itineraries and 0 otherwise, and M_A is a factor variable for the airline marketing the itinerary which captures typical passenger airline preferences. An example for this level of choice would be whether to travel between Gatwick and Edinburgh with EasyJet or British Airways. The logsum term from this estimation,

$$L_{A^o A^d} = \log\left(\sum_{j \in ITNS_{A_i^o A_i^d}} e^{U_j}\right),$$

calculated for all airport-pairs, is used in the middle-level nest, which evaluates airport choice for a given origin-destination city-pair given the characteristics of the routes between them (as encapsulated in the logsum term). For an airport-pair *k* between between cities *o* and *d* containing airports A^o and A^d, the market share $MS_{A_k^o A_k^d}$ of routes between A^o and A^d is modelled as:

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

where

$$V_k = \beta_1 L_{A_k^o A_k^d} + C_{A^o} + C_{A^d}$$

and C_A are airport fixed effects which capture airport-specific qualities (e.g. facilities, reputation, ease of access). An example for this level of choice is whether to travel between London and Belfast using London Heathrow, Gatwick, City or Stansted as the origin airport, and Belfast International or City as the destination airport, given the characteristics of routes between those airports.

Finally, the aviation share of total city-pair level demand is estimated, given the characteristics of air and ground travel including logsums from the airport choice model. Similarly to Jamin et al. (2004)[24] this formulation estimates both aviation demand and (implicitly) demand across all modes. The demand function is:

$$D_{o_i d_i} = \alpha_1 Min\left(P_{o_i}, P_{d_i}\right)^{\alpha_2} Max\left(P_{o_i}, P_{d_i}\right)^{\alpha_3} \left(I_{o_i} I_{d_i}\right)^{\alpha_4} e^{\alpha_5 FracLH_{o_i d_i}} e^{\alpha_6 Dom_{o_i d_i}} \times$$

$$e^{\alpha_7 CL_{o_i d_i}} e^{\alpha_8 North_{o_i d_i}} e^{\alpha_9 Spec_{o_i d_i}} e^{\alpha_{10} Visa_{o_i d_i}} e^{\alpha_{11} L_{o_i d_i}} \times \frac{e^{\alpha_{12} L_{o_i d_i}^{air}}}{e^{\alpha_{12} L_{o_i d_i}^{air}} + e^{U_{o_i d_i}^{ground}}},$$

where the mode choice logsum term

$$L_{o_i d_i} = \log\left(e^{\alpha_{12} L_{o_i d_i}^{air}} + e^{U_{o_i d_i}^{ground}}\right), \text{ and}$$

$$U_{ground} = \alpha_{13} + \alpha_{14} Min\left(t_{drive, o_i d_i}, t_{rail,\, o_i d_i}\right) + \alpha_{15} SD_{o_i d_i}.$$

[24] Jamin, S., Schäfer, A., Ben-Akiva, M. & Waitz, I., 2004. Aviation emissions and abatement policies in the United States: a city-pair analysis. Transportation Research Part D, 9(4), 295-317.

Because wider European data is used for estimation, this model includes parameters which are relevant only for non-UK flights. $FracLH_{od}$ is the sum of the fraction of long-haul links from origin and destination airports; Dom_{od} is 1 if a domestic route, 0 otherwise; CL_{od} is 1 if the origin and destination share a common official language, 0 otherwise; $North_{od}$ is 1 if both origin and destination have significant land area North of 60°N, 0 otherwise; $Spec_{od}$ is 1 if both origin and destination are capital cities and/or major tourist destinations, 0 otherwise; $Visa_{od}$ is 1 if a full (pre-arranged) visa is required to travel between origin and destination, and 0 otherwise; and SD_{od} is 1 if a short-distance (<300km) route, 0 otherwise. Drive and rail time estimates are derived from the Open Route Service API[25] (OpenRouteService, 2022) and Google Maps Transit API[26] respectively. A comparison between flight, drive and transit times by city-pair is shown in : Figure 3. Note that the flight time shown is itinerary flight time, i.e. includes transit time for stopping itineraries.

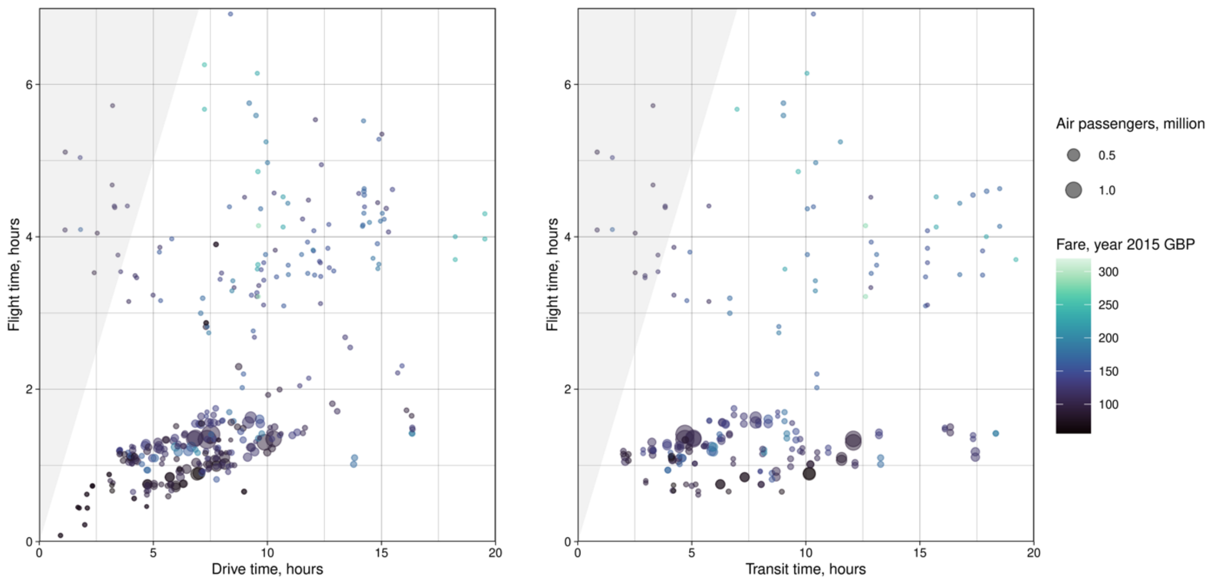


Figure 3: Comparison of baseline flight, drive and transit times for the UK domestic aviation system in 2015.

City socioeconomic characteristics are derived from the AIM model database[27]. Estimation was carried out using the nlme library in R[28]. The main parameter, estimates and standard error are shown in Table 2, below. All non-fixed effects parameters relevant to the UK domestic market are significant at a 95% level and all parameters have values consistent with expectations. The fare and time parameters for the itinerary choice nest imply a value of time for air passengers of £36.5/hour in year 2015 pounds ($56/hour), comparable to literature estimates (e.g. the

[25] Openrouteservice, 2022. Openrouteservice API.. https://openrouteservice.org.
[26] Google, 2022. Google Maps Platform Distance Matrix API. https://developers.google.com/maps/documentation/distance-matrix/overview.

[27] Dray, L., P. Krammer, K. Doyme, B. Wang, K. Al Zayat, A. O'Sullivan and A. Schäfer (2019): 'AIM2015: validation and initial results from and open-source aviation systems model', Transport Policy, 79, 93-102.
[28] Pinheiro, J., 2022. Package 'nlme'. https://cran.r-project.org/web/packages/nlme/nlme.pdf.

FAA[29] estimate a range of $39-$58 for US air passengers). A 68% air share is projected for London-Edinburgh and 76% for London-Glasgow using year-2015 characteristics, similar to those estimated in Transform Scotland (2017)[30]. The R^2 for the model is 0.7, which is lower than is achievable with similar models in other world regions[31] and reflects difficulties in predicting complex historical relationships between travel destinations in Europe (e.g., which tourist destinations are popular with travellers from which regions). Because of the relatively low demand model R^2, an additional calibration step is included in the airline behaviour model in which the utility for routes where projected demand diverges significantly (+/-20%) from historical values is iteratively adjusted to account for non-modelled factors.

Table 2. Demand and Market Share estimated parameters

Itinerary and Airport Choice		**Demand**	
Parameter	**Estimate (standard error)**	**Parameter**	**Estimate (standard error)**
γ_1 (Fare)	-0.0040 (0.00008)	α_1 (Intercept)	-15.9 (0.34)
γ_2 (Time)	-0.0043 (0.00005)	α_2 (Smaller population)	0.40 (0.006)
γ_3 (Frequency)	0.862 (0.006)	α_3 (Larger population)	0.78 (0.012)
γ_4 (Number of stops)	-0.386 (0.0024)	α_4 (Income*)	0.48 (0.01)
M_A (Airline) – BM†	-0.166 (0.165)	α_5 (FracLH)	1.26 (0.05)
M_A (Airline) – GR	-0.197 (0.263)	α_6 (Domestic)	0.67 (0.02)
M_A (Airline) – ONEWORLD	0.060 (0.040)	α_7 (Common language)	0.61 (0.02)
M_A (Airline) – T3	-0.480 (0.20)	α_8 (Far North)	1.42 (0.02)
M_A (Airline) – U2	-0.58 (0.005)	α_9 (Tourist destination)	0.57 (0.01)
M_A (Airline) – Virgin	-0.46 (0.33)	α_{10} (Visa required)	-1.84 (1.14)
M_A (Airline) - FR	-0.583 (0.050)	α_{11} (Mode choice logsum)	0.27 (0.01)
M_A (Airline) – other	0.02 (0.04)	α_{12} (Itinerary choice logsum)	2.80 (0.11)
β_1 (Airport choice logsum)	1.393 (0.004)	α_{13} (Ground transport utility intercept)	1.63 (0.19)
		α_{14} (Ground transport time)	-0.02 (0.0006)
		α_{15} (Short ground transport distance)	1.82 (0.14)

29 FAA, 2018. Treatment of Time. https://www.faa.gov/regulations_policies/policy_guidance/benefit_cost/media/econ-value-section-1-tx-time.pdf

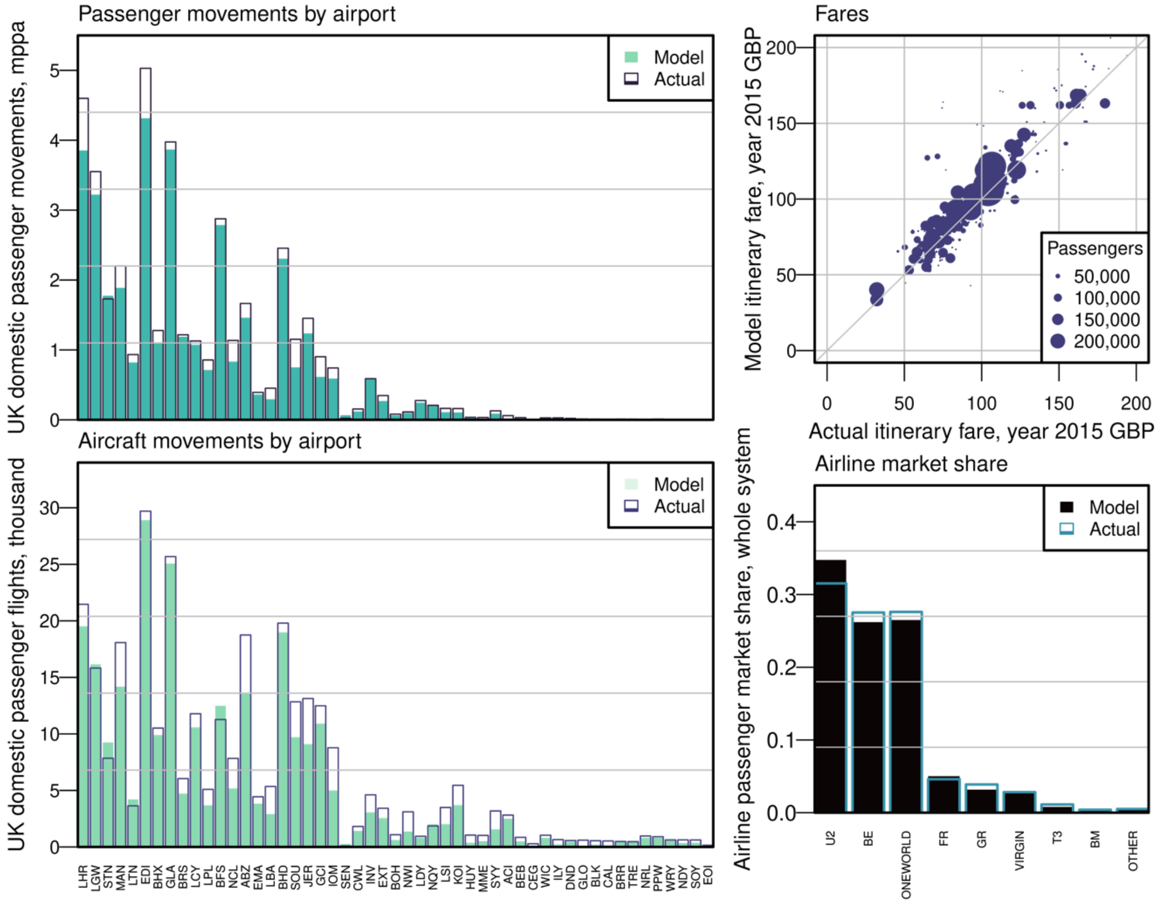
30 Transform Scotland, 2017. A Green Journey to Growth. https://transform.scot/blog/2017/08/21/new-research-shows-shift-from-air-to-rail-has-cut-carbon-in-scotland-london-travel-market/

31 Doyme, K., et al. (2022). Airline Behaviour Modelling in North America. In preparation.

*Because both origin and destination income levels are included, this income parameter is equal to income elasticity/2, i.e., an income elasticity of around 0.8 is implied.
†Airlines modelled: BE: FlyBe; ONEWORLD: BA and other affiliated airlines; BM:LoganAir; U2: EasyJet; T3: Eastern Airlines; FR: Ryanair; GR: Aurigny.

These demand and market share parameters, along with the UK-specific costs, airlines, fleet and networks discussed above, are incorporated into the ABM.

Figure 4: Base year validation outcomes for the UK city-city airline behaviour model: airport-level passenger and aircraft movements, fares, and airline market share.

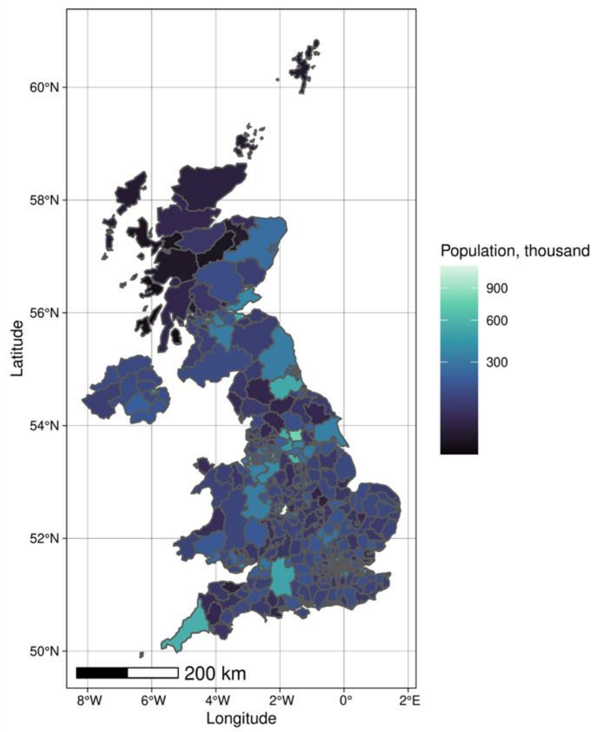


Baseline validation outcomes for the 2015 system are shown in Figure 4. The corresponding actual system values are taken from Sabre schedule and passenger itinerary data[32] and exclude non-scheduled and helicopter flights. Passenger numbers include domestic legs of international trips. R^2 values for origin-destination passenger numbers, segment flight frequency and fare charged are 94%, 73% and 83% respectively. The fit to historical operations is not exact even with additional calibration, reflecting largely local variations in achievable load factor, different seat allocation within the same aircraft type, daily/weekly schedules, operating cost, interactions with international routes, and operating constraints

[32] Sabre, 2017. Market Intelligence Database. https://www.sabreairlinesolutions.com/images/uploads/AirVision-Market-Intelligence_GDD_Profile_Sabre.pdf.

which are not modelled here. However, a sufficiently close fit to baseline operations is achieved to allow investigating the system impact of new technology availability.

Figure 5:Region specification (LAU1) used in the region-region model, showing regional population in 2019.



1.1.3 Demand modelling and validation – Region-region model

Because of the complexity of passenger decisions in the UK domestic market, and because the new technologies examined in this report are sufficiently different to existing technologies that passenger preferences are likely to play a role in their adoption, a second UK version of the ABM was developed. This version was developed from the city-city model described above, and the basic methodology and aviation system modelling are the same. However, there are two main differences to the city-city model:

- Instead of OD demand projections between city catchment areas, small origin-destination regions (at LAU1[33] level) are used.
- Mode choice is estimated from stated preference experiments included in the first NAPKIN passenger survey, and includes the impact of passenger attitudes to different technologies (See Section Passenger Acceptability of the main report for further detail on the passenger survey outcomes).

The regional specification of the model is shown in Figure 6, along with regional population estimates[34]. Data on region-region passenger movements by mode for 2019 is derived from

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[33] This level of geographic resolution is broadly equivalent to European NUTS4 regions.

[34] Office of National Statistics, 2019. Estimates of the population for England and Wales, Scotland and Northern Ireland.
https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationestimates/datasets/populationestimatesforukenglandandwalesscotlandandnorthernireland

mobile phone data with mode inference[35]. Figure 6 shows the number of domestic air trips per capita for 2019 in this dataset.

Figure 6: LAU1 regions showing the number of origin air passengers per capita for 2019.

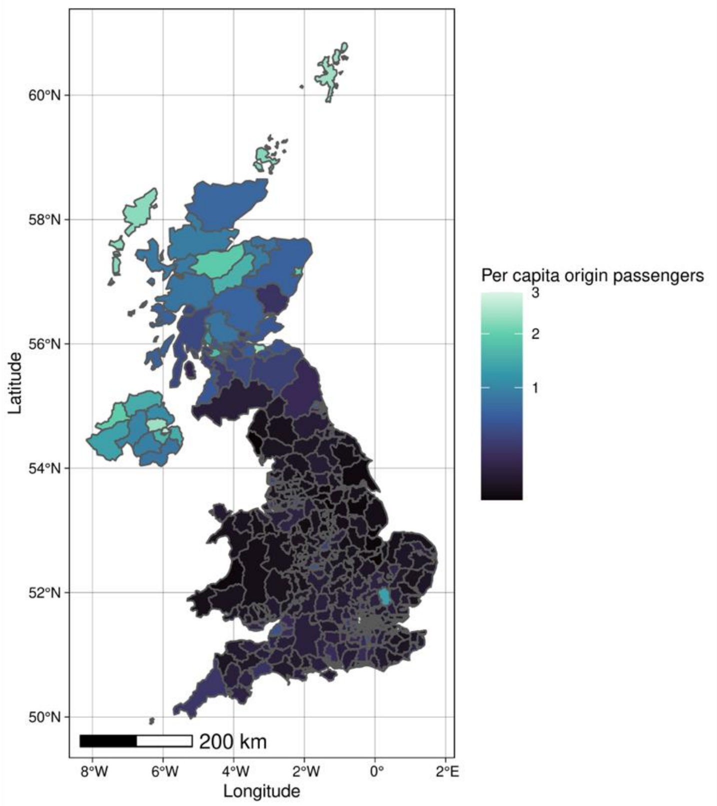

Figure 6 demonstrates the higher propensity to fly of people living in islands and remote regions with airports. In particular, residents of Northern Ireland and the Scottish Highlands and Islands are significantly more likely than residents of England and Wales to take a domestic flight. As such, these areas were oversampled in the NAPKIN passenger surveys. Similarly, the propensity of domestic passengers to travel to/from major London-area airports (often for a connecting international flight) is clearly visible. Because the available mobile data did not include the Channel Islands or Isle of Man, passengers to or from these areas were not included in the modelling or analysis for the region-region model, and airlines only serving these areas (e.g., Aurigny) were not modelled. Similarly, because the regional specification treats the Orkney Islands and Shetland Islands as single unified areas, flights within each island group were not included in the region-region model. These geographical differences mean that uptake of the smallest aircraft classes may be lower than in the city-city model.

Each passenger journey is considered as a trip from an origin LAU1 region to an origin airport to a destination airport (potentially via a hub airport) to a destination LAU1 region. Access and egress times from each region to each airport were derived from the Open Route Service API36 (OpenRouteService, 2022), as for the city-city model. Example region-region journey times by

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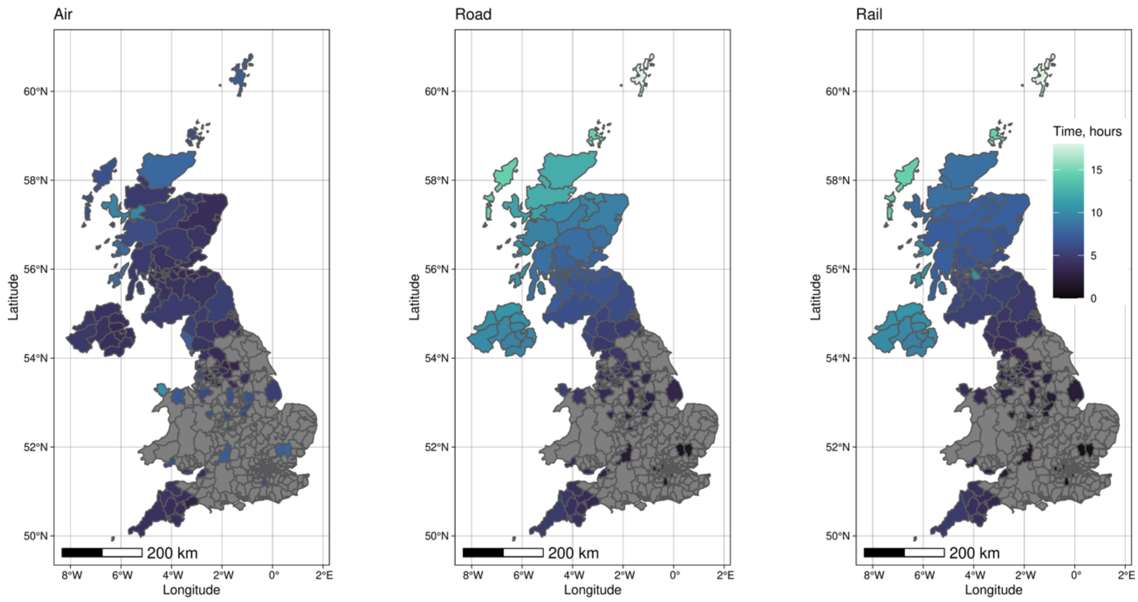
[35] CK Delta, 2021. https://www.ckdelta.ie/#quality-data.

[36] Openrouteservice, 2022. Openrouteservice API.. https://openrouteservice.org.

mode from the City of London LAU1 region for LAU1 destinations with non-zero passenger numbers in 2019 are shown in Figure 7.

Figure 7: Example journey time data by mode from the City of London LAU1 region to LAU1 destinations with non-zero air passengers in 2019.



For the region-region model, itinerary choice given a selection of itineraries is assumed to behave similarly to that in the city-city model, although the set of itineraries available for a given LAU1-LAU1 region pair is adjusted to reflect the highest-utility options available, which may involve departures from different cities. However, for demand estimation, a separate mode choice model is used which accounts in more detail for passenger technology preferences. This model was estimated using NAPKIN stated preference passenger survey data, as discussed in Section 11 ("Passenger Acceptability") of the main report. Due to constraints on multi-modal data availability, a model based on changes in air demand from values calculated at baseline costs and journey times across all modes was used:

$$D_{od,air} = D_{od,air(base)} \, e^{V_{od,air}} \sum\nolimits_{od,all\ modes(base)} e^{V_{od,mode(base)}} \Big/ e^{V_{od,air(base)}} \sum\nolimits_{od,all\ modes} e^{V_{od,mode}},$$

where $D_{od,air}$is the modelled OD LAU1-LAU1 passenger demand for a given scenario; $D_{od,air(base)}$ is the corresponding value in the baseline mobile dataset, and

$$V_{mode} = ASC_{mode} + b_{cost}Cost_{mode} + b_{time}Time_{mode} + b_{wait}Wait_{mode},$$

where $Cost_{mode}$, $Time_{mode}$ and $Wait_{mode}$ refer to the LAU1-LAU1 travel time, whole-journey cost and journey waiting time for each mode respectively. Values with the subscript *(base)* are calculated using base year input data. Because this model is based on changes in mode choice from base year values, it does not calculate any additional induced demand which may arise from improvements in offered air itineraries (i.e., cases where total region-region demand across all modes increases due to changes in air trip characteristics, rather than just air mode share).

Table 3. Estimated parameters for the region-region mode choice model.

Parameter	**Estimate (standard error)**
ASC_{EAHA}*	-1.149 (0.116)
ASC_{flight}	-1.166 (0.115)
ASC_{train}	-0.439 (0.046)
b_{cost}	-0.027 (0.0012)
b_{time}	-0.009 (0.0004)
b_{wait}	-0.0039 (0.00091)

*EAHA: Electric and/or hydrogen aircraft.

Estimation was carried out in Biogeme[37]. Estimated parameters are shown in

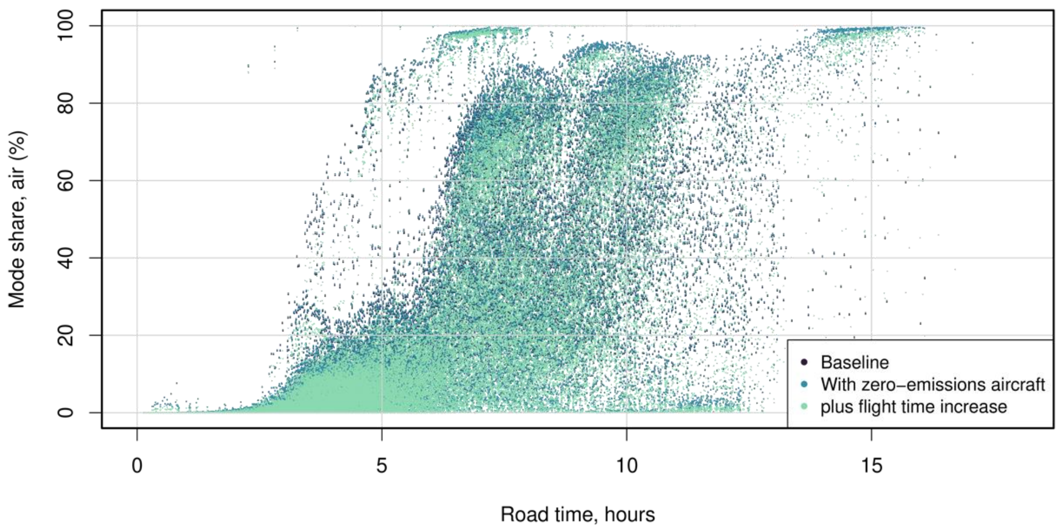
Table 3. The baseline number of air passengers for each LAU1-LAU1 region-pair was derived from the mobile passenger dataset. The model mode choice outcomes were compared to those within the mobile data and were found to correctly predict the most-used mode in 74.9% of cases. On further investigation, however, it was found that mode share predictions for some key routes differed from expected values, likely because of the covid-affected timescale on which the survey was carried out and/or differences in actual passenger behaviour from survey answers. To better match observed mode choice, adjustments were made to the fixed effects parameters in the model based on the difference between observed and projected mode choice for a selection of routes. For future projections, where a mix of aircraft types is offered on a given itinerary, a linear transition is assumed between the case where 100% conventional aircraft are available and 100% alternative aircraft are available.

To illustrate the extent to which passenger preferences might affect the uptake of alternative aircraft, Figure 8 shows projected mode share across all LAU1-LAU1 routes with non-zero baseline air demand for three cases: baseline 2019 system characteristics; baseline 2019 system characteristics with all aircraft assumed substituted by zero-emissions aircraft with the same cost and journey time characteristics; and baseline 2019 system characteristics with all aircraft assumed substituted by zero-emissions aircraft with the same cost characteristics but 50% greater flight time. Each point shows a single LAU1-LAU1 pair for a given case; In aggregate, these scenarios suggest that the impact of positive attitudes to zero-emissions aircraft on mode choice is likely small but non-negligible (around 130,000 additional yearly passengers across the whole system at baseline characteristics), with the greatest increases in absolute passenger numbers likely on routes with 4-7 hours drive time. These demand increases are typically projected for routes where other modes than air are currently competitive; that is, medium-distance routes that are not to remote or island regions. This partially reflects the model specification, which cannot project significant increases in air demand where air mode share is close to 100%. However, it does suggest there is the potential that that positive attitudes to zero-emissions aircraft could make shorter-distance domestic

[37] Bierlaire, 2021. Biogeme. https://biogeme.epfl.ch/

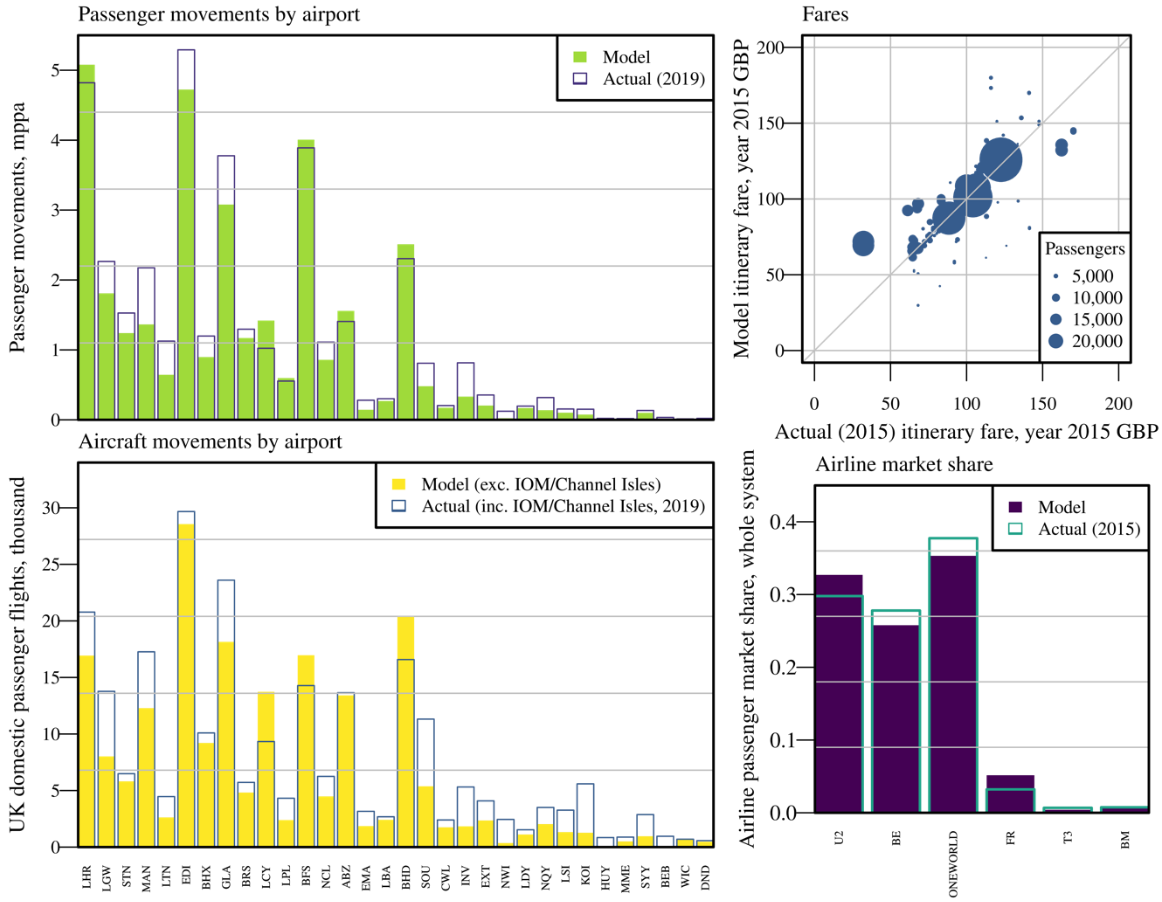
routes upon which it is currently difficult to make a profit offering air service economically feasible if offered with a zero-emissions aircraft. However, the negative impact of increased flight time likely exceeds the positive impact of attitudes to zero-emissions aircraft, and the net impact of zero-emissions aircraft plus a 50% greater flight time is a fall in total passenger numbers.

Figure 8: Projected mode share across all LAU1-LAU1 routes with non-zero baseline air demand for three cases: 2019 baseline, baseline conditions with zero-emission aircraft, and baseline conditions with zero-emissions aircraft that have a 50% longer flight time.



This model is incorporated into an adapted region-region version of the ABM, using the assumptions and data sources described above. Because 2019 passenger movement data is used, networks were adjusted to remove airlines and flight segments no longer operating in 2019, as well as airlines and flight segments outside the scope of the passenger movement data used (e.g., flights to and from the Channel Isles). Baseline validation outcomes for the region-region ABM are shown in Figure 9.

Figure 9: Base year validation outcomes for the UK region-region airline behaviour model: airport-level passenger and aircraft movements, fares, and airline market share.



The corresponding actual system values are taken from Sabre fare data for 2015[38] and CAA passenger and flight data for 2019[39]. Passenger numbers include domestic legs of international trips but do not include passengers travelling to domestic destinations outside the dataset used (e.g., Channel Isles, Isle of Man, inter-Orkney flights). The R^2 value for origin-destination passenger numbers is 85%. Fare data is not available for 2019 but a comparison with the 2015 fares used for the city-city model shows fare R^2 of 60%; it is not unexpected that this fit is less close, as the competitive landscape changed in several ways between 2015 and 2019 (for example, several routes were abandoned and Virgin ceased operating UK domestic routes, lowering the level of competition for some region-pairs). An exact comparison cannot be made with segment flight frequency as CAA numbers include some flights that are outside the scope of the region-region model; however, a comparison with CAA numbers (Figure 9) suggests that once shortfalls associated with the Isle of Man and Channel Islands are accounted for (affecting e.g. Southampton and Gatwick), outcomes are reasonably close. As

[38] Sabre, 2017. Market Intelligence Database. https://www.sabreairlinesolutions.com/images/uploads/AirVision-Market-Intelligence_GDD_Profile_Sabre.pdf.

[39] CAA, 2021. UK Airport Data. https://www.caa.co.uk/data-and-analysis/uk-aviation-market/airports/uk-airport-data/

with the city-city model, it should be noted that the fit to historical operations is not expected to be exact even with additional calibration, reflecting largely local variations in achievable load factor, different seat allocation within the same aircraft type, daily/weekly schedules, operating cost, interactions with international routes, and operating constraints which are not modelled here.

Because there are many more region-airport-airport-region itineraries than city-city pairs in the UK, and because model run time scales as number of itineraries squared, the region-region model runs significantly more slowly than the city-city model. As such, the grids of model runs in the main report use the city-city model, but the region-region model is used for selected sensitivity tests (reported in the section 'region-region model sensitivity tests', below).

1.1.4 Future scenarios

In the main report and the remainder of this appendix, projected uptake of different alternative aircraft designs in different future scenarios using the ABM is reported. Although different aircraft are evaluated, these model runs have a common setup and range of assumptions. Starting from the validated baseline shown above, changes are made to model input parameters to simulate the availability of hydrogen aircraft under potential future conditions and see how the system responds. As discussed above, the ABM projects system changes (e.g., uptake of new aircraft, changes in fares, changes in flight frequency) where these would lead to increased profit for the airline in the context of a competitive aviation system. As such, the use cases do not project the case where uptake of alternative aircraft is mandatory or where one or more airlines optimise networks for market share rather than profit. For each future year modelled it is assumed:

- Airlines have the option of adding new aircraft to their fleet (i.e., they have anticipated the current cost and operating conditions and have been able to purchase new aircraft appropriate for those conditions). They can also discontinue use of aircraft currently in their fleet.
- All airlines have the option of purchasing new conventional aircraft of sizes similar to those that they currently operate. These are assumed to be current-technology designs, i.e. the impact of additional generations of competing conventional aircraft is not considered.
- Each airline will only consider hydrogen aircraft that are of a similar size to those that it already operates (that is, large-scale changes in business model are not modelled). For the case of 90-seater aircraft, based on discussions with members of the NAPKIN advisory board, the use cases consider both the case where low-cost carriers would consider operating them and the case where they would not[40].

[40] One situation where low-cost carriers would not adopt 90-seater hydrogen aircraft is if a hydrogen aircraft design closer in size to the aircraft they currently operate is or is about to become available. However, this size class of hydrogen aircraft is outside the scope of NAPKIN.

- The announced halving in domestic APD[41] from 2023 is included in all cases.
- The airport and airline set used is kept constant, including landing changes and the amount of airport capacity which is available for domestic flights. As discussed above, due to the frequently short-lived nature of airlines, the airline set is used as a representative sample of network, low-cost and regional carriers rather than the exact set of airlines that are anticipated to be operating on UK domestic routes in future.
- Demand drivers other than the domestic APD cut and changes in fuel prices are kept constant. This reflects the significant uncertainty in how domestic demand may develop; although some projections envisage an increase in demand[42], the number of UK domestic flights fell by almost a third between 2008 and 2018[43]. Note that this is separate from the projections of long-term airport-level hydrogen infrastructure requirements in the main report which include international demand: growth projections for international demand are significantly more robust.

For new aircraft designs, cruise speed may differ to existing designs. Many of the hydrogen aircraft designs explored in NAPKIN have cruise speeds similar to turboprop or propeller aircraft rather than turbofan aircraft. In practice, this means that scheduled flight time will increase in the case that these aircraft are used on flight segments which are currently operated by turbofan aircraft. This in turn will have an impact on demand and may discourage adoption. To model this impact, data from historical flight schedules[44] on scheduled flight time for flight legs that are operated both by turboprop and turbofan aircraft is used to derive a relationship between scheduled flight time, distance and cruise speed. This data is shown in Figure 10 and the resulting model is also implemented in the ABM. For UK-domestic type routes at typically 600 km or below, up to around half an hour longer flight time is projected in the case that turboprop-type aircraft are substituted for turbofan-type aircraft.

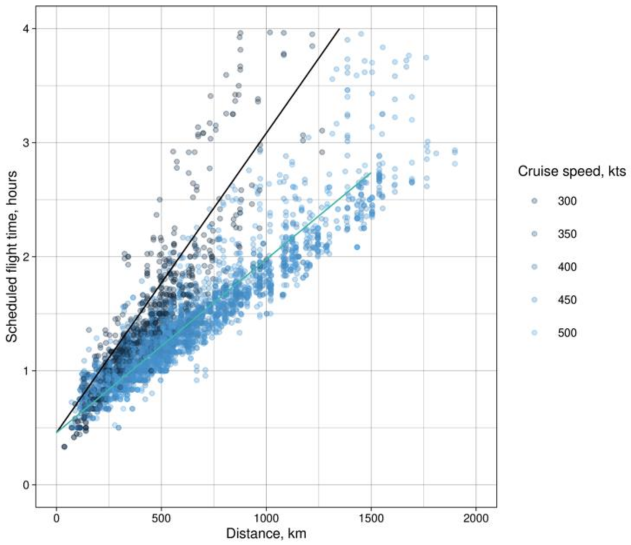
[41] HM Treasury, 2021. Autumn budget and spending review 2021: documents. https://www.gov.uk/government/publications/autumn-budget-and-spending-review-2021-documents.

[42] DfT, 2017. UK aviation forecasts 2017. https://www.gov.uk/government/publications/uk-aviation-forecasts-2017.

[43] CAA, 2022. UK airport data. https://www.caa.co.uk/data-and-analysis/uk-aviation-market/airports/uk-airport-data/

[44] Sabre, 2017. Market Intelligence Database. https://www.sabreairlinesolutions.com/images/uploads/AirVision-Market-Intelligence_GDD_Profile_Sabre.pdf.

Figure 10: Comparison of scheduled flight time by aircraft design cruise speed.



For the use cases in the main report, availability of multiple models of hydrogen aircraft of different sizes is considered, and outcomes over a range of hydrogen and effective Jet A prices appropriate to the use case year are evaluated. The assumptions about fuel prices that are used to generate these ranges are shown in Table 4. Effective Jet A prices include carbon price and, because liquefaction is likely to be a significant fraction of LH_2 prices, separate prices are modelled for gaseous and liquid hydrogen[45]. Where carbon prices are modelled which are part of the UK ETS free allowance allocation is not subtracted; instead, this is considered as a lump sum payment to airlines that does not affect their marginal costs. The impact on fuel prices of increasing SAF blend in Jet A is not explicitly considered. Even under optimistic scenarios, SAF blends by 2040 are likely to be around or below 30%[46] and, as SAF is additionally exempt from UK ETS carbon prices, kerosene prices including SAF blending are likely to be within the range of effective Jet A prices modelled.

Table 4. Fuel cost assumptions by year. All values are in year 2020 UK pounds. Where a range of values is modelled, this is indicated as Central (Lower-Upper).

	2025	2035	2040	Source
Jet A price/kg	0.5 (0.3-0.8)	0.6 (0.4-1.0)	0.7 (0.4 – 1.1)	EIA (2021)[47]
Carbon price/tCO_2	94 (57-141)	207 (77-373)	264 (83-489)	

[45] Note that this price difference is not valid if hydrogen is delivered to the airport as LH2 and subsequently converted to gaseous hydrogen.
[46] DfT, 2021. Sustainable Aviation Fuels Mandate consultation. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1005382/sustainable-aviation-fuels-mandate-consultation-on-reducing-the-greenhouse-gas-emissions-of-aviation-fuels-in-the-uk.pdf
[47] U.S. Energy Information Administration, 2021. Annual Energy Outlook 2021. https://www.eia.gov/outlooks/aeo/. The range across all included future scenarios is used.

Carbon price/kg Jet A	0.3 (0.18-0.44)	0.65 (0.24-1.17)	0.83 (0.26-1.54)	DfT (2022)[48]
Effective Jet A price/kg	0.8 (0.5-1.2)	1.3 (0.6-2.2)	1.5 (0.7-2.6)	
Gaseous H_2 price/kg	2.5 (2.0-4.5)	1.3 (1.0-4.5)	1.2 (0.8-4.5)	IRENA (2020); Dray et al. (2022); Mayyas et al. (2019); Noack et al. (2015)[49]
Gaseous H_2 price/kg kerosene equivalent	0.9 (0.7-1.6)	0.5 (0.4-1.6)	0.4 (0.3-1.6)	
Liquefaction and storage cost/kg	2.5	1.3	1.1	Ohlig & Decker (2015); Dray et al. (2022); Stolzenburg & Mubbala, (2013); Connelly et al. (2019).[50]
LH_2 price/kg	5.0 (4.5-7.0)	2.6 (2.3-5.8)	2.3 (1.9-5.6)	
LH_2 price/kg kerosene equivalent	1.8 (1.6-2.5)	0.9 (0.8-2.1)	0.8 (0.7-2.0)	
Aviation gasoline price/kg	2.1	2.1	2.1	NAPKIN WP3

Use Case A is evaluated under year-2025 projected conditions. Only 7- and 19-seater gaseous hydrogen aircraft designs are assumed to be available. Use Case B is evaluated under year-2035 projected conditions. As well as 7- and 19-seater gaseous hydrogen aircraft, 40- and

[48] DfT, 2022. Further Jet Zero Consultation, Annex B. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1062042/jet-zero-further-technical-consultation.pdf

[49] IRENA, 2020. Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5°C Climate Goal. https://www.irena.org/publications/2020/Dec/Green-hydrogen-cost-reduction, International Renewable Energy Agency, Abu Dhabi; Dray, L., Schäfer, A., Grobler, C., Falter, C., Allroggen, F., Stettler, M., Barrett, S., 2022. Cost and emissions pathways towards net-zero climate impacts in aviation. Nature Climate Change, https://doi.org/10.1038/s41558-022-01485-4; Mayyas A., Ruth M., Pivovar B., Bender G., Wipke K., 2019. Manufacturing Cost Analysis for Proton Exchange Membrane Water Electrolyzers (NREL), https://www.nrel.gov/docs/fy19osti/72740.pdf; Noack C. et al, 2015. Studie über die Planung einer Demonstrationsanlage zur Wasserstoff-Kraftstoffgewinnung durch Elektrolyse mit Zwischenspeicherung in Salzkavernen unter Druck, https://elib.dlr.de/94979/.

[50] As previous footnote, plus: Ohlig K. & Decker, L., 2015. The latest developments and outlook for hydrogen liquefaction technology. AIP Conference Proceedings 1573, 1311 (2014); Stolzenburg, K. & Mubbala, R., 2013. Integrated Design for Demonstration of Efficient Fuel Cells and Hydrogen Joint Undertaking (IDEALHY) project final report. https://www.idealhy.eu/uploads/documents/IDEALHY_D3-16_Liquefaction_Report_web.pdf; Connelly, E., Penev, M., Elgowainy, A. & Hunter, C., 2019. DOE Hydrogen and Fuel Cells Program Record, Record #: 19001 Current Status of Hydrogen Liquefaction Costs. https://www.hydrogen.energy.gov/pdfs/19001_hydrogen_liquefaction_costs.pdf.

50-seater fuel cell and direct combustion LH_2 aircraft are assumed to be available. Use Case C is evaluated under a range of conditions appropriate to the year 2035-40 period. As well as the above four designs, 90-seater turbofan direct combustion LH_2 aircraft are assumed to be available. Two variants of Use Case C (C1 and C2) are run with different assumptions on how low-cost carriers may respond to the availability of 90 seat aircraft. In the first case (C1), low-cost carriers are given the option of adopting this design. In the second case (C2), they are not. There are several differences between the aircraft designs modelled which affect their uptake in these use cases:

- The 7- and 19-seater use gaseous hydrogen, which has a lower projected price than liquid hydrogen, although this may be offset by increased fuel use for these designs. However, fuel is a relatively small fraction of operating costs for commuter-sized aircraft for the routes that they are typically operated on. Sometimes the aircraft they are competing against use aviation gasoline, which is significantly more expensive than Jet A. This means that these aircraft may be cost-competitive across a wide range of Jet A prices if all other operating costs are the same as the corresponding conventional aircraft. However, significant increases in non-fuel operating costs above the corresponding conventional aircraft are likely to limit their adoption.
- The 40- and 50-seater designs use liquid hydrogen, which is projected to be more expensive than gaseous hydrogen. As such, the difference in per-passenger costs between the 40-50 seater and 19-seater aircraft will be lower than it would be for conventional aircraft, and these designs are likely to require lower hydrogen prices (which are anticipated by 2035) before they can be cost-effective to operate.
- The 90-seater design is the only one modelled which has comparable cruise speed to existing turbofan aircraft, and is the largest aircraft design considered in NAPKIN. Its size reduces typical per-passenger costs but also increases the fraction of per-passenger costs attributable to fuel. The key competitive dynamic for this design is with larger conventional aircraft, particularly where capacity constraints apply. For example, at low hydrogen prices it may be cost-effective to substitute the LH_2 90-seater for a larger conventional aircraft and increase flight frequency accordingly, but this strategy is not compatible with capacity constraints.

Outcomes for these use cases are given in the section on each respective use case. A further use case based on Use Case C1 but exploring uptake in the case that a more evolutionary design is used instead of the UK-domestic optimised 50-seater design is included at the end of this Technical Report.

1.2 Region-region model sensitivity tests

As discussed above, the region-region form of the ABM is used to assess the extent to which including changes in passenger opinion to alternative aircraft designs could affect outcomes. For each of the three main use cases, the region-region ABM is run for central fuel prices (as reported in Table 4) only. Outcomes compared to the respective city-city model outcomes are shown below. Note that a smaller selection of flight legs is used in the region-region model.

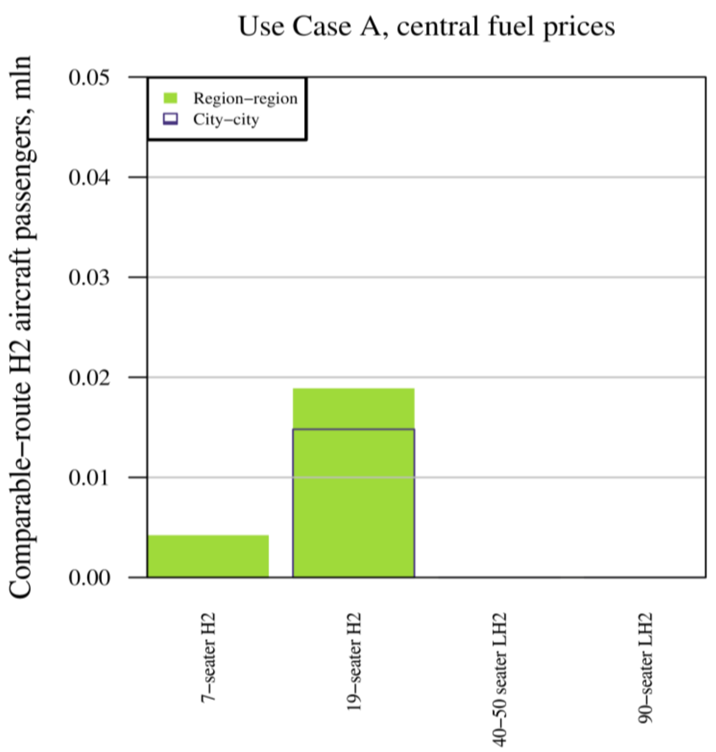
1.2.1 Use Case A

Use Case A simulates the potential adoption of 7- and 19-seater gaseous hydrogen aircraft under conditions appropriate for the time period around 2025. The city-city model outcomes are shown in Section 6.2 of the main project report, including sensitivity to Jet A and hydrogen prices. For the region-region model sensitivity case, we use central fuel price assumptions of £0.8/kg Jet A (inclusive of UK ETS carbon price) and £2.5/kg gaseous hydrogen (corresponding to around £5/kg liquid hydrogen). As with the city-city model runs, these simulations assume 7- and 19-seater hydrogen aircraft are APD-exempt, that domestic APD is halved from baseline values, and that airlines also have the choice of adopting additional conventional aircraft if they wish to expand operations.

Figure 11 shows a comparison between uptake of different sizes of hydrogen aircraft (by passenger numbers) on routes which are included in both models. Note that the reduced geographical scope of the region-region model, excluding flights to and from the Channel Islands, Scilly Isles and Isle of Man, as well intra-Orkney Islands flights, means that comparable-route city-city 7-seater uptake is zero (i.e., all 7-seater use in the city-city model is on routes which are outside the scope of the region-region model). However, as shown in

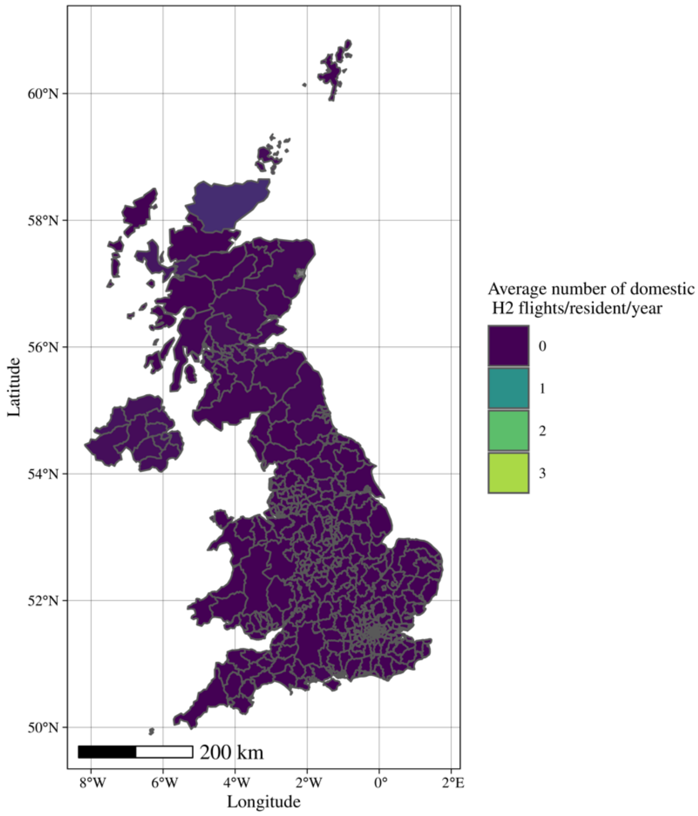
Figure 11, additional uptake is projected in the region-region model on minor Scottish routes (e.g. Aberdeen-Wick) which compensates for the change in scope. Similarly, although many routes where the 19-seater design is projected to be used by the city-city model are not included in the region-region model scope, on routes which are included in both models uptake is slightly higher in the region-region model. These outcomes straightforwardly reflect that positive attitudes towards green aviation are included in the region-region demand model, increasing uptake by a small amount.

Figure 11: Comparison of city-city and region-region model outcomes for Use Case A on comparable routes.



Because the region-region model considers passenger origin and destination regions, it is also possible to examine the ultimate origin and destination of projected hydrogen aircraft passengers. Figure 12 shows hydrogen aircraft passengers by origin/destination LAU1 region in the Use Case A region-region model run. In general, uptake of hydrogen aircraft in this use case is limited to local populations in regions which have hydrogen flights (e.g., Northern Scotland), with a limited number of longer-distance connecting passengers.

Figure 12: Use Case A: average number of domestic hydrogen flights per resident per year, LAU1 regions.

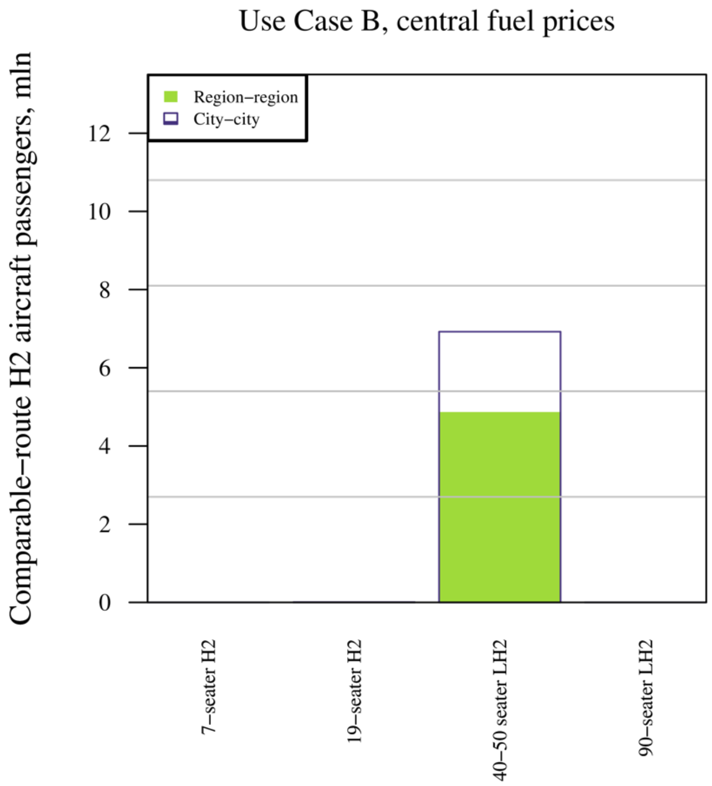


1.2.2 Use Case B

Use Case B simulates the potential adoption of 7- and 19-seater gaseous hydrogen aircraft, and 40- and 50-seater liquid hydrogen aircraft, under conditions appropriate for the time period around 2035. The city-city model outcomes are shown in Section 7.3 of the main project report, including sensitivity to Jet A and hydrogen prices. For the region-region model sensitivity case, we use central fuel price assumptions of £1.3/kg Jet A (inclusive of UK ETS carbon price) and £2.6/kg liquid hydrogen (corresponding to around £1.3/kg gaseous hydrogen). As with the city-city model runs, these simulations assume 7- and 19-seater hydrogen aircraft are APD-exempt, that domestic APD is halved from baseline values, and that airlines also have the choice of adopting additional conventional aircraft if they wish to expand operations. A comparison of outcomes between the city-city and region-region model is shown in Figure 13. As with the main use cases, outcomes for the 40 and 50-seater are presented together as the exact balance of uptake for these aircraft is sensitive to uncertain costs. Outcomes for 7-seater and 19-seater aircraft are similar to those in Use Case A (i.e., similar levels of uptake in both models which is well below projected uptake of the 40-50-

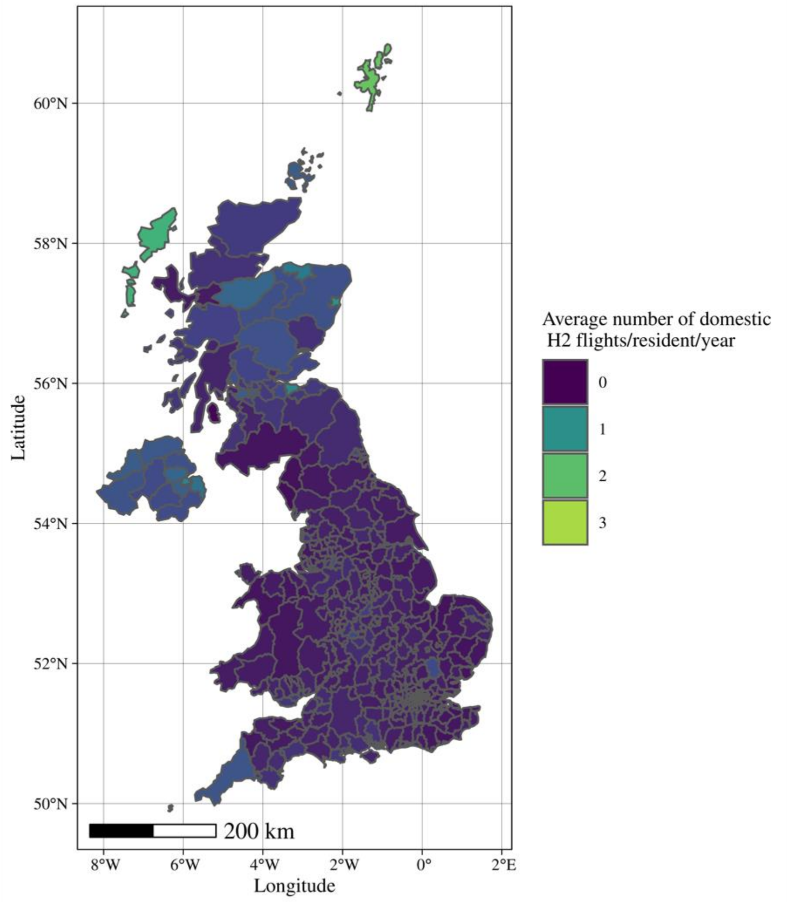
seater aircraft). Overall uptake of the 40-50 seater aircraft in the region-region model on routes simulated in both models is in fact below that in the city-city model (although at a similar order of magnitude), despite the modelled impact of positive attitudes to green aviation. This difference arises from other differences in methodology and assumptions between the two models. First, changes in baseline region-region demand due to decreases in flight cost are not modelled (that is, if the flight cost between two regions decreases significantly, the share of air passengers can increase, but it is not assumed that the total number of passengers travelling between those regions across all modes will increase). For region-pairs where air share is already high, such as routes to and from Northern Ireland, this limits the air demand impact that decreases in cost can have and as such the number of passengers on these routes can be higher in the city-city model. Second, passenger sensitivity to journey time increases differs between the two models. For the region-region model, a larger shift towards ground modes from increasing flight time is projected and this also acts to limit uptake of the 40-50 seater designs. Third, mode share response to flight frequency changes is included in the city-city model but not the region-region model; this means that competing airlines have less of an incentive to increase flight frequency in the region-region model as they can only gain market share from airline competitors not from other transport modes. Fourth, outcomes also reflect baseline decreases in demand on some routes between 2015 and 2019. In combination with the upwards influence on uptake from positive attitudes to green aviation, these factors lead to an overall small decrease over the city-city model in uptake under these conditions. They also highlight the uncertainty involved in this type of modelling.

Figure 13: Comparison of city-city and region-region model outcomes for Use Case B on comparable routes.



As with Use Case A, using the region-region model it is possible to identify the origin and destination regions of hydrogen aircraft passengers. Figure 14 shows the corresponding outcomes for Use Case B. Although use of hydrogen flights is still projected to be high in Northern Scotland, a significantly wider distribution of origin and destination regions for hydrogen flight passengers is projected than in Use Case A. As well as Scotland, other regions with limitations on ground transportation, including Cornwall and Northern Ireland, see increased uptake. Areas around London airports also see relatively high hydrogen flight uptake, largely associated with connecting passengers who are travelling to these airports to take an onward international flight.

Figure 14: Use Case B: average number of domestic hydrogen flights per resident per year, LAU1 regions.



1.2.3 Use Case C

Use Case C simulates the potential adoption of 7- and 19-seater gaseous hydrogen aircraft, and 40-, 50- and 90-seater liquid hydrogen aircraft, under conditions appropriate for the time period around 2040. The city-city model outcomes are shown in Section 8.3 of the main project report, including sensitivity to Jet A and hydrogen prices. For the region-region model sensitivity case, we use central fuel price assumptions of £1.5/kg Jet A (inclusive of UK ETS carbon price) and £1.9/kg liquid hydrogen (corresponding to around £0.8/kg gaseous hydrogen). These simulations assume hydrogen aircraft are APD-exempt, that domestic APD is halved from baseline values, and that airlines also have the choice of adopting additional conventional aircraft if they wish to expand operations. Two versions of Use Case C were run: Use Case C1 in which low-cost carriers were assumed to consider adopting 90-seater hydrogen aircraft if by using them they could increase their profits, and Use Case C2, where low-cost carriers were assumed to only consider larger hydrogen aircraft outside the scope of NAPKIN. A comparison of outcomes between the city-city and region-region model for both cases is shown in Figure 15. As with Use Case B, uptake for 7- and 19-seater aircraft are similar between the region-region and city-city model outcomes (and similar to that shown for Use Case A, above), but in both cases this uptake is well below that of the 40-50 and 90-seater designs. For the larger designs, relative uptake remains similar but is below that for the city-city model, reflecting similar factors to those seen in Use Case B, i.e., that the relatively small positive impact of attitudes to green aviation is counteracted by different assumptions about passenger response to changes in flight time, flight frequency and fare. For Use Case C2, the key factor affecting different uptake of the 90-seater design is the different assumptions used about passenger response to flight frequency. In Use Case C2, low-cost carriers are assumed to not consider adopting the 90-seater design (i.e., they may be waiting for a hydrogen 150-seat aircraft). Instead, they continue using large narrowbody aircraft with low per-passenger costs on trunk routes. For the city-city model, other airlines have a greater incentive to compete on flight frequency on these routes using smaller hydrogen aircraft; in the region-region model this incentive is slightly lower and instead there is more use of larger conventional aircraft on these routes.

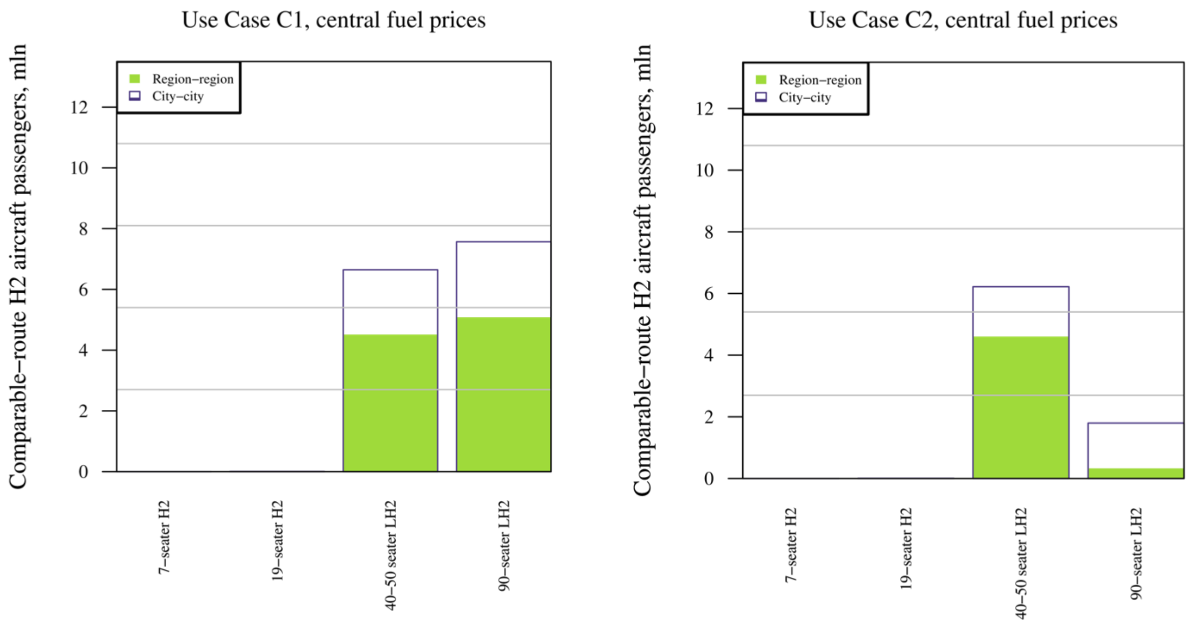


Figure 15: Comparison of city-city and region-region model outcomes for Use Cases C1 and C2 on comparable routes.

In general, however, all three use cases run with the region-region model confirm that key observed model outcome trends persist across both models despite substantial changes in modelling methodology. These include lower potential uptake for 7- and 19-seater aircraft focussed strongly on remote regions; higher potential on other routes for larger designs with lower per-passenger costs; and high uncertainty about the role of low-cost carriers in any hydrogen transition.

As with Use Cases A and B, using the region-region model it is possible to identify the origin and destination regions of hydrogen aircraft passengers. This is shown in Figure 16 for Use Cases C1 and C2. For these use cases, similar dynamics to Use Case B are observed. Particularly for Use Case C1, regions whose residents make significant use of hydrogen flights include Northern Ireland, Scotland (with higher use in the Highlands and Islands region of Scotland), and Cornwall. Significant uptake at regions containing London airports typically reflects passengers who are travelling domestically to make an onward international connection, as discussed for Use Case B.

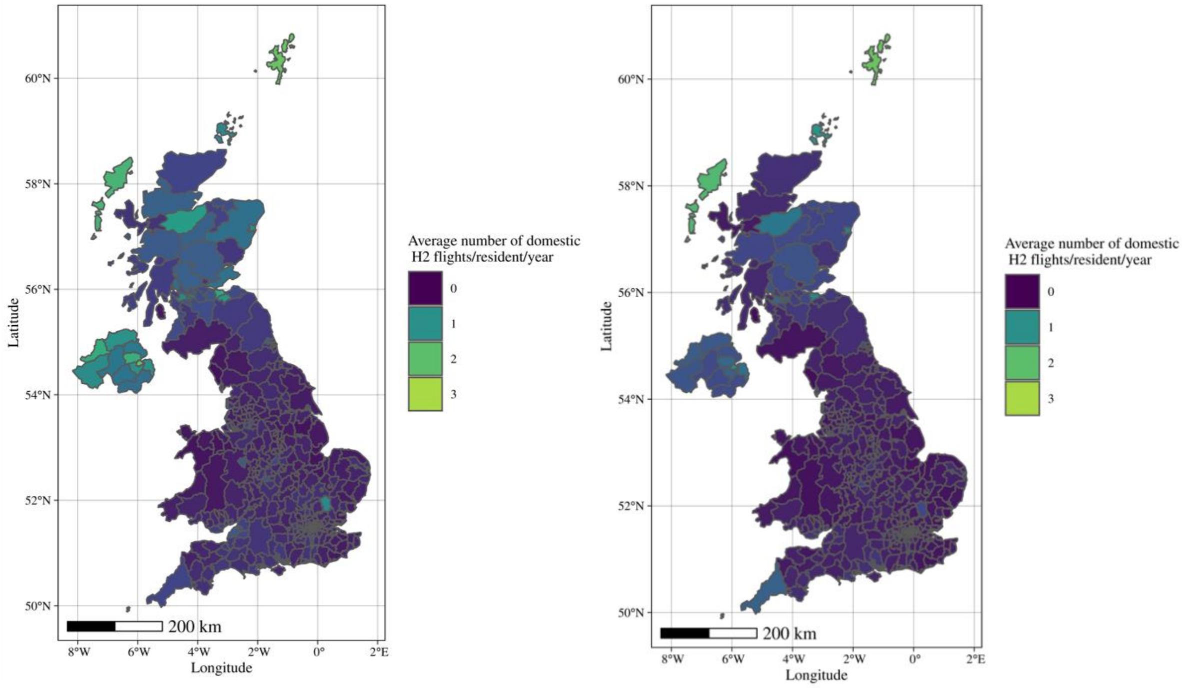


Figure 16: Use Cases C1 (left) and C2 (right): average number of domestic hydrogen flights per resident per year, LAU1 regions.

1.3 Projected adoption of individual aircraft designs generated in NAPKIN

As well as the main Use Cases A, B and C, selected aircraft designs generated during the NAPKIN project are also evaluated individually. This includes designs that are included in the main use cases, but also those that were developed during the project but not used in the main use cases. In each case the model setup is identical to the use cases described above, but only one design of hydrogen aircraft is assumed available. The city-city model is used throughout. For these runs, a specific year is not considered but outcomes are simulated across the whole range of potential fuel prices from Table 4 to allow a direct comparison at the same fuel prices between the uptake behaviour of different designs. Where outcomes for 'central' fuel prices are plotted in this section, central values for 2035 from Table 4 are used. For selected small aircraft concepts where non-fuel operating costs are likely to have a particularly large impact on uptake, cost sensitivity runs are also included. These model runs assume deviations of -25% to +50% from baseline values in maintenance and capital costs, and are named with suffix 'c' (for reduced cost) and 'h' (for increased cost). For larger concepts, outcomes with and without APD eligibility are also considered. Model runs which assume hydrogen aircraft are APD eligible are given the suffix 'a'. Model outcomes are summarised in Table 5, Figure 17 and Figure 18.

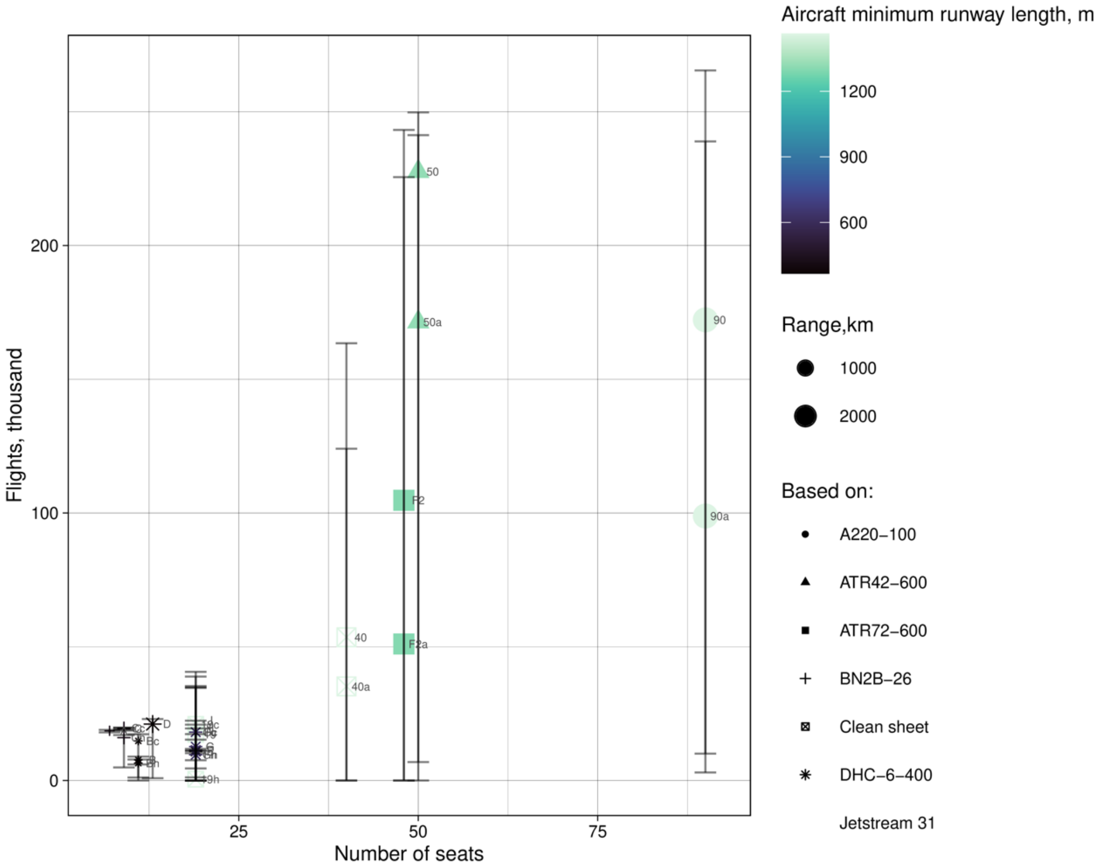
Table 5. Summary of outcomes from individual technology uptake simulations. For uptake, values at year-2035 central fuel prices are shown and ranges across all fuel prices evaluated are given in brackets.

Concept	Based on	Propulsion	Seats	Range, km	Min. runway, m	Uptake, thousand flights	Uptake, million passengers

A	BN2B-26	GH_2/elec. motor	7	230	427	18.5 (18.0 - 18.9)	0.07 (0.06 – 0.07)
B	DHC-6-400	GH_2/elec. motor	11	220	366	7.7 (1.1 – 8.9)	0.07 (0.01-0.08)
Bc	DHC-6-400	GH_2/elec. motor	11	220	366	14.8 (6.0 -17.3)	0.15 (0.06-0.17)
Bh	DHC-6-400	GH_2/elec. motor	11	220	366	6.5 (0-7.8)	0.07 (0 - 0.07)
C	BN2B-26	GH_2/elec. motor	9	300	442	19.3 (18.7-19.7)	0.08 (0.08-0.09)
Cc	BN2B-26	GH_2/elec. motor	9	300	442	19.5 (19.0-19.8)	0.08 (0.08-0.09)
Ch	BN2B-26	GH_2/elec. motor	9	300	442	16.0 (4.9-17.0)	0.08 (0.03-0.08)
D	DHC-6-400	LH_2/elec. motor	13	530	366	21.1 (0.9 – 23.0)	0.22 (0.01 – 0.24)
E	DHC-6-400	LH_2/turboprop	19	300	366	10.8 (0 – 11.8)	0.12 (0 - 0.13)
F	DHC-6-400	LH_2/elec. motor	19	300	567	11.4 (4.5 – 17.4)	0.13 (0.06-0.20)
Fc	DHC-6-400	LH_2/elec. motor	19	300	567	18.1 (10.2 – 20.9)	0.21 (0.12-0.25)
Fh	DHC-6-400	LH_2/elec. motor	19	300	567	9.6 (0 – 11.1)	0.11 (0 – 0.12)
G	DHC-6-400	GH_2/elec. motor	19	300	627	12.7 (1.2 – 19.5)	0.14 (0.02-0.23)
Gc	DHC-6-400	GH_2/elec. motor	19	300	627	18.1 (7.6 – 22.4)	0.21 (0.09-0.26)
Gh	DHC-6-400	GH_2/elec. motor	19	300	627	9.6 (0 – 11.1)	0.11 (0 - 0.12)
H	Jetstream 31	LH_2/elec. motor	19	1110	1360	19.6 (0 – 35.3)	0.24 (0 – 0.44)
I	Jetstream 31	LH_2/elec. motor + battery	19	1140	1365	19.6 (0 – 34.8)	0 .24 (0 – 0.43)
J	Jetstream 31	LH_2/turboprop	19	1050	1360	22.5 (0 – 40.6)	0.27 (0 – 0.51)
19HP	New	LH_2/elec. motor	19	926	1463	17.2 (0 – 34.6)	0.22 (0 – 0.43)
19HPc	New	LH_2/elec. motor	19	926	1463	21.0 (0 - 38.9)	0.26 (0 – 0.49)
19HPh	New	LH_2/elec. motor	19	926	1463	0.5 (0 – 15.3)	0.006 (0 – 0.20)
40	New	LH_2/elec. turbofan	40	1464	1507	53.6 (0 - 163)	1.7 (0-5.2)
40a	New	LH_2/elec. turbofan	40	1464	1507	35.2 (0 - 124)	1.1 (0-3.9)
2F	ATR72-600	LH_2/turboprop	48	1963	1300	105 (0 - 243)	4.3 (0-9.6)
2Fa	ATR72-600	LH_2/turboprop	48	1963	1300	51.0 (0 - 225)	2.1 (0-8.9)
50	ATR42-600	LH_2/turboprop	50	1111	1319	228 (6.9 - 250)	9.4 (0.3-10.4)

50a	ATR42-600	LH_2/turboprop	50	1111	1319	171 (0 - 241)	6.9 (0-10.0)
A220LH_2	A220-100	LH_2/turbofan	90	2654	1460	172 (10 - 265)	12.2 (0.7-18.9)
A220LH_2a	A220-100	LH_2/turbofan	90	2654	1460	99 (3 - 239)	6.9 (0.1-17.0)

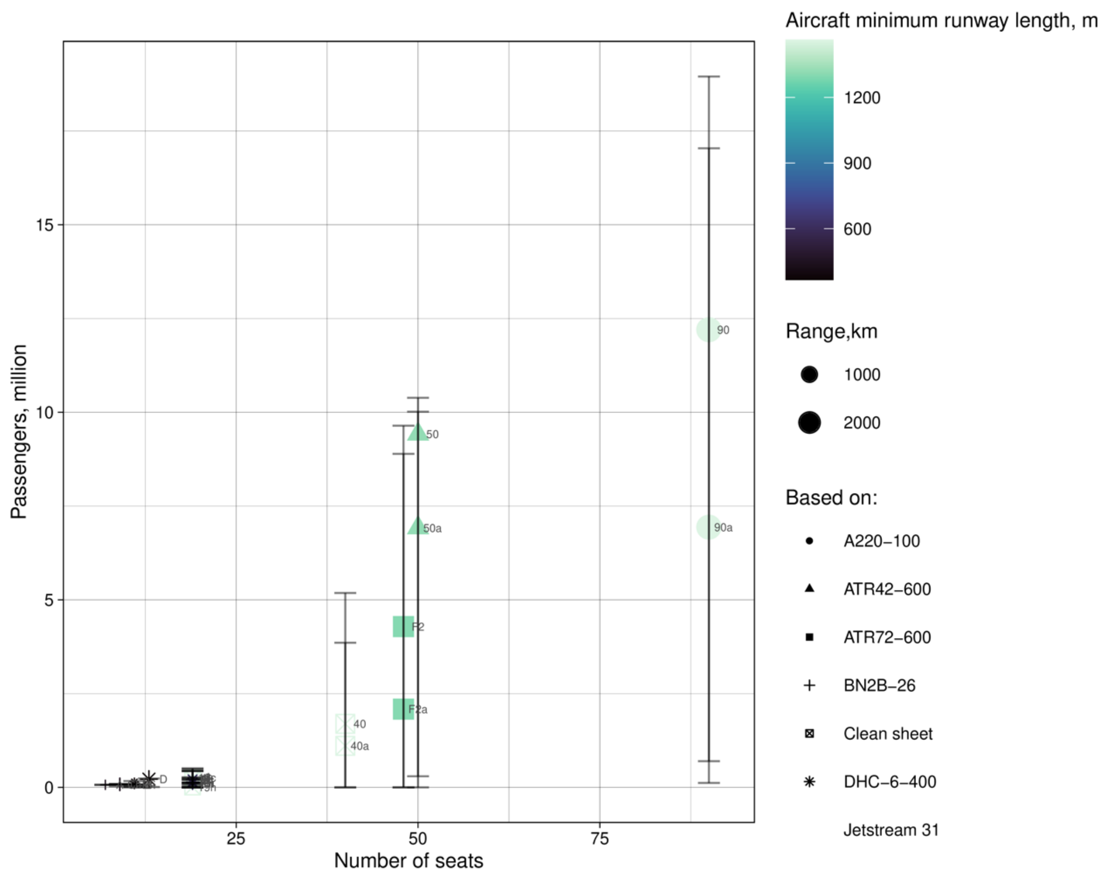
Figure 17: Profit-optimal uptake of NAPKIN aircraft designs by number of UK domestic flights, assessed individually over the full range of kerosene and hydrogen prices considered in this report. Suffix 'a' indicates runs where the hydrogen aircraft is assumed APD



In general, these simulations support outcomes from the main use cases. The aircraft concepts assessed differ in several key characteristics (Table 5). First, they differ in which routes they can be used on (due to range and required airport runway length). This is related to other design priorities; for example, some 19-seater designs are non-pressurised utility aircraft which target short runway capability and short range, whilst others are higher-performance designs intended for longer-distance flights. Second, they differ in fuel efficiency, which is also related to the extent to which they are retrofits of existing aircraft or new designs, as well as to design trade-offs with range, costs, number of seats and required runway length. Third, they differ in fuel and propulsion system type (fuel cell/direct combustion, electric motor/turboprop/turbofan, gaseous/liquid hydrogen) which in turn affects fuel use and other operating costs. Finally, they differ in number of seats, which affects potential markets and competition with conventional designs of different sizes.

All else equal, larger designs have higher potential for use in the UK domestic system due to their typically lower per-passenger costs and greater range. This is reflected in the strong relationship between aircraft size and typical/maximum uptake (e.g., Figure 17) However, the smaller designs examined here have specialised use on specific routes which cannot be served by the larger designs. The uptake of mid-sized designs is highly dependent on operating cost. This includes non-fuel operating costs and particularly maintenance costs, which may are uncertain and differ between different designs. At low operating cost (e.g., the 50-seater design used in Use Cases B and C), it may be cost-competitive with larger designs. Uptake is also a function of the range and required airport runway length to operate the aircraft. All concepts examined with more than 19 seats have sufficient range to perform all UK domestic flights. The 7-19 seat aircraft examined typically have range shorter than that necessary to perform London-Scotland flights, however (around 500km). Conversely, most of the smaller aircraft designs are STOL capable and can fly into and out of remote airports with short runways; the larger designs typically cannot. This means that no single hydrogen design of those examined here can fully substitute all UK domestic operations – at least one small, STOL-capable and one larger design are required.

Figure 18: Profit-optimal uptake of NAPKIN aircraft designs by number of UK domestic passengers, assessed individually over the full range of kerosene and hydrogen prices considered in this report. Suffix'a' indicates runs where the hydrogen aircraft is assumed A

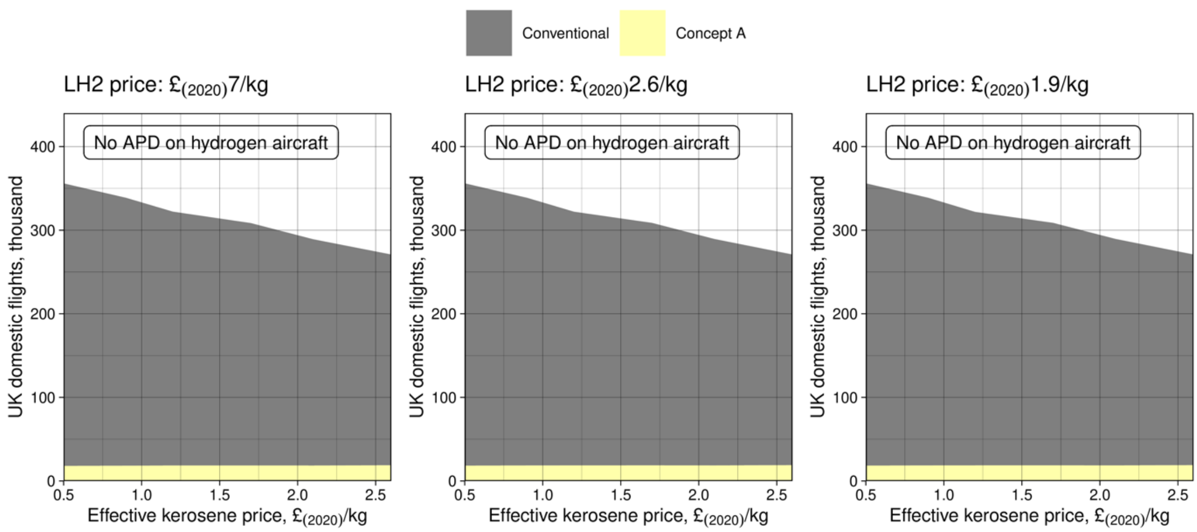


Individual outcomes for each concept are discussed in the sections below.

1.3.1 7 seat retrofit gaseous hydrogen design (CAeS Concept A)

This concept is a retrofit of a Britten-Norman Islander. Although the Islander has 9 seats, Concept A has 7 seats due to constraints on the mass of payload and fuel that can be carried after the increased mass of propulsion and fuel systems is accounted for. It is powered by fuel cells using gaseous hydrogen and uses electric motor-driven propellers. The baseline conventional Britten-Norman Islander is powered by aviation gasoline. As a result, fuel costs for this concept are anticipated to be below those of the baseline across a wide range of hydrogen prices. However, some sources of non-fuel operating cost, such as depreciation, are projected to be higher. Concept A is the smallest aircraft evaluated in NAPKIN by number of seats. It is STOL-capable, not pressurised, carries less baggage per passenger than larger aircraft, and is generally similar to existing small utility-type aircraft that are currently used on regional and island-hopping routes. Figure 19 shows projected profit-optimal uptake across the full range of effective Jet A and hydrogen prices examined in this report. Because of the high price of aviation gasoline, and because concept A uses gaseous hydrogen which is lower-cost than liquid hydrogen, there may be a cost-effective use case even at relatively high hydrogen price. However, aircraft of this size are generally not cost-competitive against much larger designs and, as such, UK usage is likely to be limited to the set of UK domestic-domestic routes where 9- and 19-seater aircraft currently operate, i.e., routes to, from and between islands and remote regions.

Figure 19: Projected profit-optimal uptake by number of flights for Concept A (7-seater gaseous hydrogen) in the UK domestic aviation system across a range of kerosene and hydrogen price assumptions.



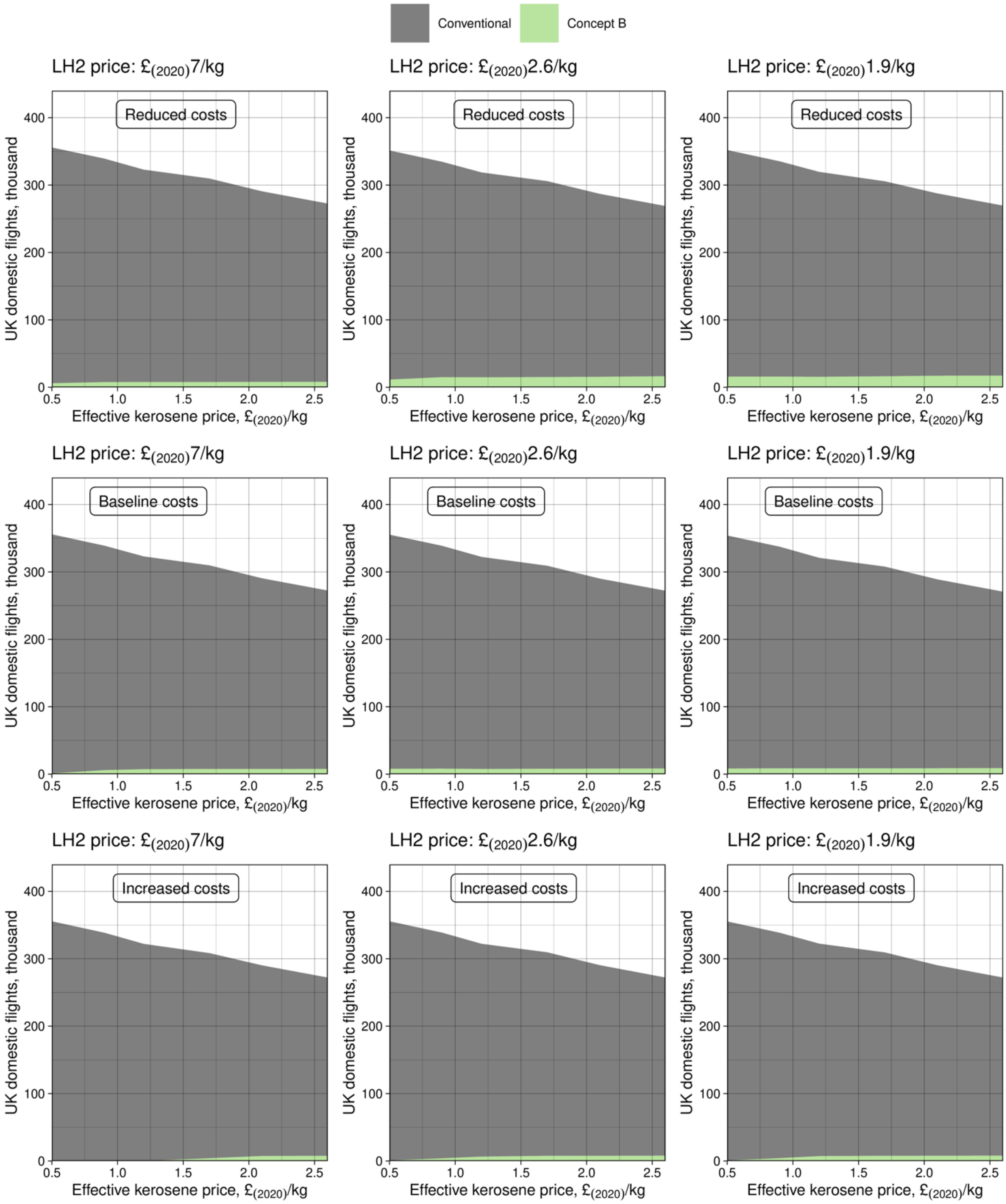
Although the impact of changing non-fuel operating costs is not evaluated for Concept A, this is examined for concept C, below, which is a similar design.

1.3.2 11 seat retrofit gaseous hydrogen design (CAeS Concept B) including impact of non-fuel operating costs

This concept is a retrofit of a DHC-6 Twin Otter Series 400. Although the Twin Otter has 19 seats, Concept B has 11 seats due to constraints on the mass of payload and fuel that can be carried after the increased mass of propulsion and fuel systems is accounted for. It is powered by fuel cells using gaseous hydrogen and uses electric motor-driven propellers. Concept B is

STOL-capable, not pressurised, carries less baggage per passenger than larger aircraft, and is generally similar to existing small utility-type aircraft that are currently used on regional and island-hopping routes. It will compete against both small kerosene aircraft and aircraft which use aviation gasoline (e.g., the baseline Britten-Norman Islander). As a retrofit design, depreciation and insurance costs are projected to be relatively low; however, fuel cell maintenance costs are both uncertain and potentially large. Because of the high price of aviation gasoline, and because concept B uses gaseous hydrogen which is lower-cost than liquid hydrogen, there may be a cost-effective use case even at relatively high hydrogen price, provided that fuel and other operating cost reductions can compensate for likely increased maintenance costs. However, aircraft of this size are generally not cost-competitive against much larger designs and, as such, UK usage is likely to be limited to the set of UK domestic-domestic routes where 9- and 19-seater aircraft currently operate, i.e., routes to, from and between islands and remote regions.

Figure 20: Projected profit-optimal uptake by number of flights for Concept B (11-seater gaseous hydrogen) in the UK domestic aviation system across a range of kerosene and hydrogen prices and different capital and maintenance cost assumptions.



Because fuel cell maintenance costs in particular are uncertain, three sets of simulations for this design are run, shown in Figure 20. 'Baseline costs' includes the baseline capital and maintenance costs discussed in the accompanying NAPKIN operating cost technical report. 'Reduced costs' assesses sensitivity around these numbers by considering the case where capital and maintenance costs are reduced by 25%. 'Increased costs' considers the case where capital and maintenance costs are increased by 50%. Because maintenance costs are a significant fraction of operating costs for small aircraft, these assumptions have an impact on uptake. At increased costs, uptake of Concept B requires Jet A prices on the higher end of the range used here. At baseline and reduced costs, some uptake is also feasible where Jet A prices remain on the lower end of the range used here. In practice, as Jet A prices are projected to increase over time, the reduced costs scenario translates to earlier uptake of this concept. However, in both cases, use is limited to the sorts of UK routes where small aircraft currently operate and reducing fuel costs further does not significantly increase use beyond these routes.

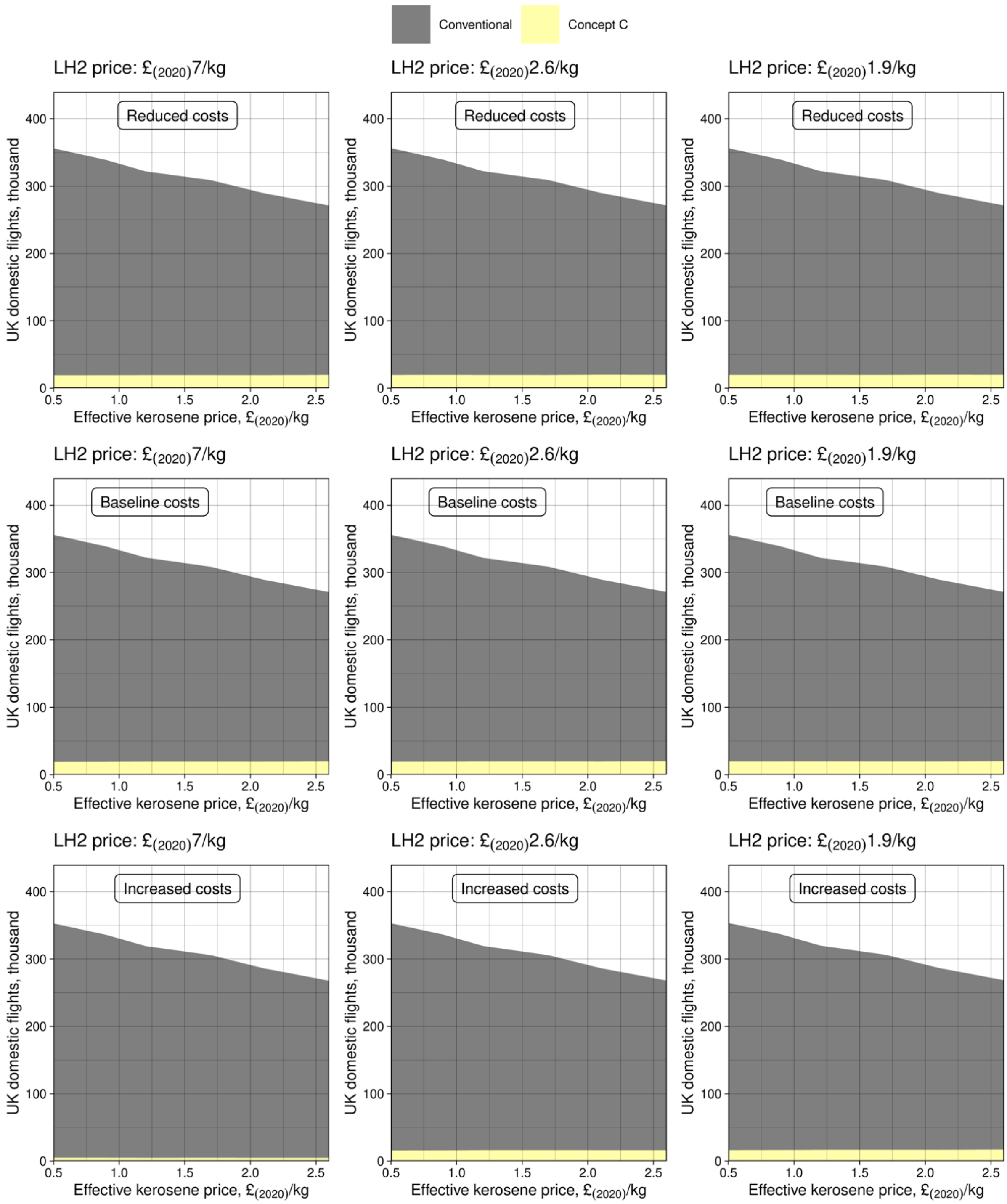
1.3.3 9 seat new gaseous hydrogen design (CAeS Concept C2)

Concept C2 is a 9 seat gaseous hydrogen fuel cell concept based on the specifications of the Britten-Norman Islander, using electric motor-driver propellers for propulsion. This concept has a short range (300 km) and is intended for island-hopping and regional flights. It has lower per-passenger luggage capacity than the larger concepts examined in NAPKIN and is not pressurised, and requires only a single pilot. The small size of this aircraft and the short routes it is likely to be used on limit its fuel costs. It will compete against both small kerosene aircraft and aircraft which use aviation gasoline (e.g., the baseline Britten-Norman Islander). Because of the high price of aviation gasoline, because it has lower pilot costs than larger aircraft, and because concept C2 uses gaseous hydrogen which is lower-cost than liquid hydrogen, concept C2 is projected to be cost-effective to operate across a wide range of hydrogen prices. However, as with concepts A and B, it is unlikely to be cost-competitive against much larger aircraft and as such UK domestic use is projected to be limited to routes where similar-sized aircraft currently operate.

Concept C2 is projected to have slightly lower operating costs than similarly-sized conventional alternatives, so in general is expected to be cost-effective to operate on routes where 9-seaters are currently used. However, because fuel cell maintenance costs in particular are uncertain, we run three sets of simulations for this design, shown in Figure 21. 'Baseline costs' includes the baseline capital and maintenance costs discussed in the accompanying NAPKIN operating cost technical report. 'Reduced costs' and 'Increased costs' assess sensitivity around these numbers by considering the case where capital and maintenance costs are reduced by 25% and increased by 50%, respectively. Uptake of this concept has limited sensitivity to Jet A price (partly because it is competing against aviation gasoline-using aircraft, and partly because fuel is a relatively small fraction of operating cost). Although uptake does not increase substantially at 'Reduced costs' (reflecting that the aircraft is already cost-competitive on the types of routes where it is likely to be used), it is suppressed at 'Increased costs', particularly where hydrogen prices are also high.

More flights are projected than for Concept B because Concept C has fewer seats, i.e., more flights are needed to carry a similar number of passengers.

Figure 21: Projected profit-optimal uptake by number of flights for Concept C2 (9-seater gaseous hydrogen) in the UK domestic aviation system across a range of kerosene and hydrogen prices and different capital and maintenance cost assumptions.



1.3.4 13 seat LH_2 fuel cell electric motor design (CAeS Concept D)

Concepts D and E are similar to each other. Both are retrofits of a DHC-6 Twin Otter Series 400 using liquid hydrogen. Concept D uses fuel cells to power electric motor-driven propellers, whilst concept F uses direct hydrogen combustion in turboprop engines. Similarly to Concepts B, F and G, these are short-range, STOL-capable utility-type aircraft and similar constraints apply to their use. The two concepts also differ in that concept D has a longer range (sufficient for most domestic UK routes) but only 13 seats, whereas concept E is limited to 300 km but has 19 seats.

Figure 22: Projected profit-optimal uptake by number of flights for Concept D (19-seater liquid hydrogen fuel cell) in the UK domestic aviation system across a range of kerosene and hydrogen prices.

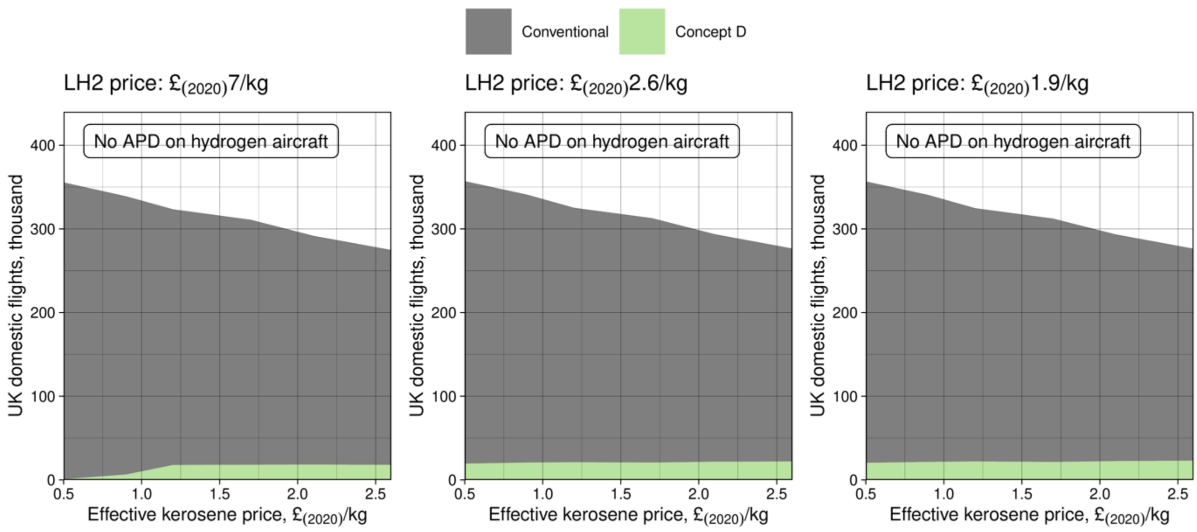
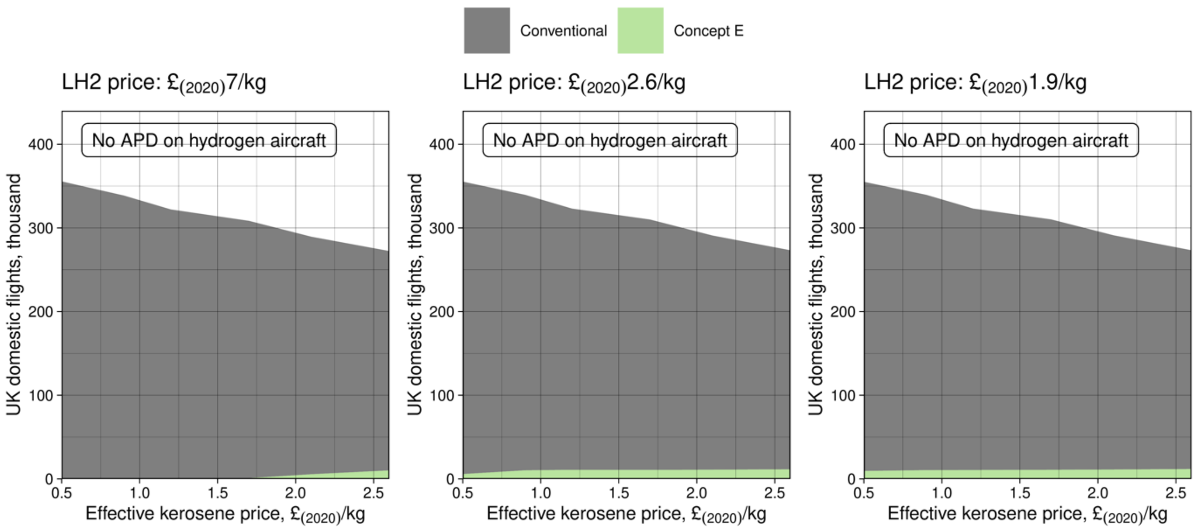


Figure 22 shows projected profit-optimal uptake in the UK domestic aviation system for Concept D. Patterns of uptake are similar to Concept B, which is a similar size and has similar operating costs, but potential uptake is greater at low hydrogen prices due to this concept's longer range. This allows it to supplement frequency on longer-distance regional routes for scenarios where fuel costs are particularly low.

1.3.5 19 seat LH_2 fuel cell turboprop design (CAeS Concept E)

Concept E is similar to concept D other than that it uses direct hydrogen combustion rather than fuel cells. The two concepts are discussed together in the previous section. Simulation outcomes for Concept E are shown in Figure 23. Compared to Concept D, Concept E carries more passengers per flight, has a shorter range, and has higher projected operating costs per flight but lower operating costs per passenger. These factors affect uptake. In particular, the limited range caps the number of passengers that can be carried when hydrogen prices are low and Jet A prices are high. In general, the higher number of routes on which Concept D can operate means that projected usage is higher for Concept D than for Concept E despite Concept E's lower per-passenger costs.

Figure 23: Projected profit-optimal uptake by number of flights for Concept E (19-seater liquid hydrogen direct combustion) in the UK domestic aviation system across a range of kerosene and hydrogen prices

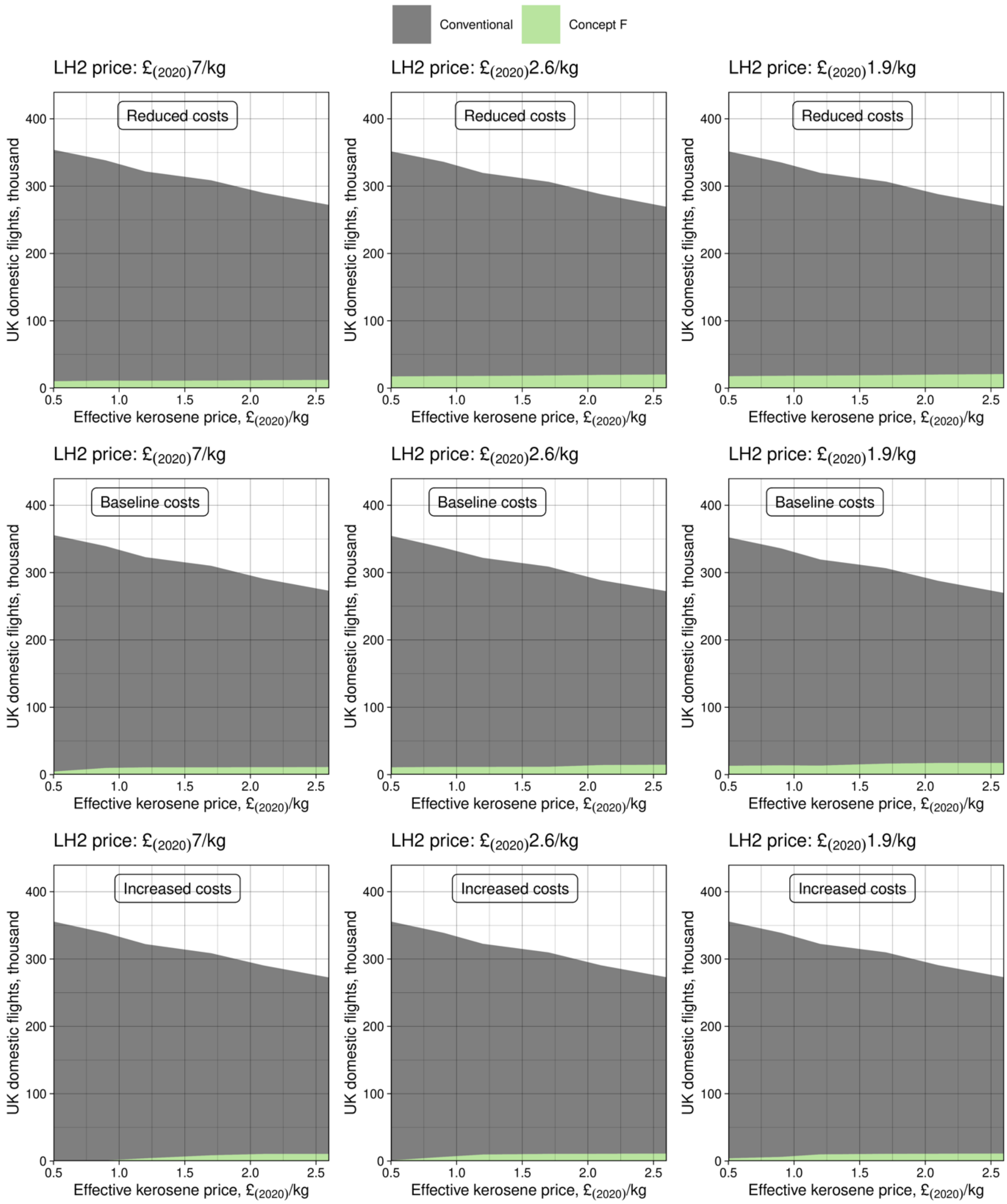


1.3.6 19 seat new LH_2 fuel cell design (CAeS Concept F2)

Concepts F and G are similar to each other. Both are 19-seater utility-type fuel cell aircraft with electric motor driven propellers and targeted range around 300km. Other capabilities are similar to the other utility-type aircraft discussed above. Concept F uses liquid hydrogen, whilst concept G uses gaseous hydrogen. In both cases, the second iteration of the concept developed in NAPKIN is used in modelling. Although gaseous hydrogen has a lower price in these simulations, the uptake of both concepts (shown in Figure 24 for Concept F and Figure 25 for Concept G) relatively similar, with slightly higher uptake of Concept G across most combinations of fuel price but lower uptake of Concept G where hydrogen prices are highest. This is for two reasons. First, concept F uses less fuel for a comparable flight. At the higher end of the hydrogen price range modelled here, the lower fuel use and higher fuel cost almost exactly cancel out. At the lower end of the hydrogen price range modelled here, concept G is less expensive to operate; however, both concepts cost less to operate than conventional alternatives and, as such, the main constraint on uptake is demand and PSO requirements on suitable routes, which are the same for both aircraft, again leading to similar uptake.

Because non-fuel operating costs are uncertain and have a particularly large potential impact on uptake of the smallest aircraft designs, three sets of simulations are run for this design and for Concept G. 'Baseline costs' includes the baseline capital and maintenance costs discussed in the accompanying NAPKIN operating cost technical report. 'Reduced costs' assesses sensitivity around these numbers by considering the case where capital and maintenance costs are reduced by 25%. 'Increased costs' looks at the case where capital and maintenance costs are increased by 50% over baseline values. The impact of reducing capital and maintenance costs is similar to that for other 9- and 19-seater designs, i.e., it increases the cost-effectiveness of the design at high hydrogen price, but does not make it cost-competitive against much larger designs, with typical routes remaining similar to those operated currently by 9- and 19-seater aircraft. As with other similar designs, increasing capital and maintenance costs has the potential to significantly suppress uptake, particularly where kerosene prices are also low.

Figure 24: Projected profit-optimal uptake by number of flights for Concept F2 (19-seater fuel cell LH2 utility) in the UK domestic aviation system across a range of kerosene and hydrogen prices and different capital and maintenance cost assumptions.

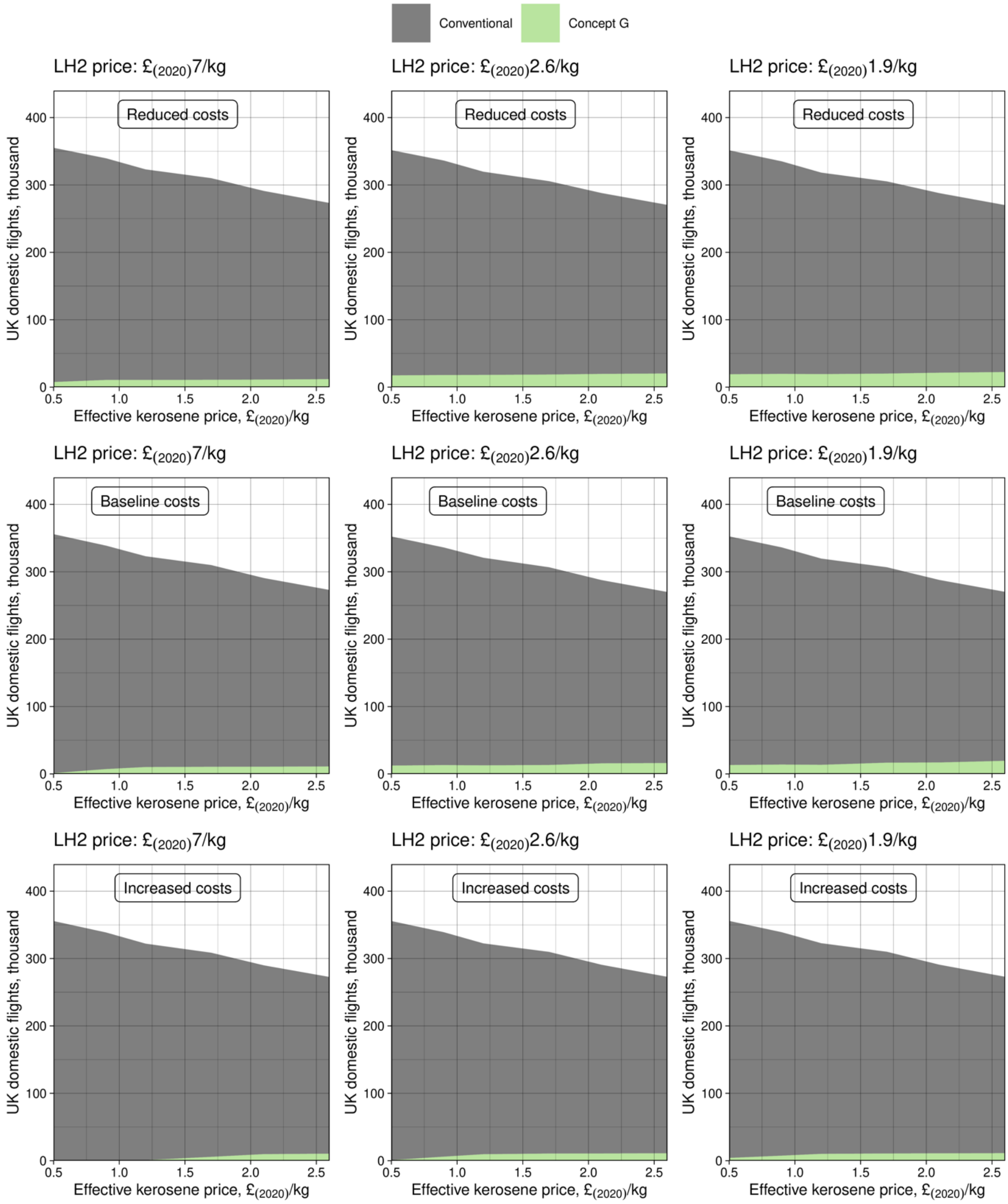


1.3.7 19 seat new gaseous hydrogen design (CAeS Concept G2) including impact of non-fuel operating costs

Concept G is similar to concept F other than that it uses gaseous rather than liquid hydrogen. The two concepts are discussed together in the previous section; both have similar uptake mainly because the lower fuel price applicable to gaseous hydrogen is partly cancelled out by

Concept G's higher fuel use. Simulation outcomes for Concept G, including sensitivity to maintenance and capital costs (the same 'reduced costs' and 'increased costs' scenarios as evaluated for the previous concepts) are shown in Figure 25.

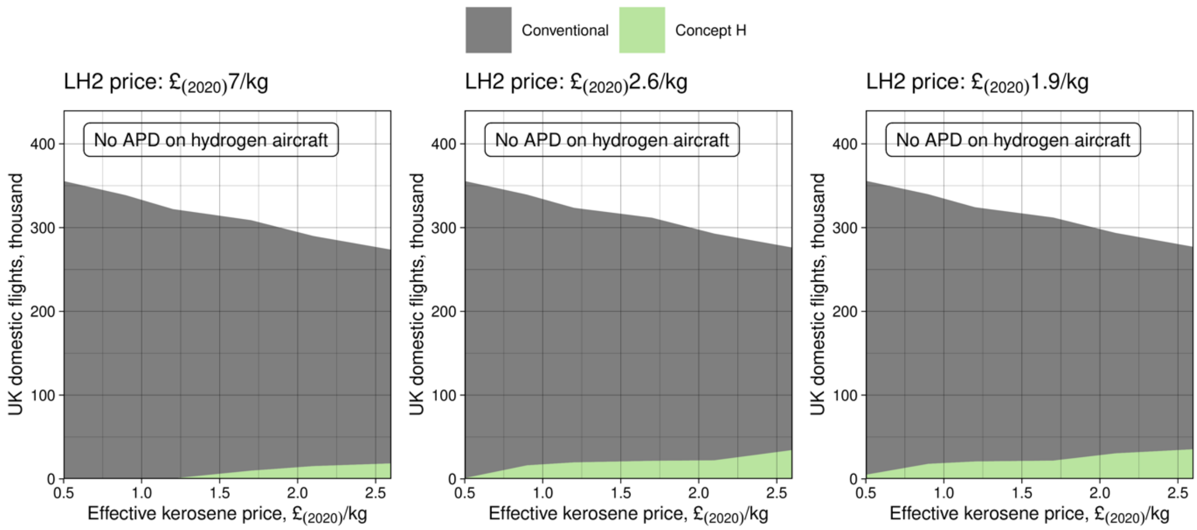
Figure 25: Projected profit-optimal uptake by number of flights for Concept G (19-seater fuel cell GH2 utility) in the UK domestic aviation system across a range of kerosene and hydrogen prices and different capital and maintenance cost assumptions.



1.3.8 19 seat higher-performance LH_2 fuel cell electric motor/conventional propeller design (CAeS Concept H)

Concepts H-J are based on the BAe Jetstream 31, a higher-performance, pressurised 19 seat aircraft. Unlike the utility designs considered above, it does not have STOL capability but is capable of longer ranges. This type of design is not similar to aircraft currently used on UK scheduled domestic routes (current 19-seater routes are generally served by STOL utility-type aircraft) and its most promising uses are likely on routes outside the UK and/or new types of UK route. As such, limited uptake is likely for these simulations. Concept H uses liquid hydrogen and fuel cells to power electric motor-driven propellers. Concept I is similar but supplements the power supplied to the electric motors with additional batteries, allowing the fuel cell maximum power requirement to be decreased. Concept J is similar to Concept H but uses direct combustion in turboprop engines rather than fuel cells. These differences in design affect the operating costs of the concepts. In general, as higher-performance designs, operating costs are projected to be higher those for than the utility-type aircraft assessed above. However, operating costs are projected to be lower for Concept J (on a similar level to utility-type designs) than for Concepts H and I because Concept J does not use fuel cells. These costs are reflected in projected uptake at higher hydrogen prices. Conversely, at low hydrogen prices the longer range of this concept allows it to be used on more routes, leading to relatively high maximum uptake (and more kerosene price sensitivity) compared to 19 seat concepts with shorter ranges. Where fuel price conditions are particularly favourable this includes some use on routes normally operated by larger regional aircraft, with corresponding increases in flight frequency. Uptake for Concept H is shown in Figure 26.

Figure 26: Projected profit-optimal uptake by number of flights for Concept H (higher-performance liquid hydrogen fuel cell 19-seater) in the UK domestic aviation system across a range of kerosene and hydrogen prices.

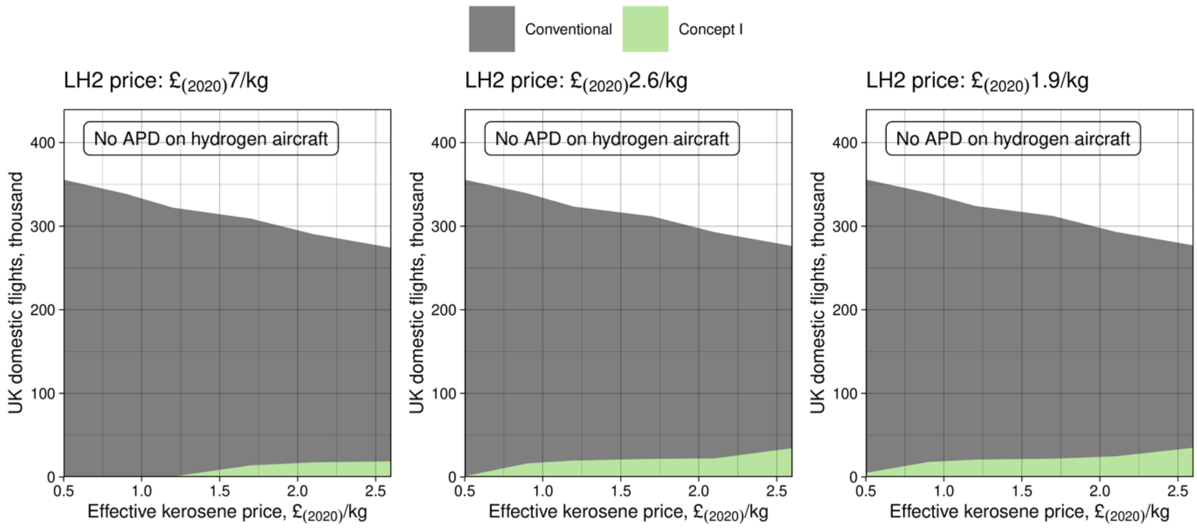


Although the impact of changing non-fuel operating costs is not evaluated for Concept H, this is examined for concept 19HP, below, which is a similar design.

1.3.9 19 seat higher-performance LH_2 fuel cell electric motor/conventional propeller design with additional batteries (CAeS Concept I)

Concept I is similar to concept H other than that it has additional batteries which allow the fuel cell maximum power requirements to be decreased. Concepts H, I and J are discussed together in the previous section. Simulation outcomes for Concept I are shown in Figure 27. These are very similar to those for Concept H, reflecting the overall similarity in terms of operation costs and capabilities of these two designs.

Figure 27: Projected profit-optimal uptake by number of flights for Concept I (higher-performance liquid hydrogen fuel cell 19-seater with supplementary batteries) in the UK domestic aviation system across a range of kerosene and hydrogen prices.

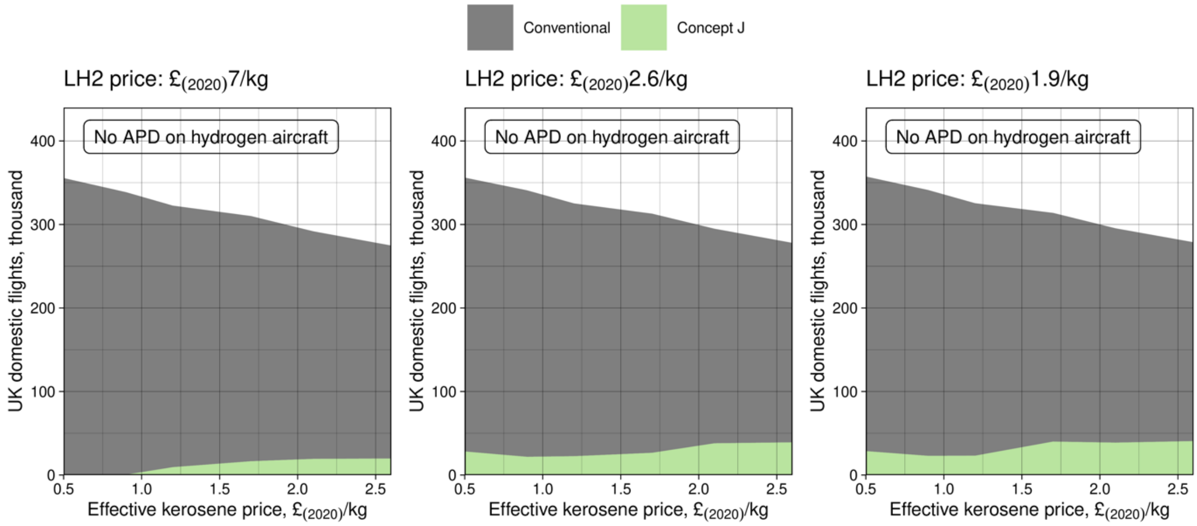


Although the impact of changing non-fuel operating costs is not evaluated for Concept I, this is examined for concept 19HP, below, which is a similar design.

1.3.10 19 seat higher-performance LH_2 direct combustion turboprop design (CAeS Concept J)

Concept J is similar to concepts H and I but uses direct hydrogen combustion in turboprop engines rather than fuel cells. Concepts H, I and J are discussed together in the previous section. Simulation outcomes for Concept J are shown in Figure 28. Compared to Concepts H and I, uptake is slightly higher, reflecting lower operating costs. At low hydrogen price and high kerosene price, potential uptake is the highest amongst the 19-seater designs evaluated in this project. This is because of this concept's combination of long range and low operating costs. This means that, where the gap between hydrogen and kerosene costs becomes particularly large, it can become cost-effective to substitute some larger aircraft flights with several 19-seater flights with Concept J instead. However, this situation requires than no larger design of hydrogen aircraft is available.

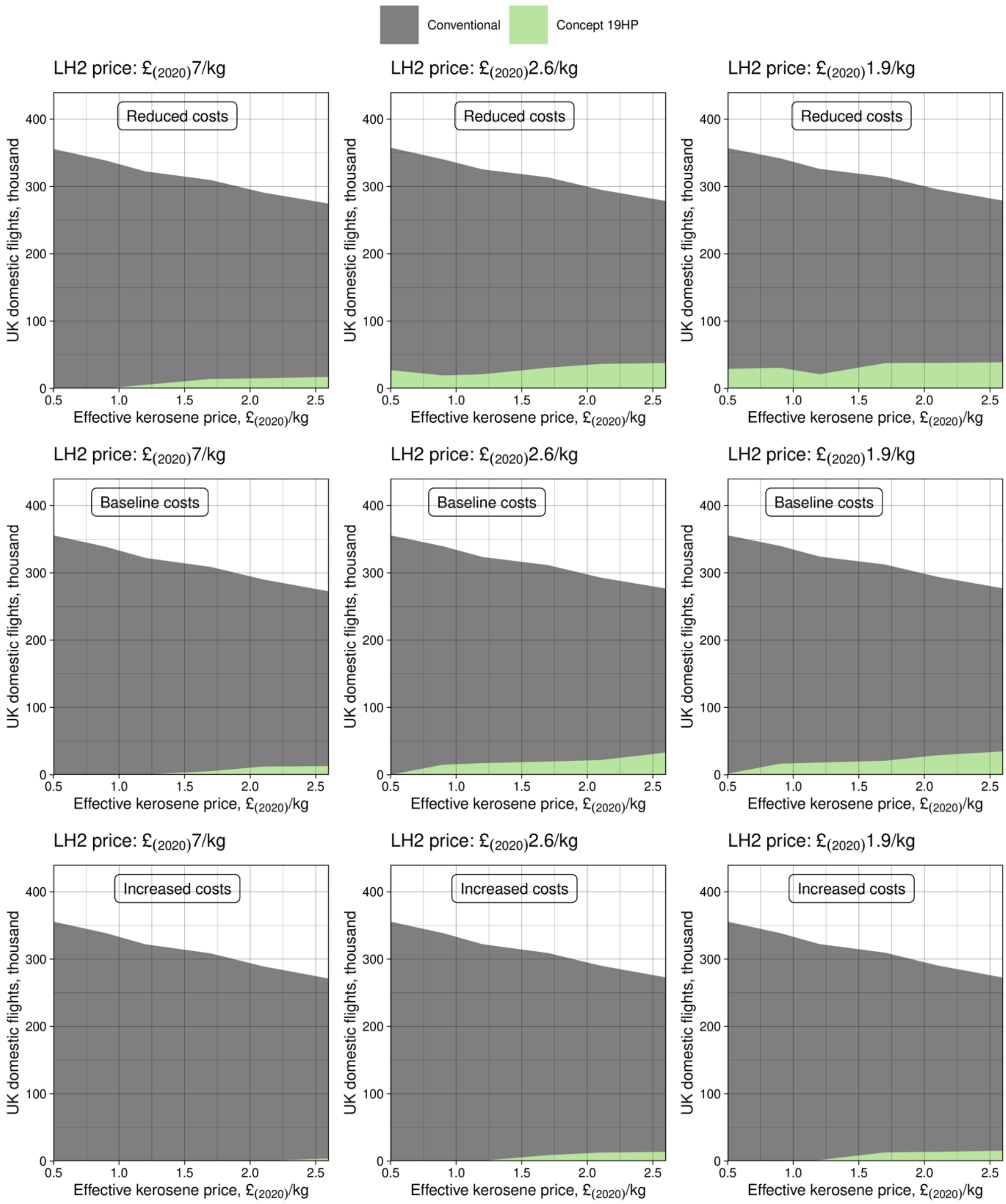
Figure 28: Projected profit-optimal uptake by number of flights for Concept J (higher-performance liquid hydrogen direct combustion 19-seater turboprop) in the UK domestic aviation system across a range of kerosene and hydrogen prices.



1.3.11 19 seat higher-performance LH_2 fuel cell design (GKN)

This is a LH_2 fuel cell clean-sheet design. Like Concepts H, I and J, but unlike most of the other 19 seat aircraft above, is not a utility-type aircraft. It is pressurised, does not assume a reduction in per-passenger baggage capacity from larger designs, does not have STOL capability, and has range capability sufficient for all domestic UK flights and short-range international flights. Three designs were considered with different cost and operating characteristics. Of these, we evaluate the third design, GKN19HP, which uses electric motors for propulsion. This is because it is projected to have the lowest capital and maintenance costs of the three. This type of design is not similar to aircraft currently used on UK domestic routes (current 19-seater routes are generally served by STOL utility-type aircraft) and its most promising uses are likely on routes outside the UK and/or new types of UK route. However, as shown in Figure 29, uptake at low hydrogen prices in particular is similar to the other longer-range 19 seat aircraft examined above, and can include use on UK routes which are normally served with larger regional aircraft in the case that only conventional designs are available in these size classes. For example, use is seen to increase flight frequency on routes such as Aberdeen-Birmingham and London City-Inverness. It is not used for many of the island-hopping type routes that the utility 19-seaters above are used on due to its lack of STOL capability. There is also some fluctuation seen in the outcomes shown in Figure 29 (for example, a small number of runs with slightly lower hydrogen uptake at higher kerosene price) which arises from the presence of multiple similar profit-optimal solutions in the solution space. Because non-fuel costs are uncertain and can have a large impact on uptake of small aircraft, we run three sets of simulations for this design. 'Baseline costs' includes the baseline capital and maintenance costs discussed in the accompanying NAPKIN operating cost technical report. 'Reduced costs' assesses sensitivity around these numbers by considering the case where capital and maintenance costs are reduced by 25%. 'Increased costs' looks at the case where capital and maintenance costs are increased by 50% over baseline values. These outcomes are likely to be representative of reduced-costs outcomes for the other higher-performance 19-seaters modelled as well (concepts H-J).

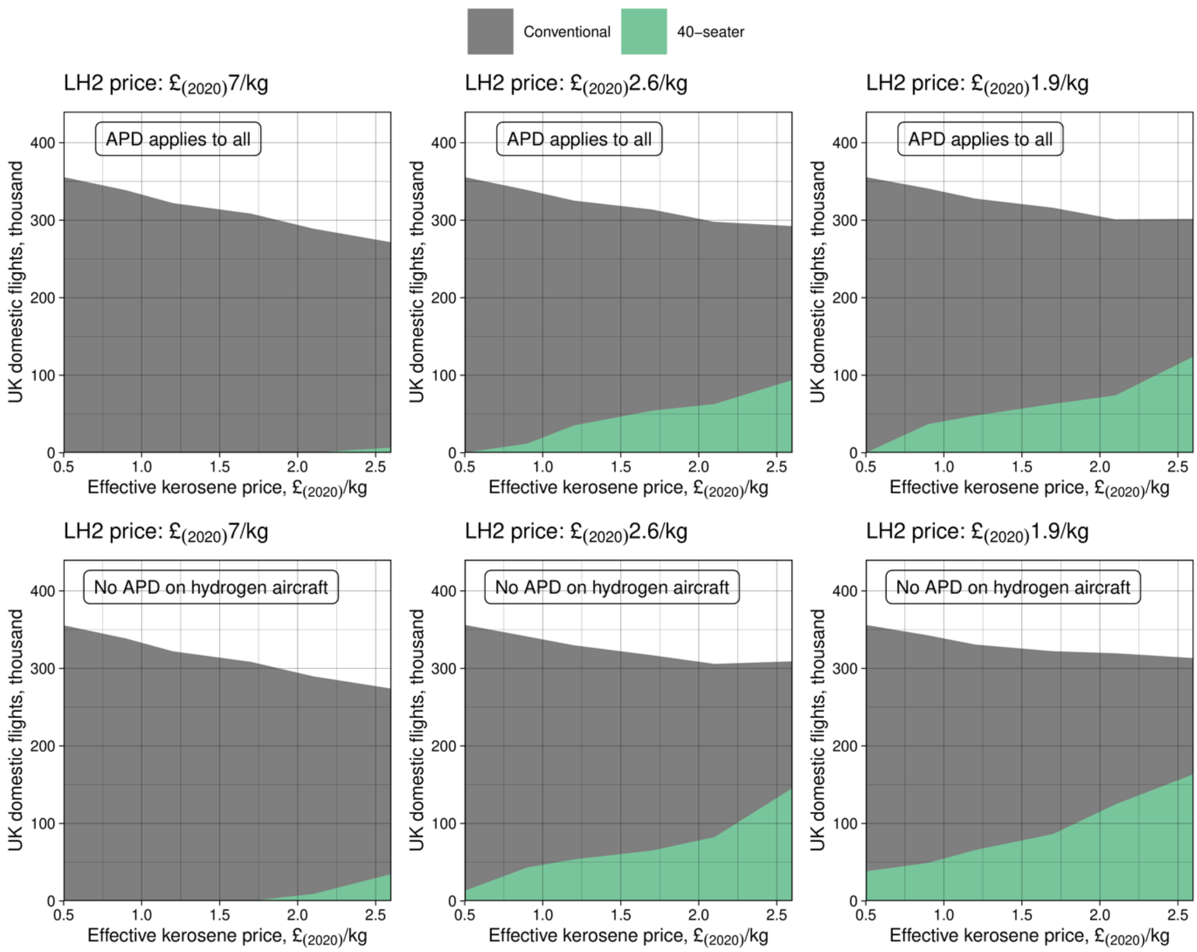
Figure 29: Projected profit-optimal uptake by number of flights for Concept 19HP (higher-performance liquid hydrogen 19-seater) in the UK domestic aviation system across a range of kerosene and hydrogen prices and different operating cost conditions.



1.3.12 40 seat new LH_2 fuel cell design (GKN)

This is a LH_2 fuel cell clean-sheet electric turbofan design, with a range sufficient to perform both UK domestic and short-haul international flights. As discussed above, this concept has similar per-flight costs to the 50-seater design used in the main use cases but higher per-passenger costs. When evaluated as the only hydrogen concept available, the total projected profit-optimal uptake of this concept is potentially significant (Figure 30); as with other concepts above 19 seats, uptake is strongly dependent on fuel price and whether the concept is subject to APD or not. In general, for similar levels of fuel price, uptake is on similar routes to those used for the 48- and 50 seat concepts evaluated below, but lower, reflecting that the aircraft's smaller size leads to higher per-passenger costs when comparing both with larger hydrogen aircraft and larger conventional aircraft. This concept is also not generally taken up on routes where the 7- and 19-seater are used when available, as it requires a longer runway. Typical use is on routes to, from and between regional airports (e.g., London City – Isle of Man).

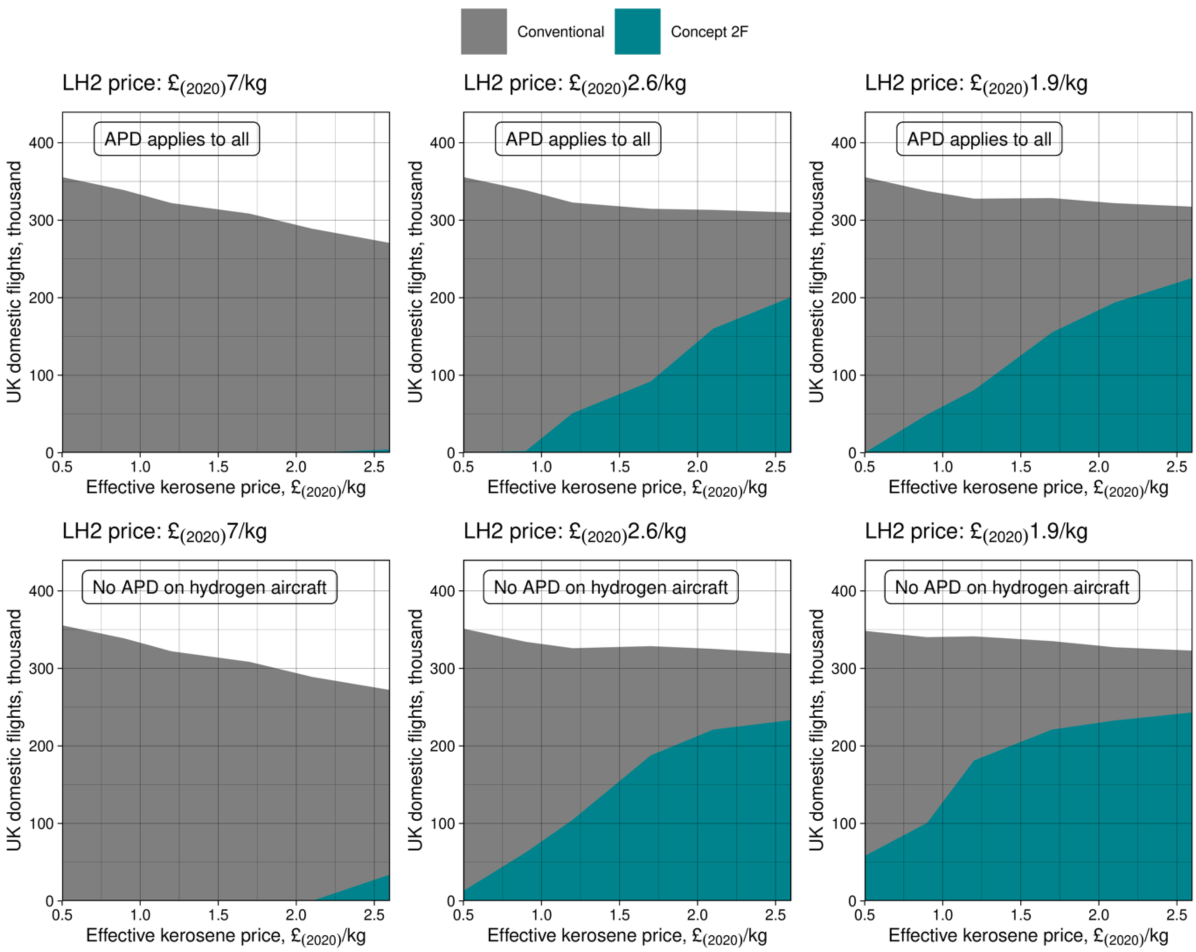
Figure 30: Projected profit-optimal uptake by number of flights for the 40-seater liquid hydrogen aircraft concept in the UK domestic aviation system across a range of kerosene and hydrogen prices and different APD conditions.



1.3.13 48 seat LH_2 direct combustion design (RR Concept 2F)

This is a LH_2 direct combustion turboprop design based on the ATR 72-600. Unlike the 50 seat design below, it is not optimised for UK domestic flight lengths but can perform longer flights (up to 2,000km). Consequently, it is less fuel-efficient on UK domestic flights than the 50 seat design, but could see additional use on international routes. Per-flight operating costs are projected to be above those of both the 40-seater and 50-seater concepts, but on a per-passenger basis they are roughly half-way in between these two concepts and Concept 2F is capable of using shorter runways than the 40-seater. These considerations are reflected in the profit-optimal uptake projections shown in Figure 31. Uptake is strongly dependent on kerosene and carbon prices, as well as whether APD applies to hydrogen aircraft, and is between projected uptake for the 40- and 50-seater designs. At the low end of kerosene prices, uptake is close to zero across most of the hydrogen price range evaluated. Where kerosene prices are high, hydrogen prices are low, and hydrogen aircraft are not APD-eligible, a significant fraction of UK domestic flights can be substituted. A typical route for this concept is between UK regions or from regional airports to and from London, but under the most favourable cost conditions they can also be used on trunk routes (e.g. London-Scotland), at the cost of reductions in passenger numbers where capacity constraints apply.

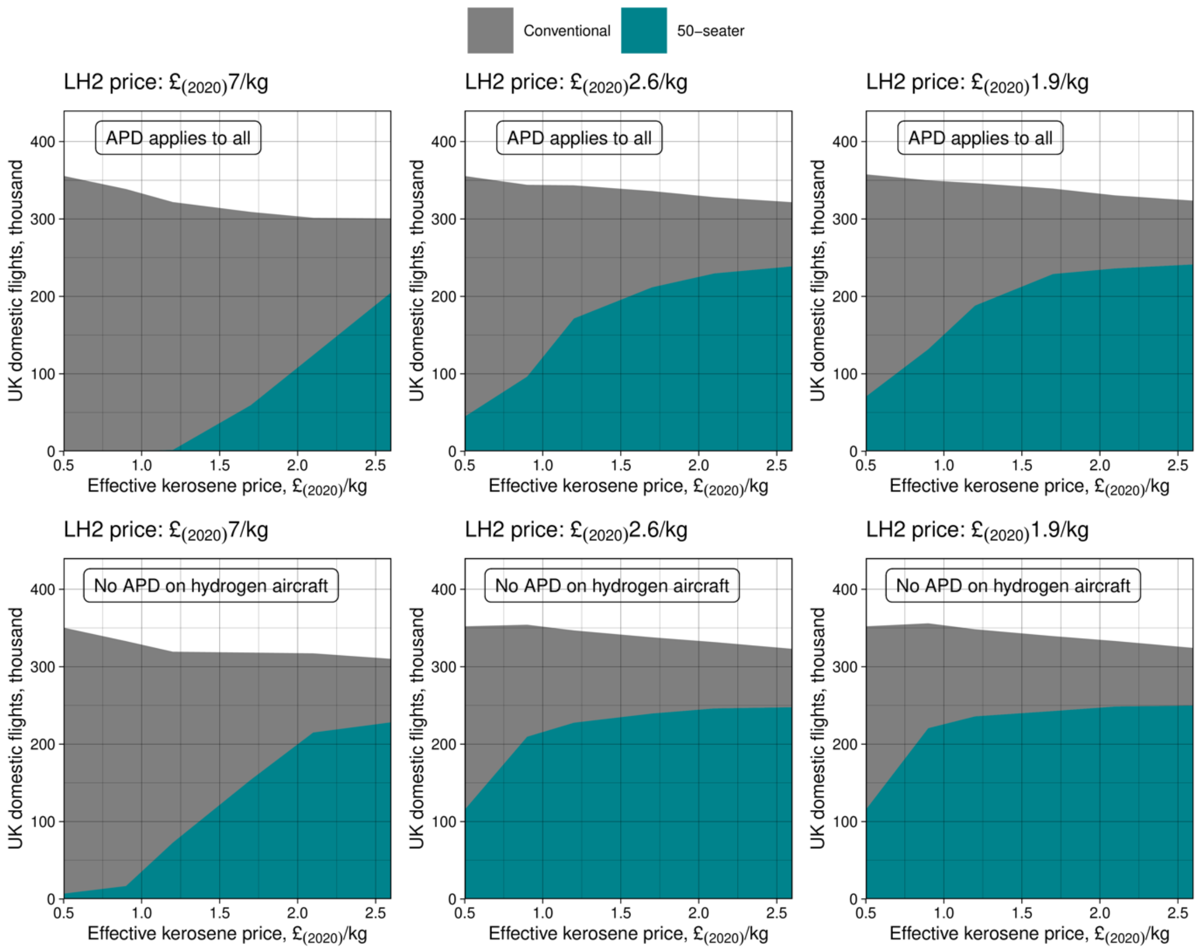
Figure 31: Projected profit-optimal uptake by number of flights for the 48-seater liquid hydrogen aircraft concept in the UK domestic aviation system across a range of kerosene and hydrogen prices and different APD conditions.



1.3.14 50 seat LH_2 direct combustion design (RR)

This is a direct LH_2 combustion turboprop design based on the ATR42-600. It is optimised for a significantly shorter range than the 48 seat design discussed above, and as a result is significantly more fuel-efficient on UK domestic routes. However, the shorter range means that it cannot be used on as many international routes. As with the 48-seater design, maintenance costs are projected to be low. This concept's increased fuel-efficiency also lowers operating costs. As such, profit-optimal uptake is projected to be higher than that of the other similarly-sized concepts considered in NAPKIN. Uptake is strongly dependent on kerosene and carbon prices, as well as whether APD applies to hydrogen aircraft. At the low end of kerosene prices and the high end of hydrogen prices evaluated, uptake is close to zero. Where kerosene prices are high and hydrogen aircraft are not APD-eligible, a significant fraction of UK domestic flights can be substituted, even at relatively high hydrogen price. As for the other similarly-sized concepts, a typical route for this concept is between UK regions or from regional airports to and from London, but under favourable cost conditions they can also be used on trunk routes (e.g. London-Scotland), at the cost of reductions in passenger numbers where capacity constraints apply.

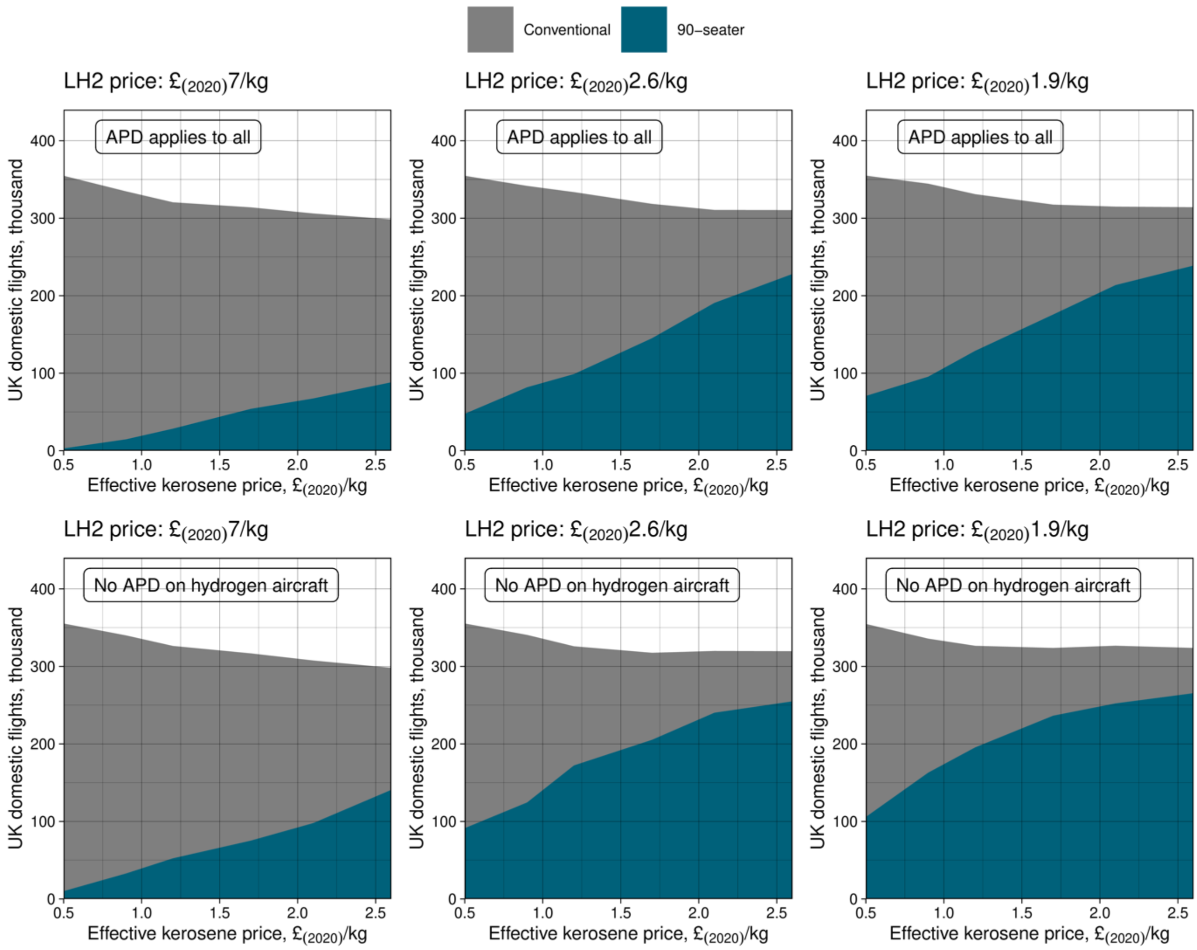
Figure 32: Projected profit-optimal uptake by number of flights for the 50-seater liquid hydrogen aircraft concept in the UK domestic aviation system across a range of kerosene and hydrogen prices and different APD conditions.



1.3.15 90 seat new LH_2 direct combustion design (RR)

The 90-seater LH_2 concept is based on the A220-100. It is the only hydrogen combustion turbofan design evaluated, the largest concept evaluated, and the concept with the greatest range. In general, larger aircraft have lower per-passenger costs so, all else equal, larger designs would be expected to outcompete smaller designs where enough demand exists to support their use at a passenger-acceptable flight frequency. The 90-seater also has higher cruise speed than other concepts evaluated, i.e., there is not a journey time penalty involved in substituting it for larger conventional aircraft on competitive routes. However, in the main use case model runs many flights that could be flown with the 90-seater LH_2 design were flown with the 50-seater LH_2 design, reflecting that concept's particularly low projected operating costs. As shown in Table 5, however, the 90-seater aircraft has the highest potential uptake of all designs evaluated in terms of passenger numbers. This is uncertain, and some simulation outcomes have very low uptake. In general, we expect higher uptake where kerosene and/or carbon price are high, hydrogen price is low, hydrogen aircraft are not eligible for APD, and no larger design of hydrogen aircraft is available. As discussed in the main report, another key uncertainty is whether low-cost carriers would consider adopting an aircraft of this size. If they do not, then uptake may be considerably lower. Figure 33 shows projected profit-optimal UK domestic uptake of the 90-seater design across a range of effective kerosene price, hydrogen price and APD eligibility conditions, assuming that low-cost carriers will consider it if no larger design is available and they can increase their profits by using it. For this concept, it is likely that any domestic use would also be accompanied by a significant amount of use on international flights, assuming suitable infrastructure is available.

Figure 33: Projected profit-optimal uptake by number of flights for the 90-seater liquid hydrogen aircraft concept in the UK domestic aviation system across a range of kerosene and hydrogen prices and different APD conditions.

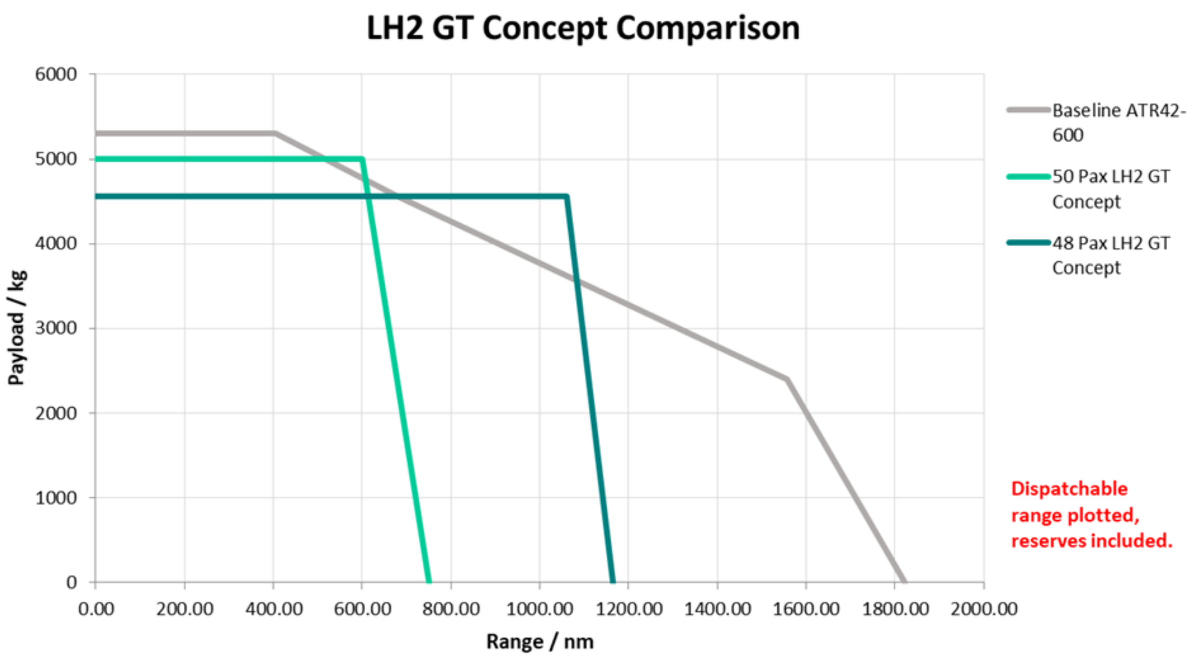


1.4 Use Case C1 using a more evolutionary regional design

For the main use cases, one NAPKIN aircraft per size class was chosen to represent available designs of hydrogen aircraft. The characteristics of the chosen designs affect the uptake of hydrogen aircraft in general, and also which specific hydrogen aircraft size classes are projected for use on UK domestic flights.

The aircraft in the wider NAPKIN fleet represent different approaches that the airframers could take in order to develop hydrogen aircraft. This is particularly noticeable when comparing two of the Rolls-Royce concepts, the 48 seat (2F) and the 50 seat. The 48 seat concept keeps the same airframe used for the ATR72 and incorporates an internal liquid hydrogen fuel tank at the cost of reducing the passenger number from 72 down to 48. This leads to an increased structural weight, as this has been sized for the original number of passengers, but it does offer a more evolutionary approach to hydrogen aircraft design for an airframer.

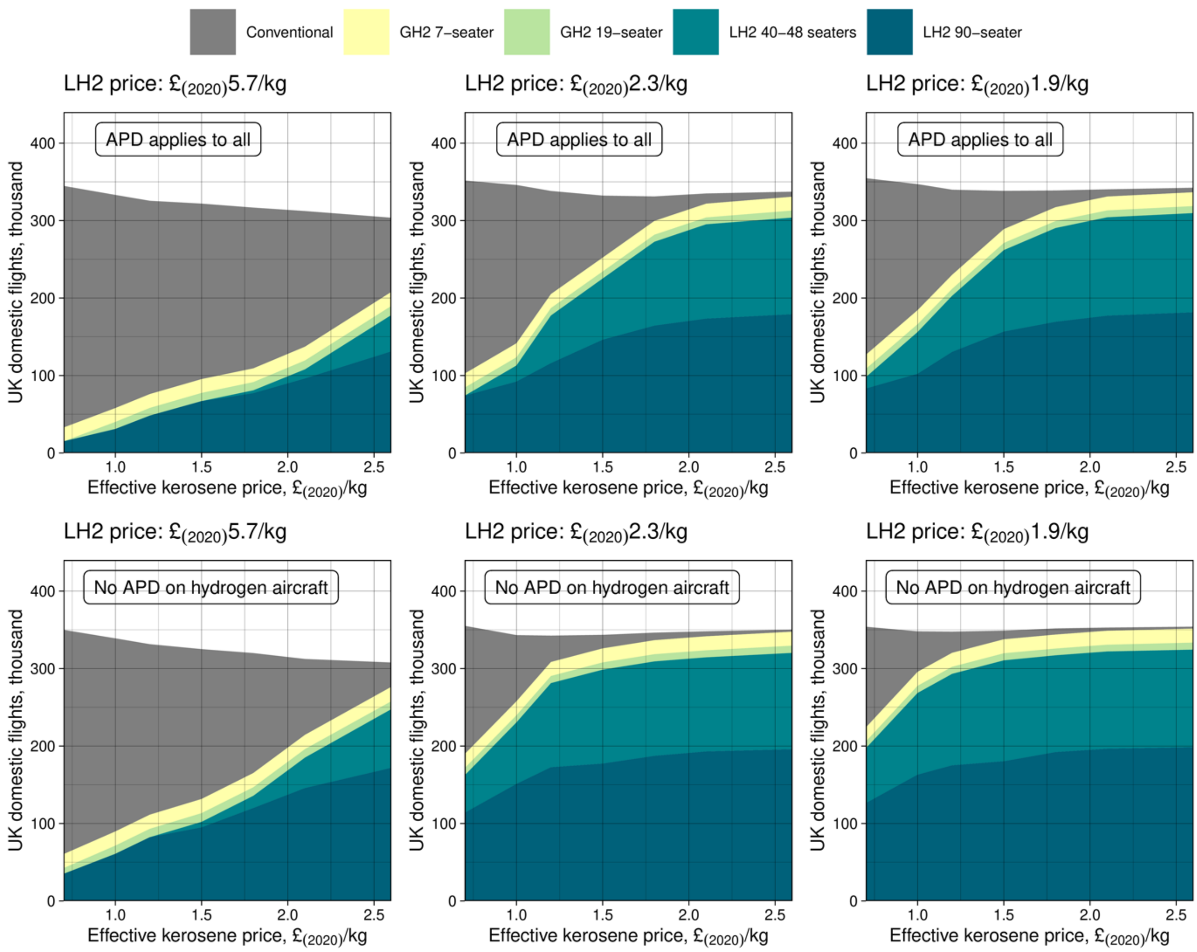
On the other hand, the 50 seat is a clean sheet concept which has been designed to mitigate the disadvantages of hydrogen aircraft, such as the large volume tanks, while enhancing the benefits such as those offered by reduced take-off weight and dry wings. The 50 seat design also has a reduced range capability of 600nm at full payload which is comparable to the range of a fully laden ATR42-600 aircraft but, due to the nature of hydrogen volume limitations, it has a reduced part-load range capability as can be seen on the payload range chart below. This 600nm range is unlikely to limit the addressable commercial routes for the 50 seat aircraft as currently 97% of turboprop ASKs are shorter than this range. However, the reduction in part-load capability may impact the operational flexibility that can be offered to airlines, especially on the ferry range.



	48- Seat Concept	50- Seat Concept
Type	Study Aircraft	Clean Sheet
Airframe	ATR72-600	-
Take-off Weight	19,600 kg	16,000 kg

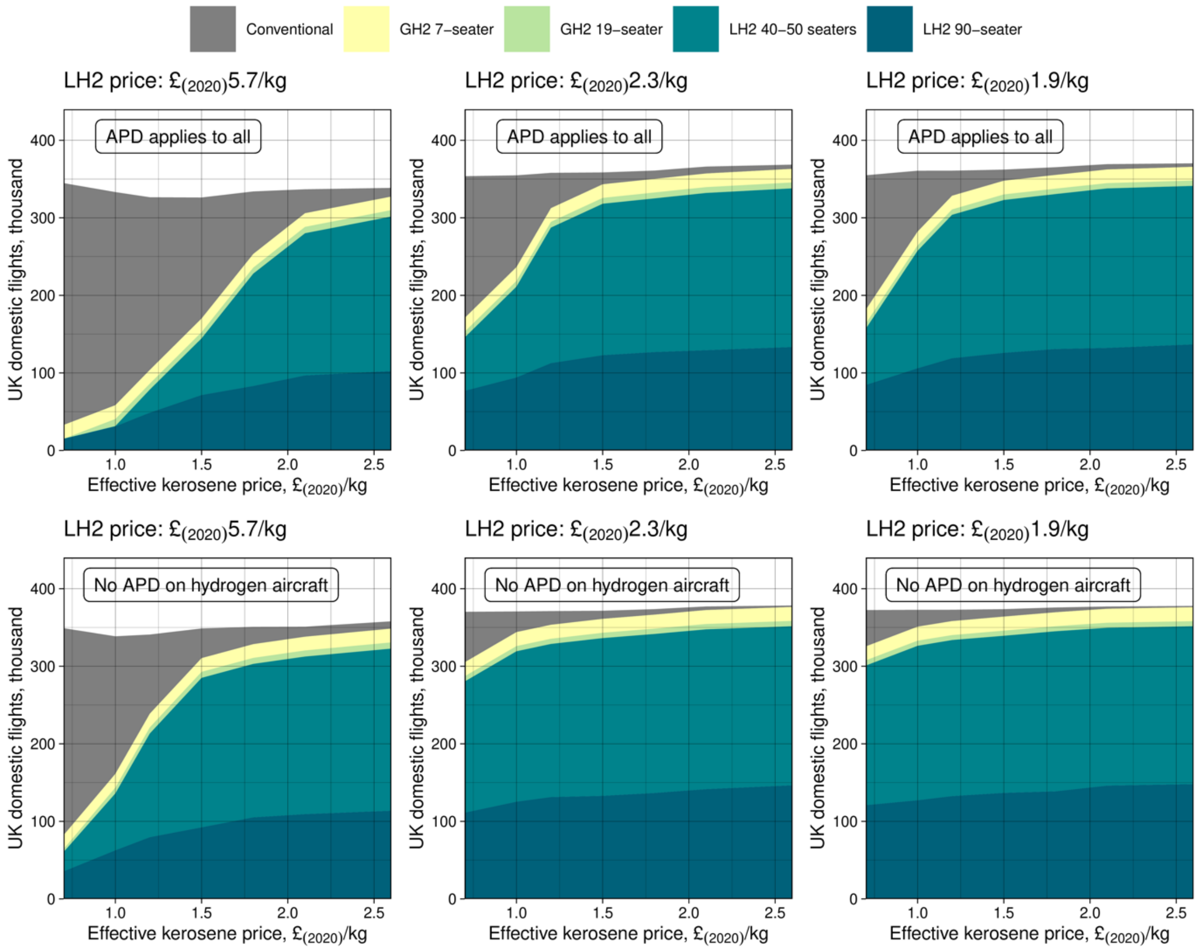
To test the impact the two design approaches would have on market outcomes, Use Case C1 was also run with the 48 seat concept 2F instead of the 50 seat used in the main use cases. Outcomes in terms of projected number of flights are shown in Figure 34 with a repeat of the 50 seat results shown in the main report in Figure 35.

Figure 34: 7- and 19-seater gaseous hydrogen, and 40-48- and 90-seater liquid hydrogen aircraft projected number of flights in the UK domestic aviation system under Year-2040 Use Case C sensitivity case conditions across a range of kerosene and hydrogen prices.



Several differences are apparent when compared to the main Use Case C outcomes. First, total uptake of hydrogen aircraft is lower at mid-range hydrogen and kerosene prices – i.e., the 48-seater design competes less well against conventional aircraft unless hydrogen prices are at the bottom end of the range considered here. Second, use of the 90-seater hydrogen aircraft is much higher than in the main Use Case C– i.e., the 48-seater LH_2 design competes less well against the 90-seater LH_2 design than the 50-seater LH_2 design did. This is in line with expectations about usage in the case that all hydrogen aircraft perform similarly to their conventional counterparts on an energy basis – i.e., designs with more seats have lower per-passenger costs and so are more cost-effective to operate provided sufficient demand exists. The 48-seater can have significant market share, but requires both relatively low hydrogen prices and relatively high kerosene prices to do so.

Figure 35: 7- and 19-seater gaseous hydrogen, and 40-50-seater and 90-seater liquid hydrogen aircraft projected profit-optimal number of flights in the UK domestic aviation system under Year-2040 Use Case C1 conditions across a range of kerosene and hydrogen pr



These outcomes require aircraft fleets of roughly 7-8 7-seaters, 0-5 19-seaters, 0-66 40-48-seaters and 8-110 90-seater hydrogen aircraft. As with the main Use Case C, the range in CO_2 outcomes is significant, from 7-99% reduction in UK domestic CO_2 from simulations with the same fuel price conditions where no hydrogen aircraft are available.

This demonstrates that the performance limitations introduced from an evolutionary approach to airframe design are likely to lead to a reduction in the uptake of aircraft in this regional market. This type of conclusion will require further research on other markets and more detailed studies when airframers are deciding their future development strategies, but it does highlight the usefulness of this market modelling approach when appraising aircraft concepts.