The Role of Sustainable Aviation Fuels and Liquid Hydrogen in the Path towards Climate Neutrality

Bauhaus Luftfahrt Symposium – Targeting Climate-Neutral Aviation

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Introduction

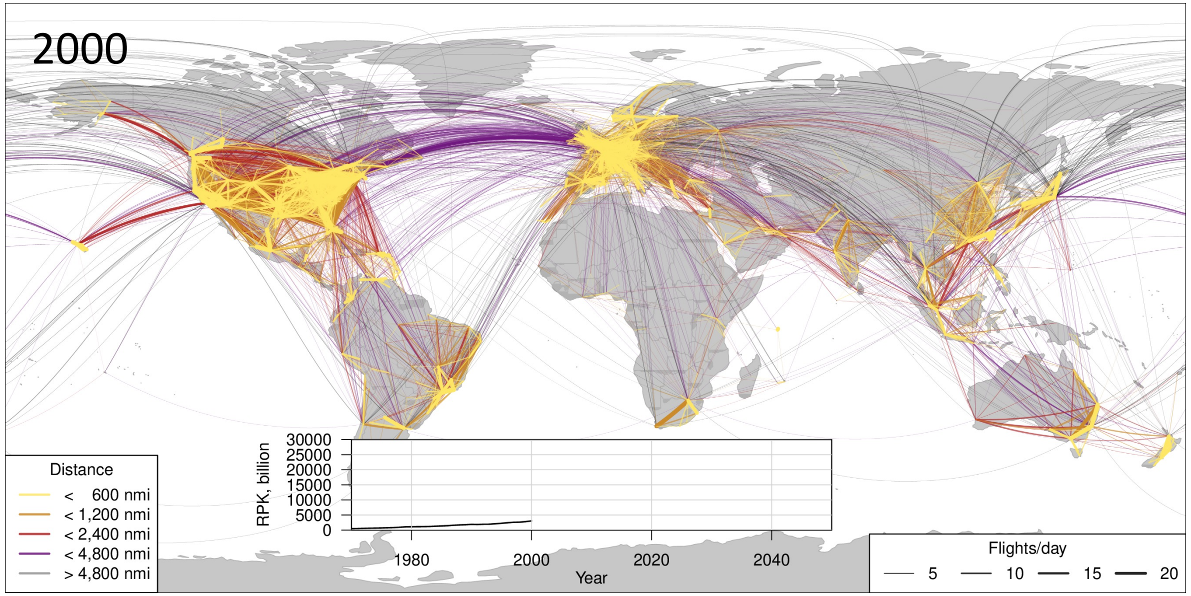
- The climate impacts of aviation are around twice that of aviation CO_2 alone
  - Around 90% of aviation GHG impacts are from passenger aircraft (plus hold freight) and around 10% freighters
  - Aviation currently accounts for around 3.5% of anthropogenic effective radiative forcing (Lee et al. 2020)

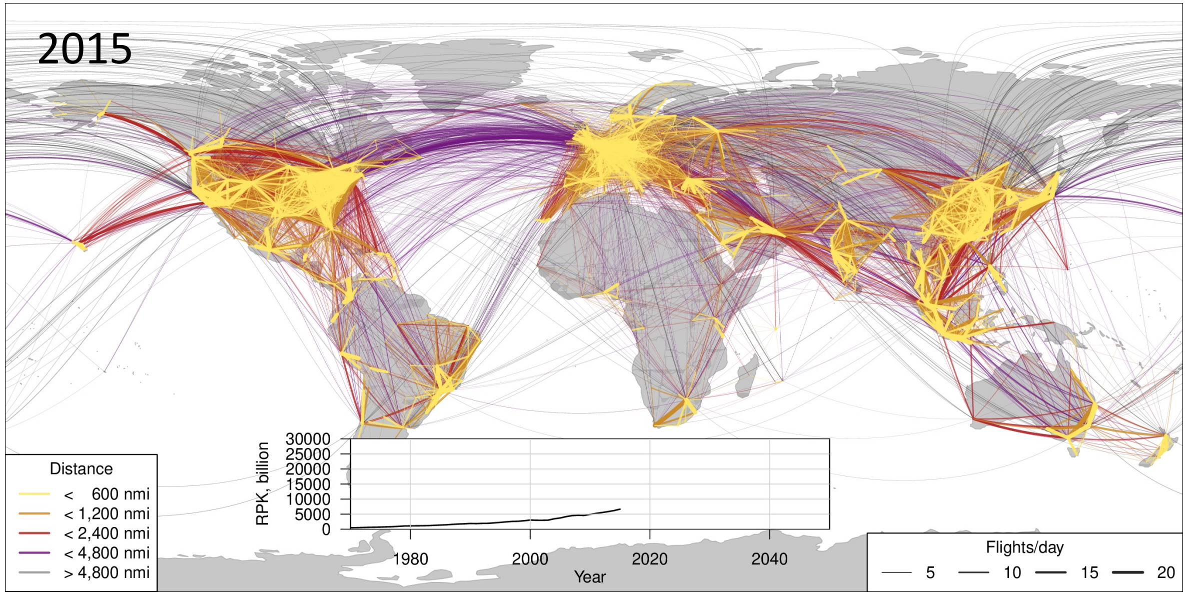
$$\text{Climate impact } (CO_2eq) = \underbrace{\frac{CO_2eq}{E}}_{\text{Fuel Emission Intensity}} \cdot \underbrace{\frac{E}{RTK}}_{\text{Energy Intensity}} \cdot \underbrace{RTK}_{\text{Air Transport Demand}} - \underbrace{Offsets}_{\text{CORSIA, DAC, ETS allowances…}}$$

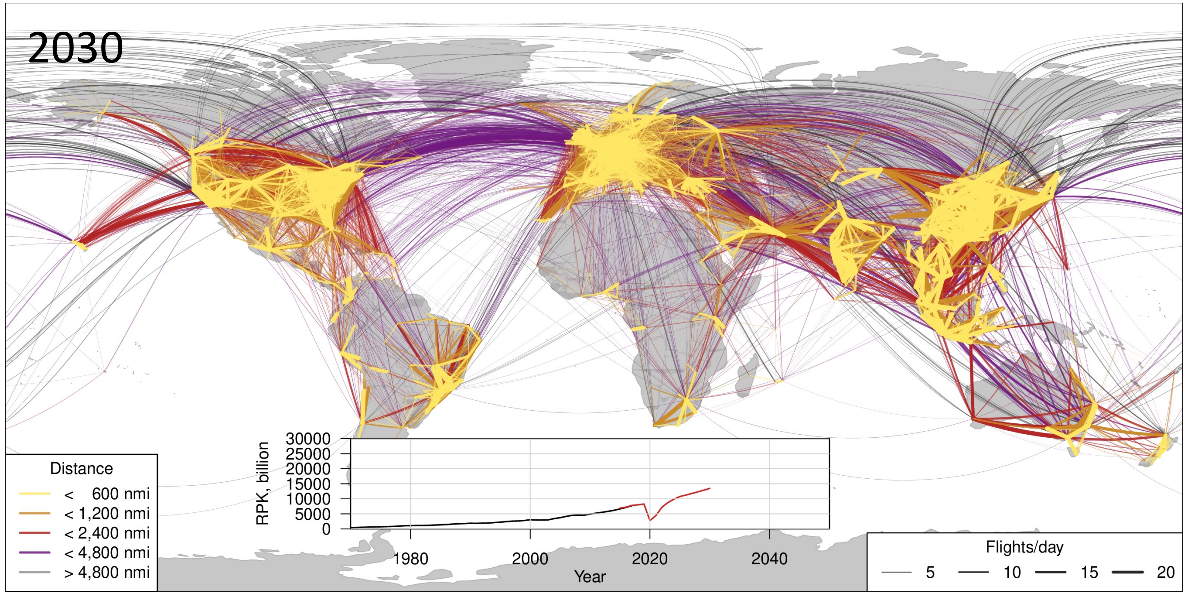
CO_2eq includes:
- **CO_2 from aircraft engines**
- **Lifecycle CO_2 from fuel production**
- **Non-CO_2 from aircraft engines (Contrails, NOx, AIC…)**
- **Lifecycle non-CO_2 from fuel production (CH_4, N_2O, …)**

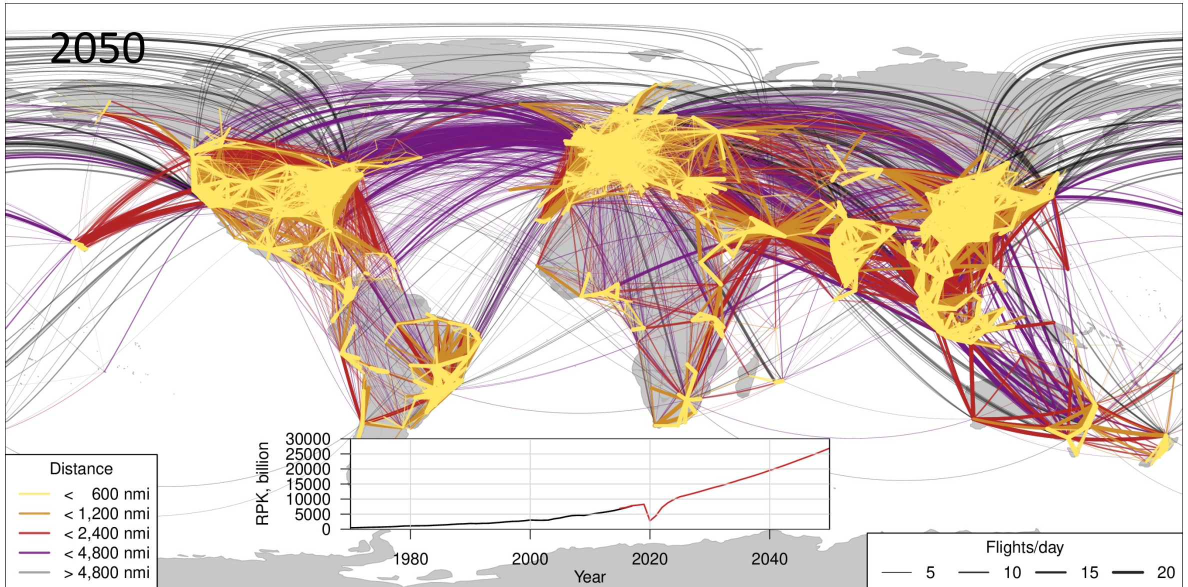
- **Fuel emission intensity:** needs move from fossil kerosene for significant change
- **Energy intensity:** -2.7%/year 1980-2018, but slower rates (<2%/year) projected in future
- **RTK:** +5.5%/year 1980-2018, 2.4-4.1%/year projected 2019-2050
- **Non-CO_2:** requires change in fuel type and/or operations for significant change
- If current trends continue, this suggests within-sector climate impact will **increase**

Introduction









[Historical data: Sabre, 2023. Projections: central scenarios, no-policy baseline, Dray et al. 2022]

CO_2eq/E: Fuels

Usable in existing aircraft

Require new aircraft designs

	Jet A	Drop-in Fuels			Cryogenic Fuels			Electricity
		Low-Cost Biofuels	High-Cost Biofuels	Power-to-Liquids	Low-cost LNG	High-Cost LNG	Liquid Hydrogen	
Feedstock	Crude Oil	Waste & Plant Oils	Cellulosic Biomass	H2 + atm. CO_2	Manure, MSW, etc.	H2 + atm. CO_2	Water + Zero-C El.	Zero-C Electricity
Electricity intensity kWh(el)/kWh	~ 0	0.02	< 0.01	2.0 (1.8)	0.05	2.0 (1.8)	1.8 (1.5)	1.0
TWh(el) for 25 EJ fuel*	~ 0	140	<70	~13,200	~350	~13,200	~11,500	~6,900
Capital intensity mln$/boe/d	0.01-0.03	0.03-0.13	0.13-0.20	1.0 (0.3)	0.3	1.0 (0.3)	1.3 (0.4)	0.14 (0.07)
Bln. $ for 25 EJ fuel	(220)	~900	~1,800	~7,300	3,400	7,300	9,500	1,200
Production Cost $/bbl(JFE)	6 – 22 (6 – 110)	150 – 230 (130 – 210)	180 – 290 (160 – 260)	380 (100)	110 – 230 (113 – 230)	390 (110)	440 (130)	60 – 150 (30 – 70)
Resource Potential EJ	> 24,000	0.3 – 20.5	60 – 110	infinite	30	infinite	infinite	infinite
Lifecycle GHG Em. %	100	27 – 48	26 – 29	19	-8 – 14	32	29	0

[Table: A. Schäfer, F. Allroggen, M. Stettler, C. Falter, C. Grobler, from Dray et al. 2022. Numbers in parenthesis are projected 2050 values.]

* 2021 Global total renewable electricity generation: 8,300 TWh (IEA, 2021)

CO_2eq/E: Drop-in fuels

- Drop-in biofuels and/or synthetic (PTL) fuels can be used in current aircraft without modification
  - Biofuels already in (limited) use at some airports (<0.1% of global fuel; IEA, 2019)
  - Targeted by proposed EU and UK blend mandates (e.g. RefuelEU)
- May reduce non-CO_2 impacts (e.g. Grewe et al. 2017) but does not eliminate them
  - E.g. ~40% decrease in contrail/AIC impacts due to reduction in soot
- Challenges:
  - Limited supply of biomass compared to likely 20-30 EJ fuel/year required by 2050
  - Not (yet) cost-competitive with fossil Jet A; biofuel cost below PTL cost at present but unit costs may go up as more supply is needed (→higher cost biomass)
  - Scaling up production requires significant infrastructure investment

[Biofuel feedstock. Source: Idaho National Laboratory]

CO_2eq/E: non drop-in fuels

Battery electric

- Very limited range and payload performance likely to 2050
- Included in modelling, but overall impact minimal

BioLNG/ SNG

- Similar supply/cost issues to synthetic kerosene, but also need to change fleet/infrastructure → excluded

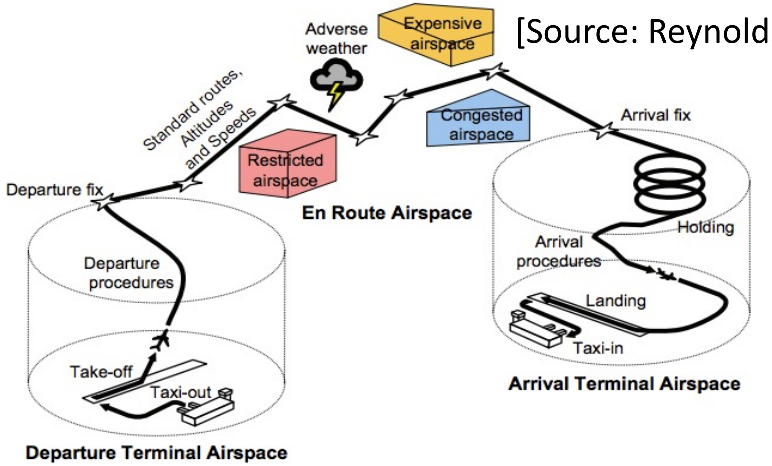
Hydrogen

- Hydrogen: Recent work (e.g. FlyZero/NAPKIN) suggests **can** be a feasible/cost-effective option
- Several options: all eliminate in-flight CO_2
    - Fuel cell + electric propulsors – small aircraft?
    - Direct hydrogen combustion – large aircraft
    - Uncertain NOx and contrail impacts
- Key challenges are requirement for new infrastructure and fleet, uncertain costs
- In development – Airbus, Rolls Royce, GKN, etc.

[Image sources: Wikimedia Commons, NASA]

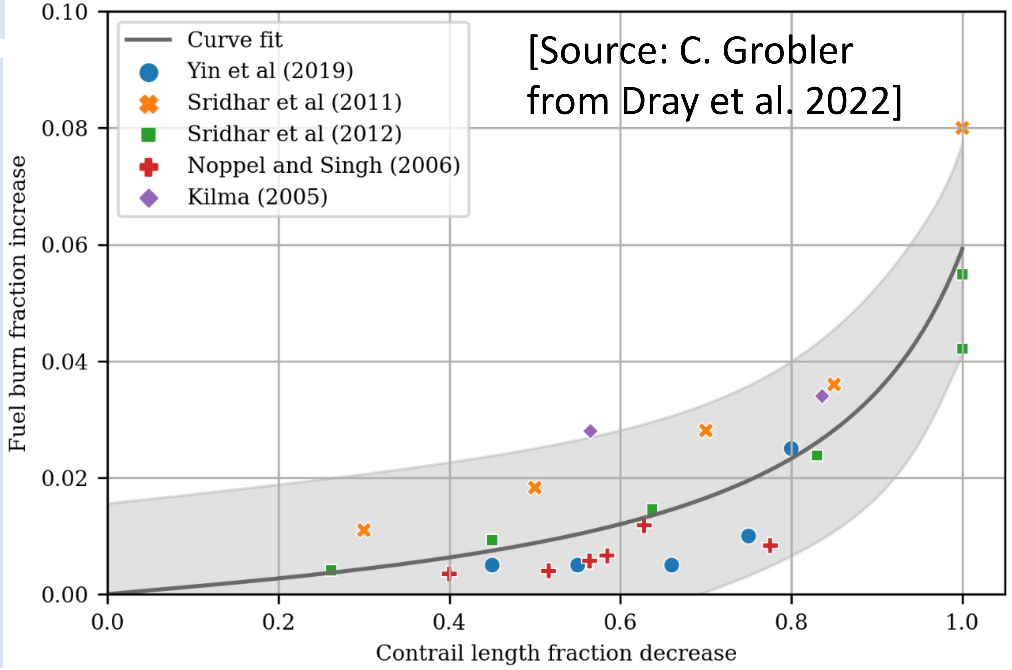
E/RTK and CO_2eq/E : Changes in aircraft operations

- Removing operational/Air Traffic Control inefficiencies – e.g. more direct routing, reduced taxi time
  - E.g. NextGen, SESAR – likely impact is a few % total CO_2/RTK reduction
- Ongoing improvements in load factor likely to continue
  - E.g. 2019 average 82%, best airline average 90% (ICAO, 2021) – worse during COVID19
- May also be ongoing changes in average E/RTK from routing changes
- Many changes are cost-effective and likely to happen without support



[Source: Reynolds, 2008]

- Contrails typically form/persist in ice supersaturated atmospheric regions
  - Large horizontally but typically <600m vertically, can often be avoided by changing cruise altitude (e.g. Mannstein et al. 2005, Teoh et al. 2020)
- Literature suggests diversion to avoid ~50% of contrail impact would require a ~1% increase in fuel use
  - This is **approximate** – response is not simple or linear with number of flights, changes by time of day, operates on different timescales to CO_2 climate impact reduction, etc.
  - Larger reductions likely more complex (operations/forecasting)
- Currently no incentive for airlines to avoid contrails



[Source: C. Grobler from Dray et al. 2022]

E/RTK: Changes to conventional aircraft designs

Airframes

High aspect ratio wing
- Likely 10-15% CO_2/RPK reduction
- In development

(More) composite materials
- Likely 10-12% CO_2/RPK reduction
- Already on 787/A350

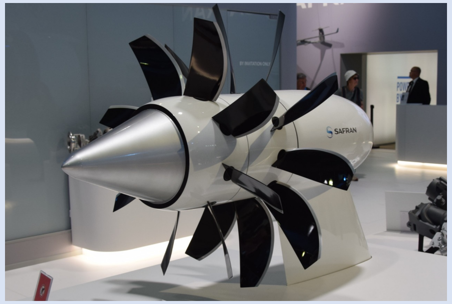
BWB/HWB/Flying wing
- Up to 30% CO_2/RPK reduction for large aircraft
- Relatively unlikely (high complexity for given benefits)

Engines

Ultra-high bypass ratio (UHBR) turbofan
- Likely 20-28% CO_2/RPK reduction
- In development

Open rotor
- Likely around 30% CO_2/RPK reduction
- Demonstrators exist, but limited benefit over UHBR - further development unlikely

Electric/hybrid electric



- Note design/certification ~ 10 yr, lifetime in fleet ~ 30 yr, production run up to 20yr
  - **Around 50% of aircraft built now will still be in service in 2050**
  - The airframes/engines on the next new aircraft generation (2030-35; likely around 14-23% combined fuel eff. improvement over year-2015 generation; ATA & Ellondee, 2018) will dominate 2050 fleet
- These measures would allow historical rates of fuel efficiency improvement (1-2%/year) to continue

[Image sources: Wikimedia Commons, NASA]

RTK: demand

- Future aviation demand is uncertain but given projected developments in demand drivers, global growth is likely (2.4-4.1%/year RTK growth; Dray & Schäfer 2021)
- Some policy interventions target demand but these generally focus on short haul flights in rich countries → may be limited overall impact
- Ongoing developments in attitudes to flying at a global level are uncertain
  - Year-2023 passenger demand is approaching pre-pandemic levels, freight exceeds them
  - Survey/focus group work suggests current limited/uneven impact of environmental issues on demand
  - However, approaching net zero in aviation will require significant changes in fuel, operations, costs, ticket prices ...
  - This is likely to have a demand impact
  - This demand impact in turn will affect the achievability of net zero (reduced demand → less alternative fuel needed → lower fuel costs → lower ticket prices → more demand → ...)

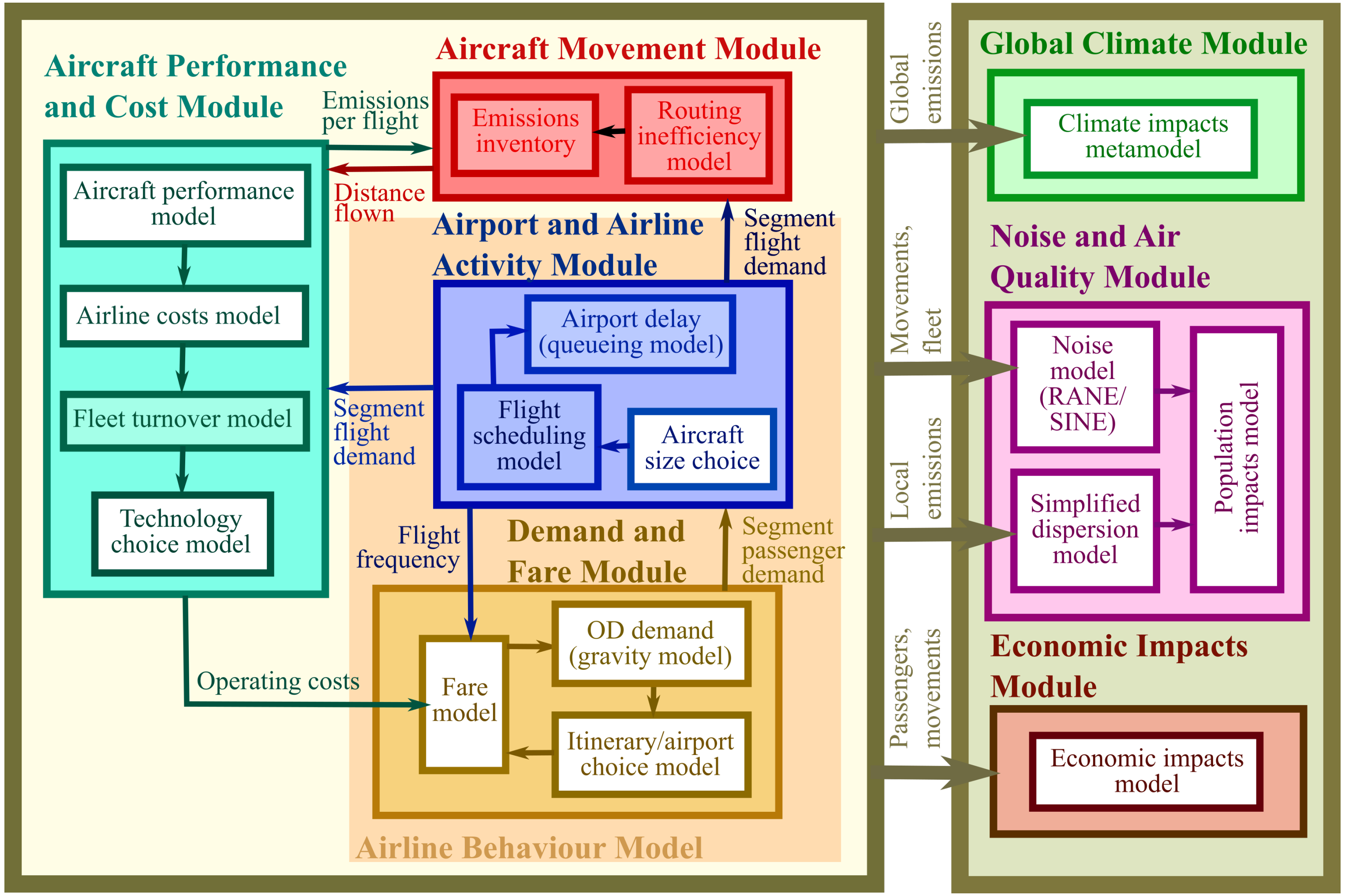
→ Need for integrated systems modelling

Modelling the global aviation system

Solve iteratively (AIM2015)

OR

Optimise profit per airline (Airline Behaviour Model)



Aircraft Performance and Cost Module

Aircraft performance model
Airline costs model
Fleet turnover model
Technology choice model

Emissions per flight
Distance flown
Segment flight demand
Operating costs

Aircraft Movement Module

Emissions inventory
Routing inefficiency model

Segment flight demand

Airport and Airline Activity Module

Airport delay (queueing model)
Flight scheduling model
Aircraft size choice

Flight frequency
Segment passenger demand

Demand and Fare Module

Fare model
OD demand (gravity model)
Itinerary/airport choice model

Airline Behaviour Model

Global emissions
Movements, fleet
Local emissions
Passengers, movements

Global Climate Module

Climate impacts metamodel

Noise and Air Quality Module

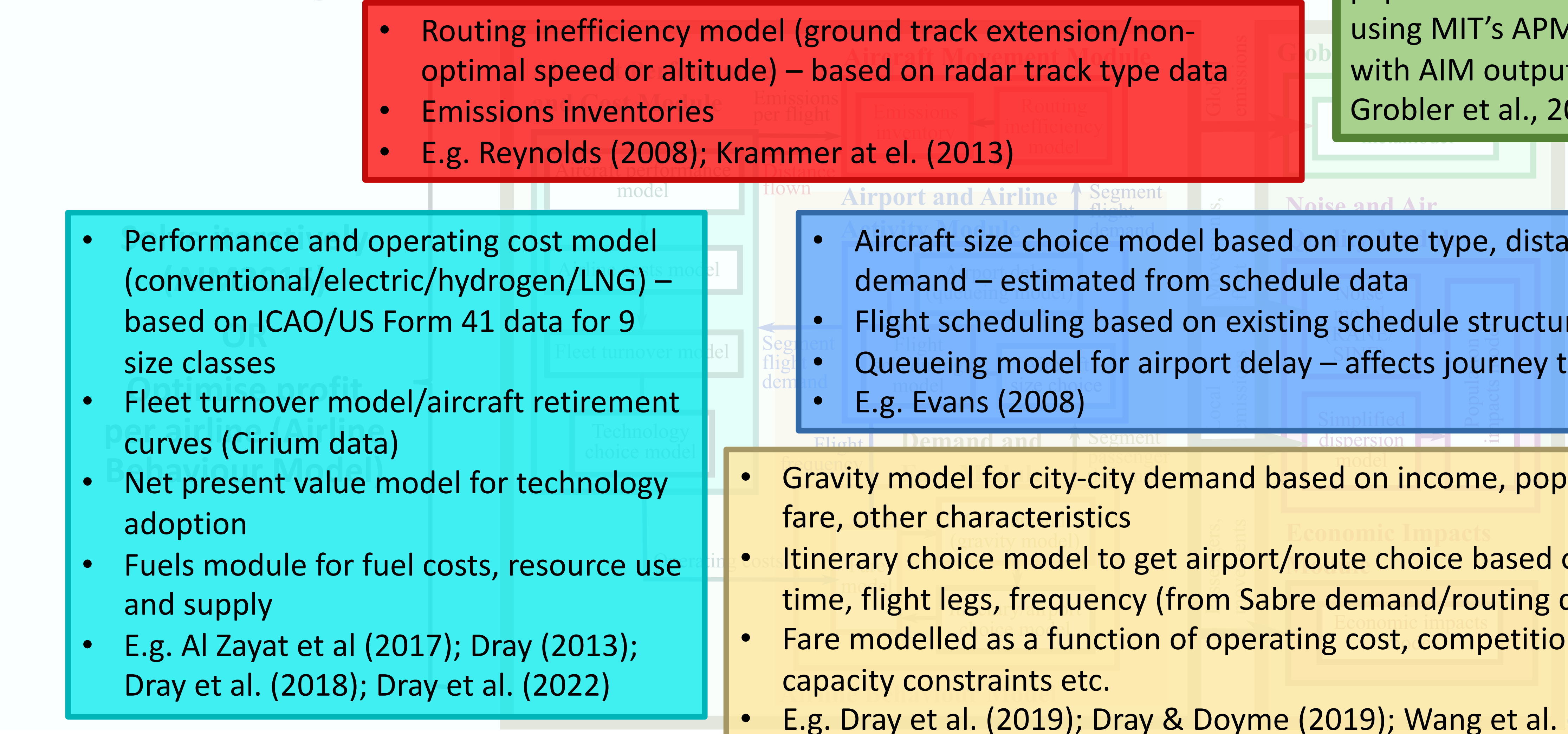
Noise model (RANE/ SINE)
Simplified dispersion model
Population impacts model

Economic Impacts Module

Economic impacts model

Open source – see www.atslab.org for code, documentation and papers

Modelling the global aviation system



- Routing inefficiency model (ground track extension/non-optimal speed or altitude) – based on radar track type data
- Emissions inventories
- E.g. Reynolds (2008); Krammer at el. (2013)

Climate modelling for this paper was carried out using MIT's APMT model with AIM outputs (e.g. Grobler et al., 2019)

- Performance and operating cost model (conventional/electric/hydrogen/LNG) – based on ICAO/US Form 41 data for 9 size classes
- Fleet turnover model/aircraft retirement curves (Cirium data)
- Net present value model for technology adoption
- Fuels module for fuel costs, resource use and supply
- E.g. Al Zayat et al (2017); Dray (2013); Dray et al. (2018); Dray et al. (2022)

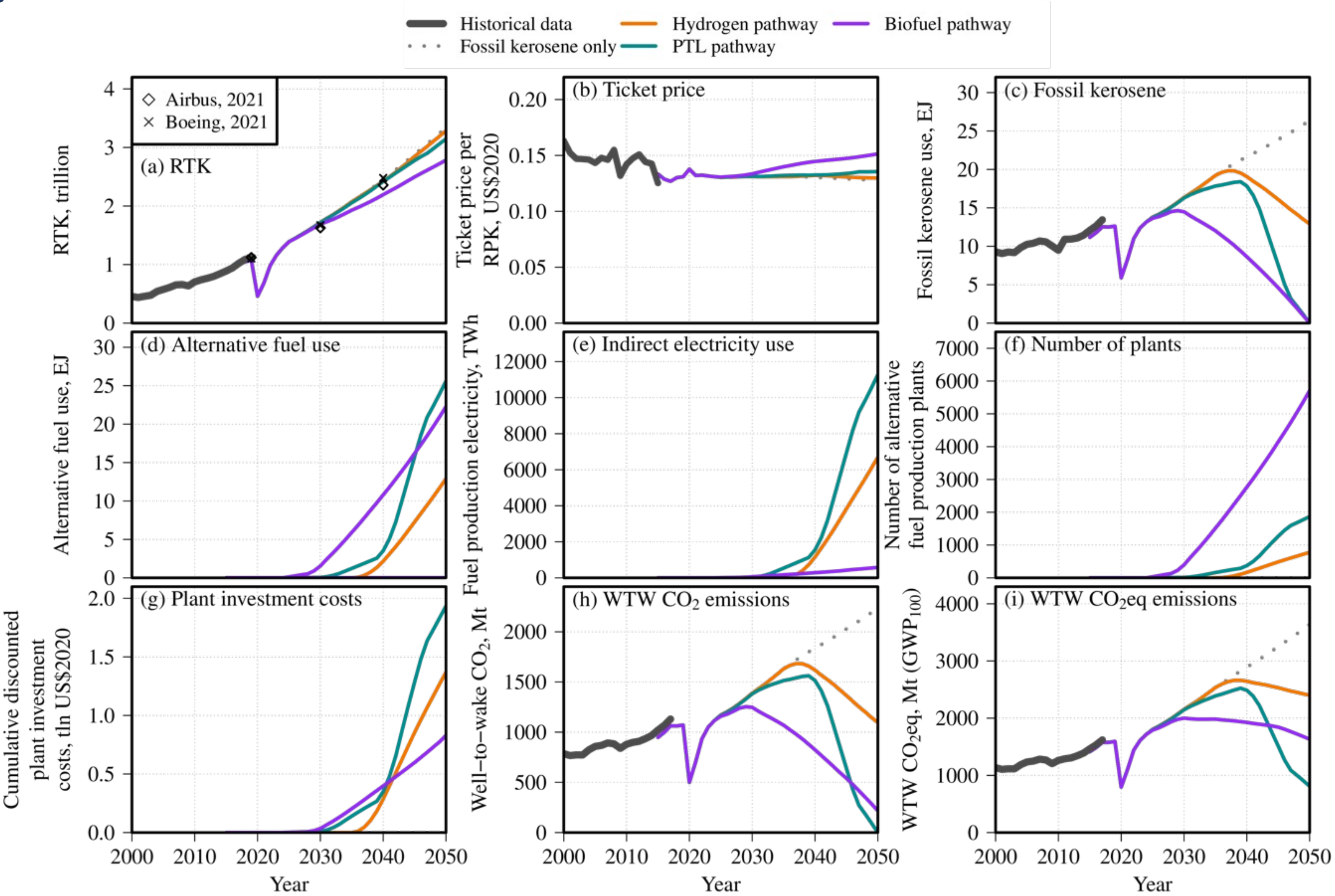
- Aircraft size choice model based on route type, distance, demand – estimated from schedule data
- Flight scheduling based on existing schedule structures
- Queueing model for airport delay – affects journey time
- E.g. Evans (2008)

- Gravity model for city-city demand based on income, population, fare, other characteristics
- Itinerary choice model to get airport/route choice based on fare, time, flight legs, frequency (from Sabre demand/routing data)
- Fare modelled as a function of operating cost, competition level, capacity constraints etc.
- E.g. Dray et al. (2019); Dray & Doyme (2019); Wang et al. (2018)

Open source – **see www.atslab.org for code, documentation and papers**

Comparing single fuel pathways

- Example for a demand scenario close to Airbus/Boeing projections
- Comparing impacts of **mandated** uptake of individual fuel pathways
  - Drop-in biofuel
  - Drop-in PTL
  - Hydrogen aircraft
- Drop-in fuels: assumed global SAF mandate increasing to 100% in 2050
  - Note proposed EU/UK mandate levels in 2050: 68/70%
- Hydrogen aircraft: assumed new aircraft purchase requirement (5-year phase-in from EIS)



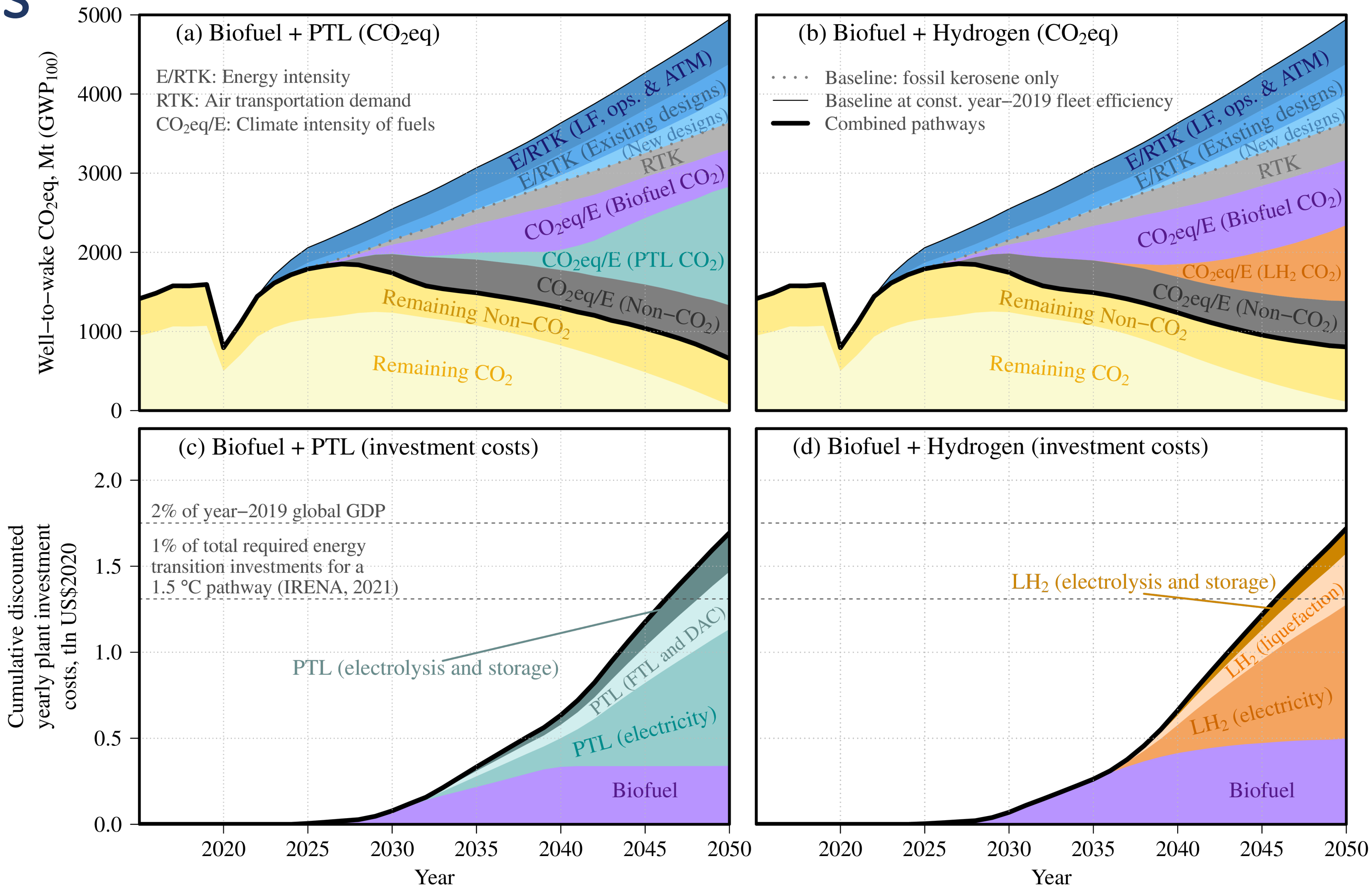
[Source: Dray et al. 2022]

Single fuel pathways – some conclusions

- Biofuel pathway has the lowest cumulative CO_2 due to earlier assumed scale-up
  - However, this assumes that aviation has access to biomass and that rapid scale-up is possible, which may not be the case
    - E.g. WEF (2020) project maximum 2050 availability for aviation of 21.7 EJ fuel – **less** than projected here
  - Still substantial fuel lifecycle CO_2 and tank-to-wake non-CO_2, even at 100% use
  - Largest year-2050 ticket price impact (+20%) – reflects that increasing supply requires higher-cost biofuels
- Initially high costs and low supply constrain PTL uptake
  - Significantly lower costs/faster scale-up potential projected for 2040s, but cumulative GHG still high
  - Key uncertainties: electricity prices/carbon capture costs – our assumptions are relatively optimistic
  - Requires >8,000 TWh renewable electricity/year
    - 2021 total global renewable electricity generation: 8,300 TWh (IEA, 2021)
- For hydrogen aircraft, 2035 entry into service + fleet turnover means that maximum hydrogen share in 2050 is around 50% (by energy used)
  - Not a feasible 2050 net zero pathway unless emissions from the remaining kerosene fleet addressed
  - Non-CO_2 impacts remain from both hydrogen and kerosene aircraft
- To address these issues, **combinations of pathways and additional operational strategies are needed**

Combined pathways

- We consider:
  - **Biofuel as a bridging fuel to PTL**
  - **Biofuel as a bridging fuel to hydrogen**
  - Both with contrail avoidance
  - Mandates assumed as before
- Potential to reduce year-2050 lifecycle GHG emissions 46-69% compared to year-2019
  - CO_2 reduced by 89-94%
  - Biofuel demand now below WEF maximum estimates, but still need 6,000-8,000 TWh electricity
  - We project total investment needed of around \$2 tln



[Source: Dray et al. 2022]

In conclusion: aviation pathways towards net zero?

- Approaching net zero within the aviation sector (without stopping flying) requires **changing fuel**
  - Given timelines/constraints on supply possible options are biofuel + PTL, or biofuel + hydrogen
  - Both require significant investment (~$2tln), infrastructure build-up, and development of technologies at low TRL
  - Long timeframes, cumulative emissions → predictable long-term incentives needed now
  - Whilst efficiency measures will likely happen without support, alternative fuels/contrail avoidance not cost-effective on their own initially and will require policy support
- Net zero climate impact requires addressing non-CO_2
  - Significant reductions possible **but uncertain** from contrail avoidance + change of fuel
  - Going beyond the level of contrail avoidance modelled here could be more disruptive
  - Only battery electric aircraft have no (direct) non-CO_2 impacts – but long-haul use not feasible in 2050
- Ticket price impacts may be relatively small (<20% in 2050)
  - However, given low airline profitability, transition period might still be difficult for airlines
- Easier transition at lower fuel demand – although operations/mode shift/efficiency/demand reduction may not be enough individually, they can help enable the fuel transition
- **Many** key uncertainties (costs, supply, climate impact, future technology capabilities, attitudes to aviation, …)
  - Many ongoing studies – e.g. UCL's ToZCA (Towards Zero-Carbon aviation)

Addendum: the Airline Behaviour Model

- If we **don’t** mandate the use of hydrogen/SAF, what can we project about uptake?
    - Depends on operating costs, aircraft capabilities, fuel infrastructure, other supporting policy, …
- Ultimately, we expect competing airlines to adopt a new technology if by doing so, they can increase their profits:

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

Revenue **Flight related costs** **Passenger related costs**

- In turn, passengers will choose whether to fly and what itinerary to take:

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

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

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

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

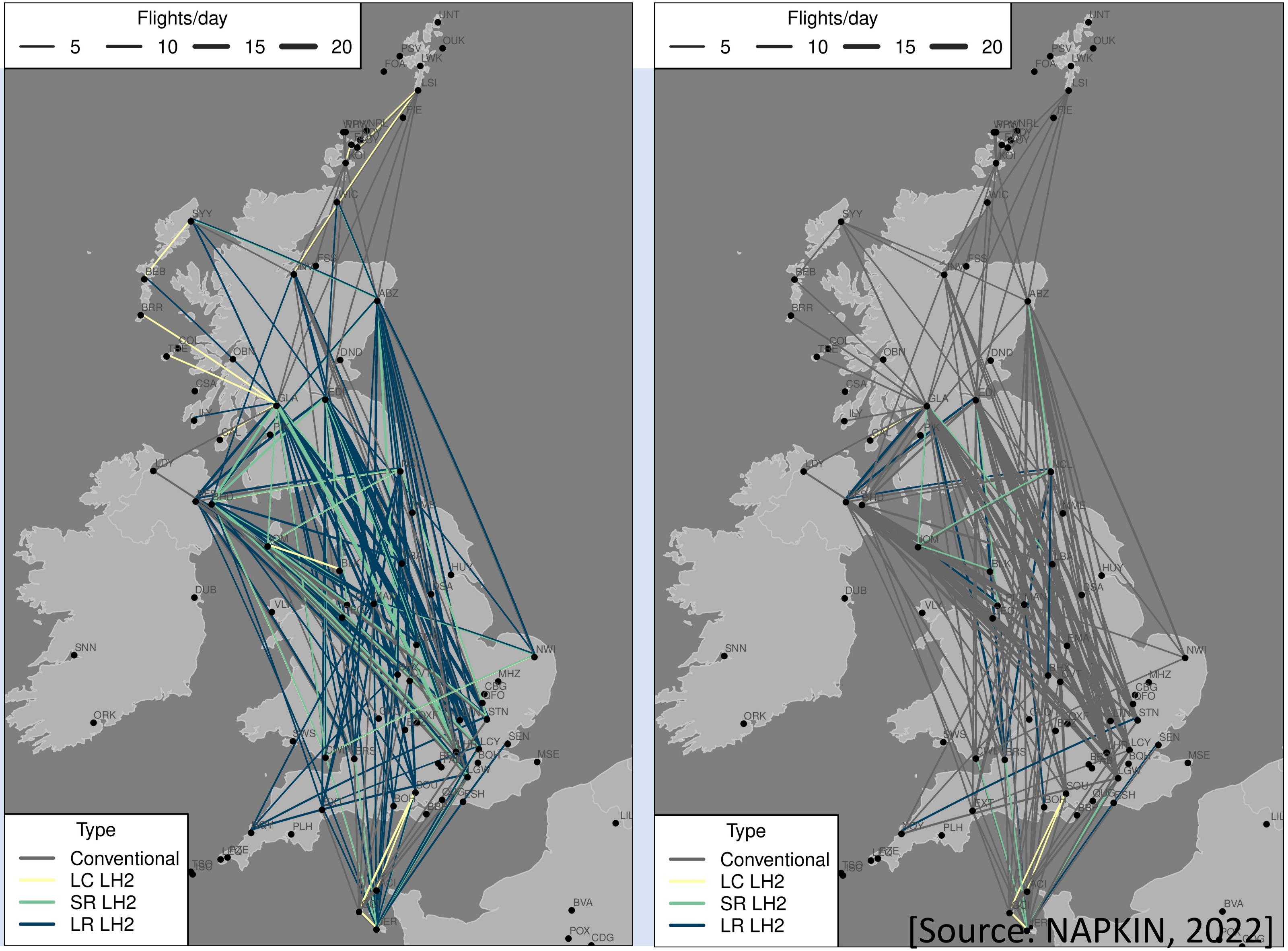
- Airlines can also choose to change fares and flight frequency by itinerary, and are constrained by airport capacity and aircraft capacity, range, runway length requirement, …

Uptake by competing airlines

- Applying this model in the UK
  - 3 small hydrogen aircraft available – 19 seats (LC), 40-50 seats (SR), 85 seats (LR)
  - Uptake depends strongly on fuel prices
  - 19-seater uptake also strongly dependent on non-fuel operating costs, and needs short runway capability
  - For larger designs, uptake more dependent on fuel price, seat capacity, cruise speed
- These simulations assume refuelling infrastructure is available
  - For small airports (NAPKIN, 2022) refuelling from trucks is likely sufficient
- More info on project NAPKIN: https://www.heathrow.com/company/about-heathrow/future-flight-challenge/napkin
- More ABM info: Doyme et al. (2019)
- For larger aircraft: project LH2GT (ongoing)

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

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



[Source: NAPKIN, 2022]

More information: www.atslab.org

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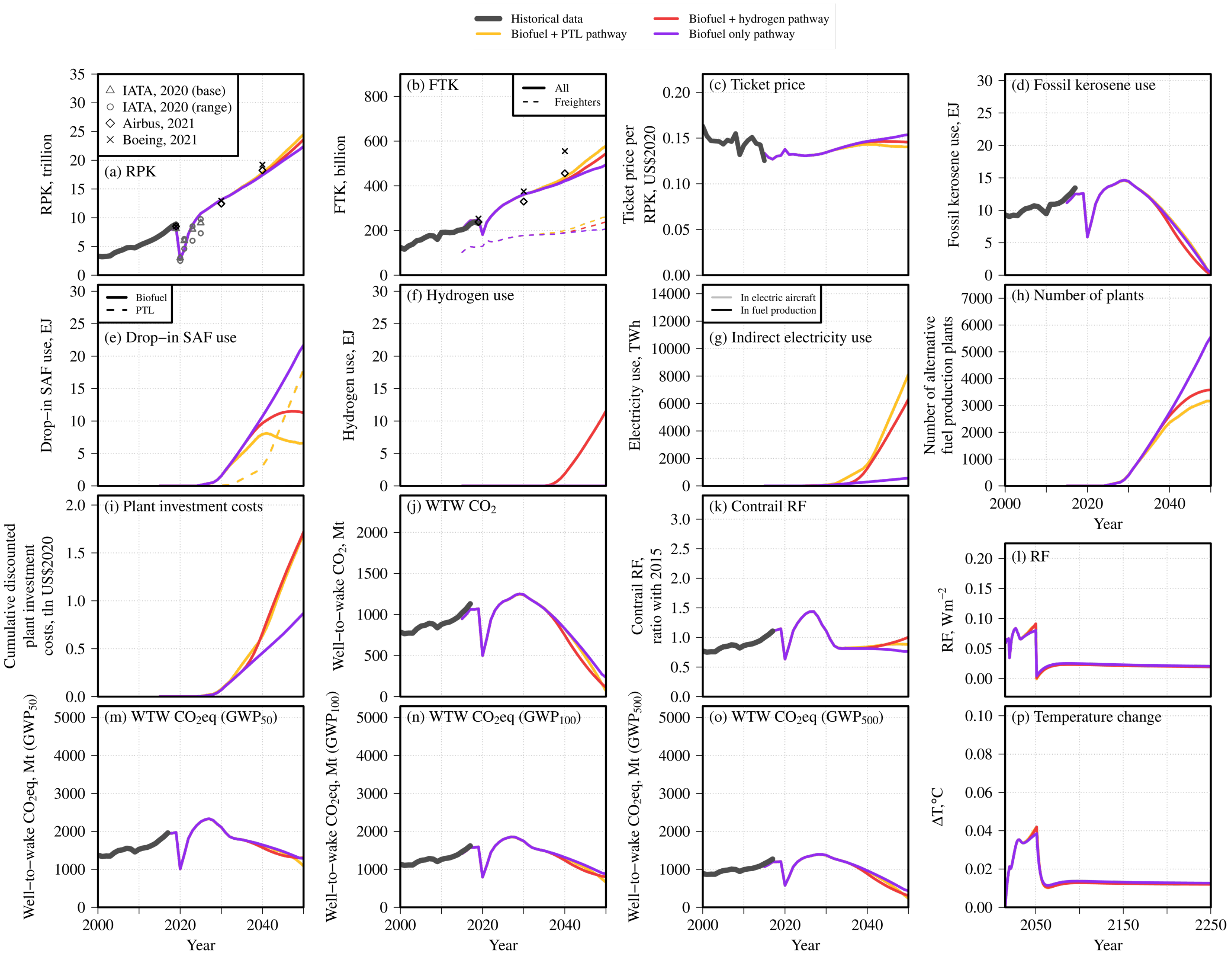
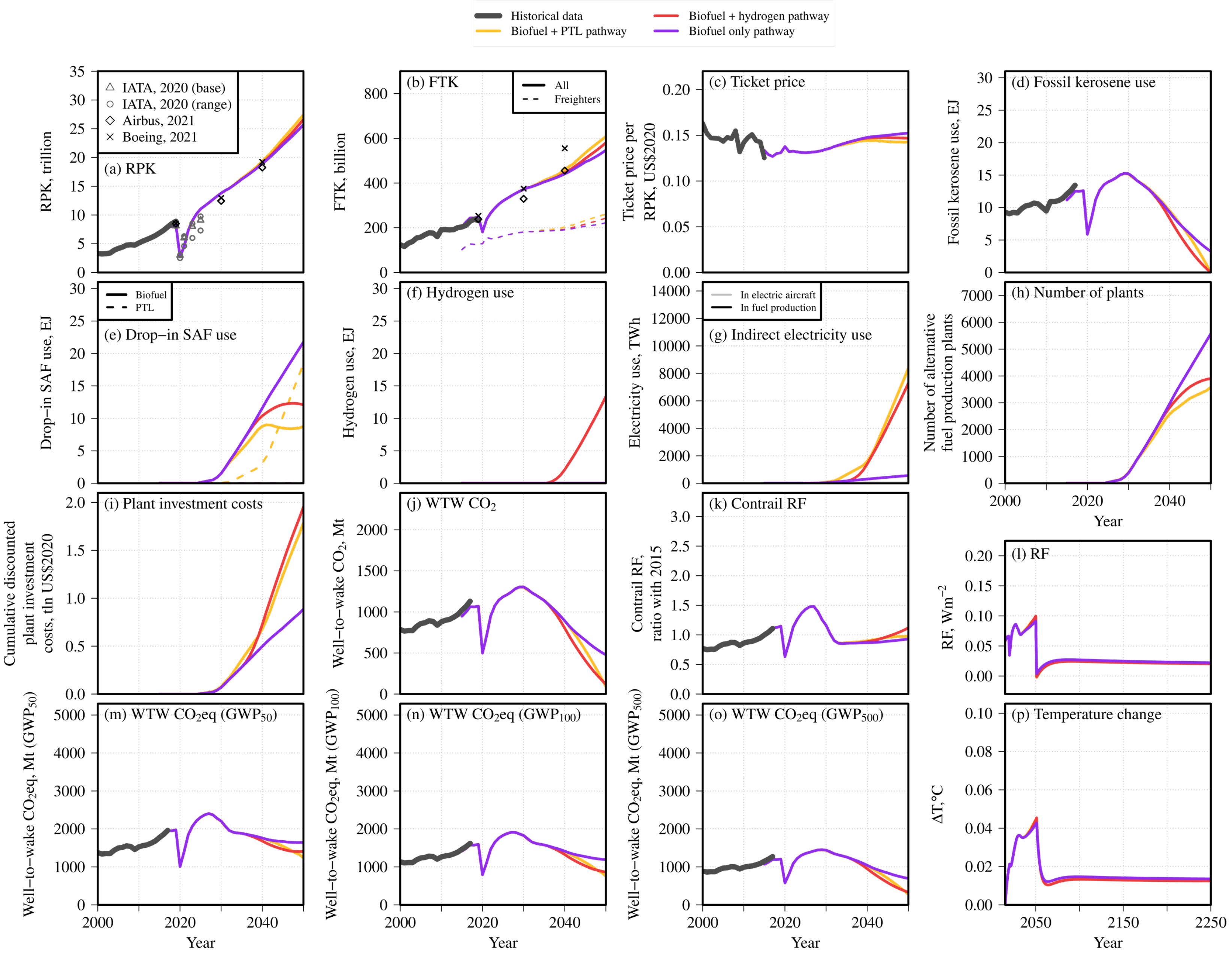
Annex: combined scenarios at central demand, additional metrics



Annex: combined scenarios at high demand, additional metrics



Annex: combined scenarios at low demand, additional metrics