Design Drivers for Efficient Hydrogen Transport Aircraft

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Founding Members Workshop

Wednesday, May 3, 2023

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Aircraft Key Requirements and Assumptions

Key Design Requirements

Specification	Value	Motivation
# of Passengers	400	Long-haul demand
Ultimate Range (fully loaded)	> 7,500 nmi	Long-haul demand
Cruise Mach	> 0.75	2x / day turnaround, market acceptance
Wing Span	< 64.8 m (213 ft)	FAA AC 150/5300-13 ICAO Group V: 52 – 65 m
Engine-out Climb Gradient	> 2.4%	Part 25.121
Fuel Source	Hydrogen	

Key Assumptions

- Clean-sheet airplane and engines
- 2023 technology level
    - GE9X engine technology level
- A hydrogen-fueled B777-300ER

B777-300ER; public domain.

Vehicle Configuration Options

Many discrete decisions to make; choices highlighted:

Hydrogen Storage Method

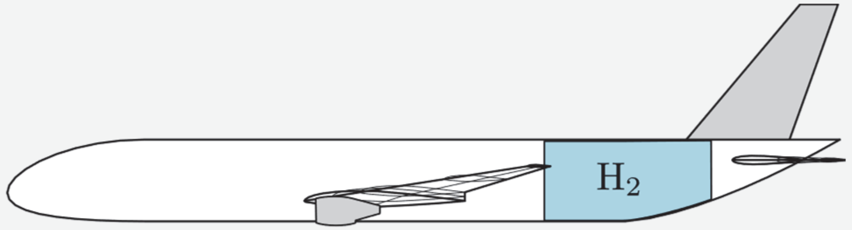
	Liquid Hydrogen (LH2)	Gaseous Hydrogen (GH2)
Density	70 kg/m^3	42 kg/m^3 (at 700 bar)
Tank Gravimetric Efficiency $\eta_{tank} = \frac{m_{fuel}}{m_{tank}+m_{fuel}}$	**74%** assumed 50 – 75% typically	**11%** assumed 8 – 12% typically

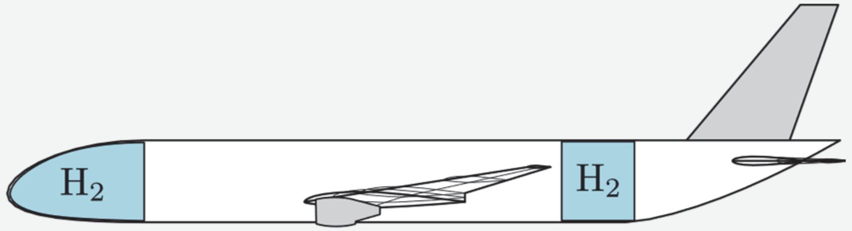
LH2 is the only feasible hydrogen choice for long-haul transport due to η_{tank}

Vehicle Configuration Options

Many discrete decisions to make; choices highlighted:

Hydrogen Tank Layout





Aft Tank Only	Forward and Aft Tanks	Unconventional Configurations
• CG shift of $\approx 0.45\bar{c}$ due to fuel burn • Large tail + trim drag • Boiloff benefit is limited: Part 25 requires discrete tanks per engine	• Minimal CG shift • Non-standard flight deck is likely to keep pressurized sections contiguous	• Higher modeling uncertainty • Further study warranted

Aircraft Sizing Methodology

Aircraft design optimization study implemented in AeroSandbox:

Objective Function

Minimize transport energy per passenger-kilometer

Variables

Aircraft Design

- Wing, fuselage, and tail OML geometry
- Fuel tank sizing
- Engine sizing
- Sizing of primary structure
- Weights of dozens of secondary components
- Initialized to B777-300ER

Mission Design

- Cruise Mach, altitude, C_L
  - Step climb

Constraints & Models

Requirements

- Payload and range
- Previously-stated reqs.
- Various FAR 25 regulations

Key Models

- **Aero**: DATCOM-like buildup
- **Propulsion**: GE9X w/ physics-based scaling
- **Structures**: Empirical where possible, physics-based for LH2 systems

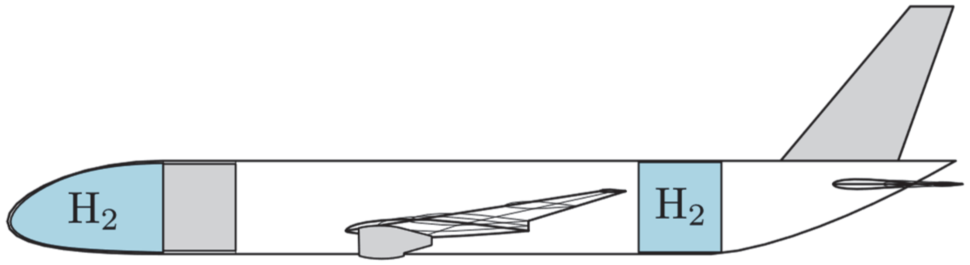
Optimized LH2 Airplane: Overview

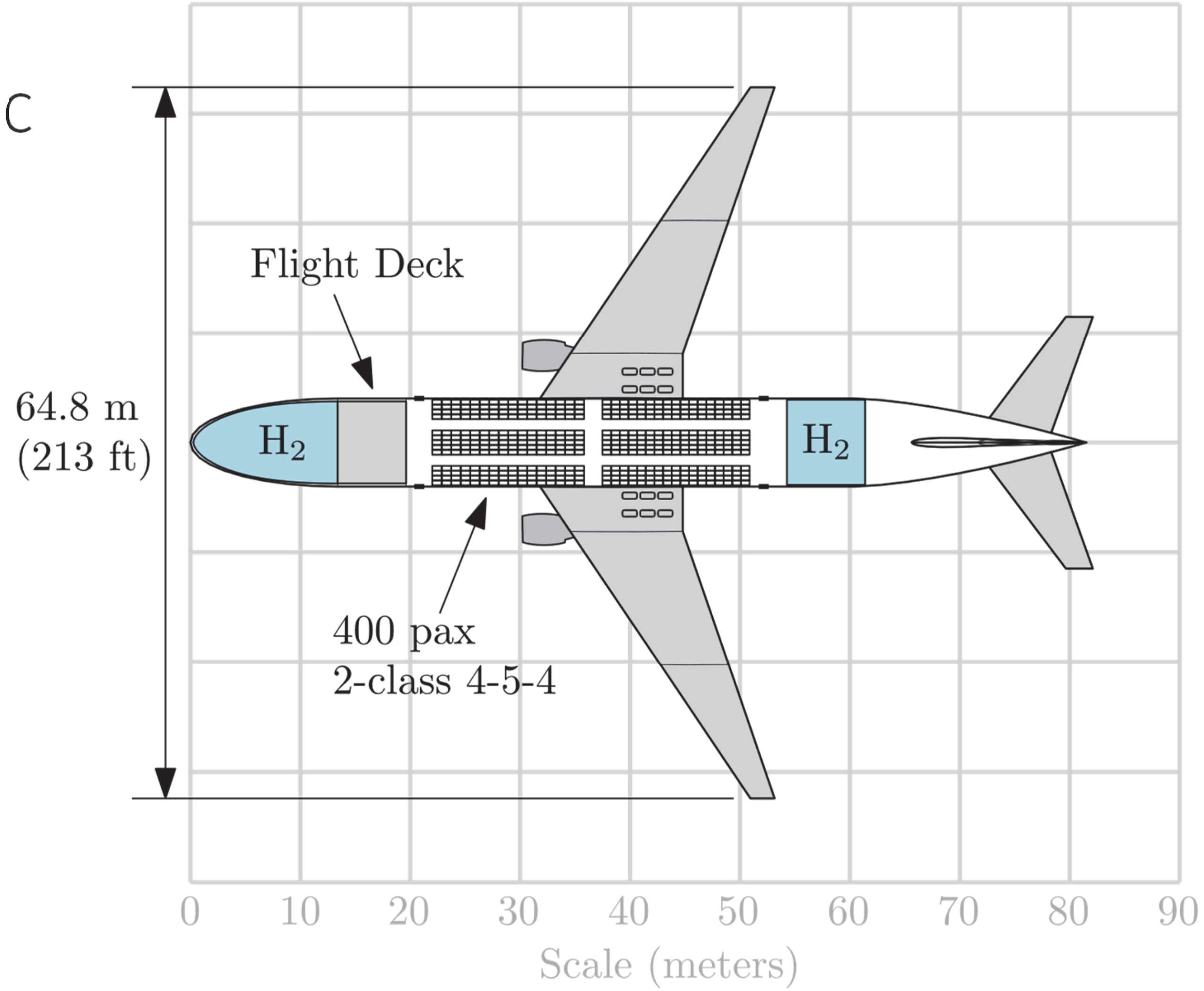
Similar to B777-300ER, with a few key changes:

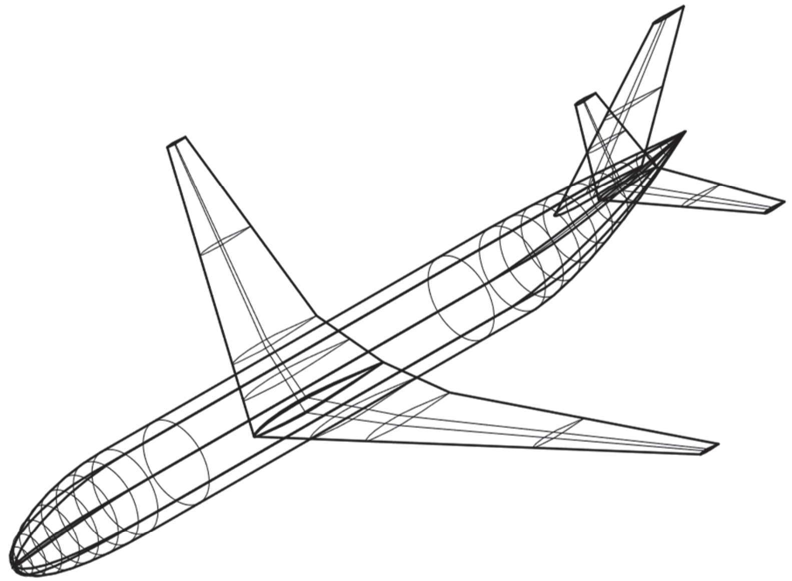
- Clean-sheet airframe and engines
- 2.2x higher fuel specific energy
- Wider cabin (4-5-4)

IFR-Only Flight Deck:

- No forward windows: EFVS + SVS for situational awareness
- Solves pressurization and access challenges

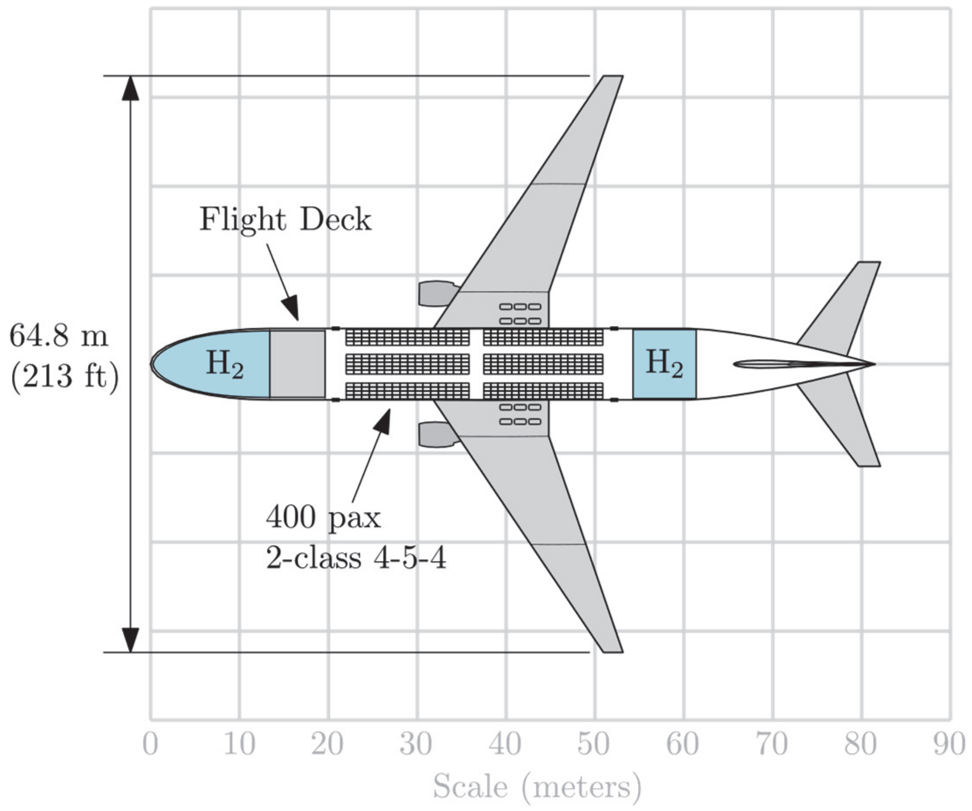






Optimized LH2 Airplane: Comparisons

	Optimized LH2 Airplane	Optimized Kerosene Airplane	As-Built B777-300ER
# of passengers	400	400	396
Ultimate range	7,500 nmi	7,500 nmi	8,200 nmi (estimated)
Cruise Mach	0.81	0.82	0.84
Cruise Altitude	40,800 ft	40,100 ft	43,100 ft
Gross Weight	**275,700 kg**	**314,500 kg**	351,500 kg
Empty Weight	**195,800 kg**	**164,900 kg**	167,800 kg
Fuel Capacity	41,900 kg	110,600 kg	145,500 kg
Wing Span	64.8 m	64.8 m	64.8 m
Length	81.5 m	73.0 m	73.9 m
Lift/Drag	17.1	18.1	-
Fuel Burn	**7.54 g/pax-km**	**19.9 g/pax-km**	19.4 to 26.1 g/pax-km
Transport Energy	**0.90 MJ/pax-km**	**0.86 MJ/pax-km**	0.84 to 1.13 MJ/pax-km

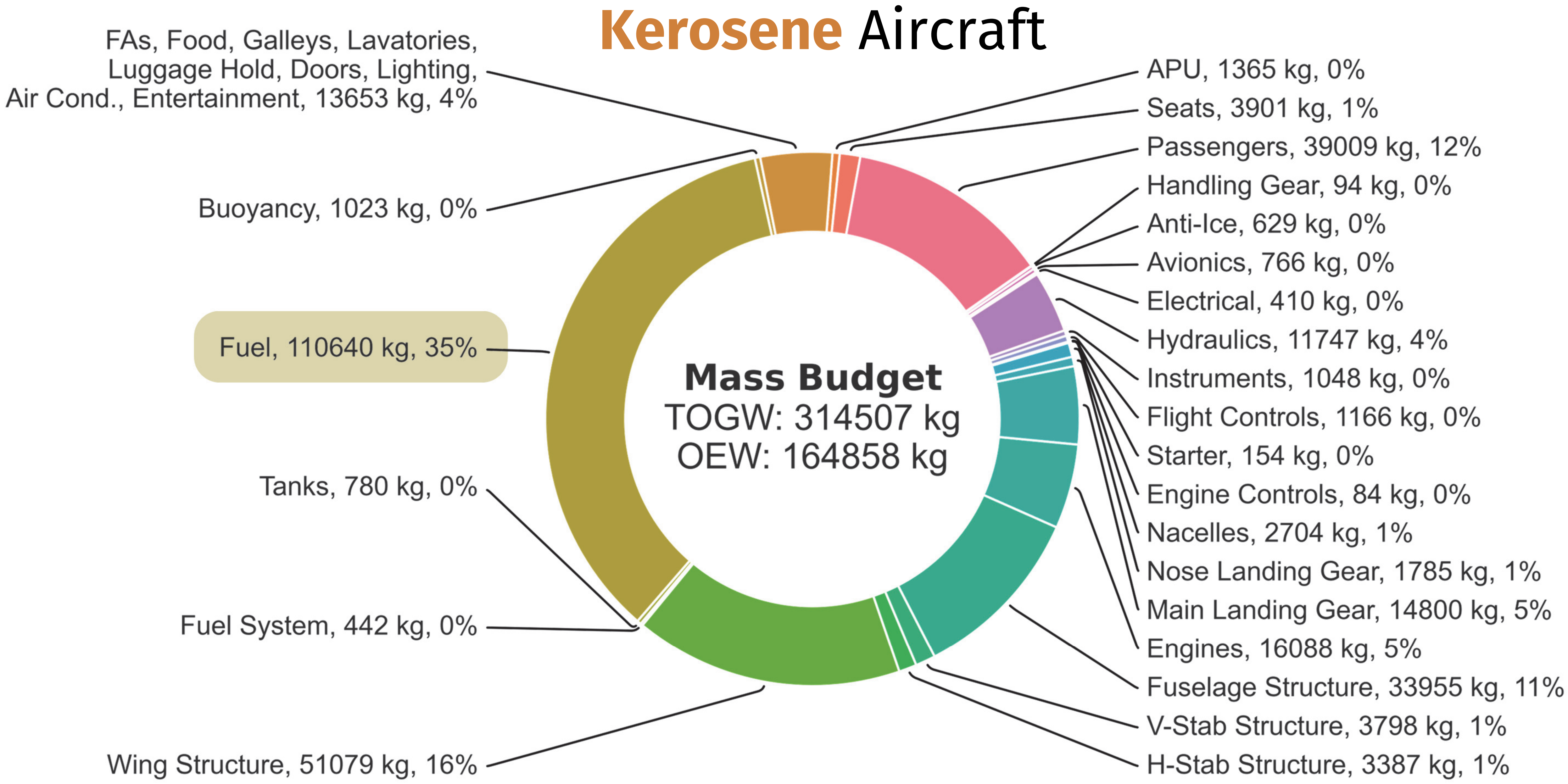


Transport Energy:

$$\frac{\text{fuel energy}}{(\text{passengers}) \cdot (\text{distance flown})}$$

an apples-to-apples metric for "the cost of useful work"

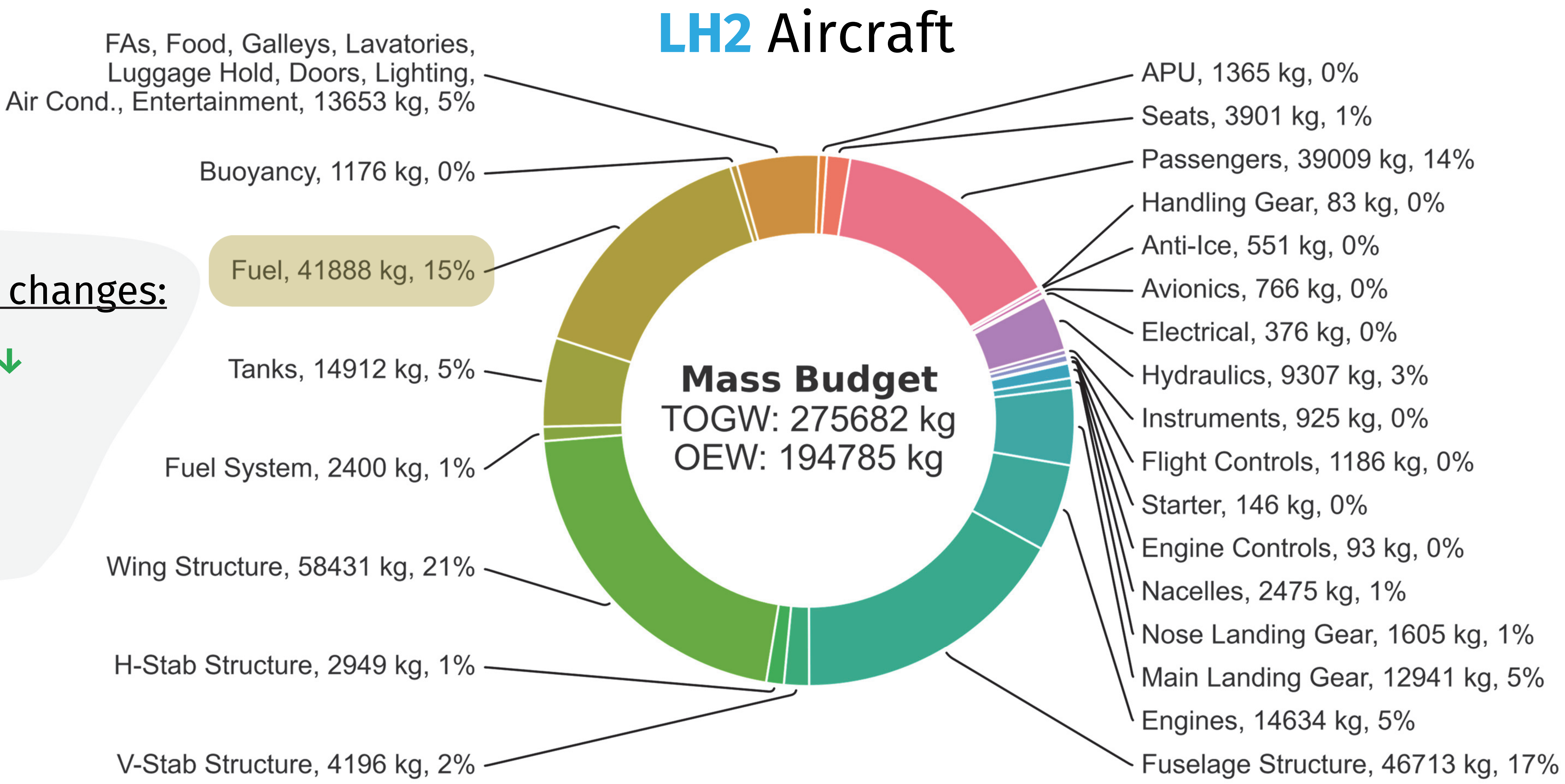
Optimized **Kerosene** Airplane: Mass Budget



Optimized LH2 Airplane: Mass Budget

LH2 major weight changes:

- Fuel ↓↓
- Fuel tanks ↑
- Wing ↑
- Fuselage ↑



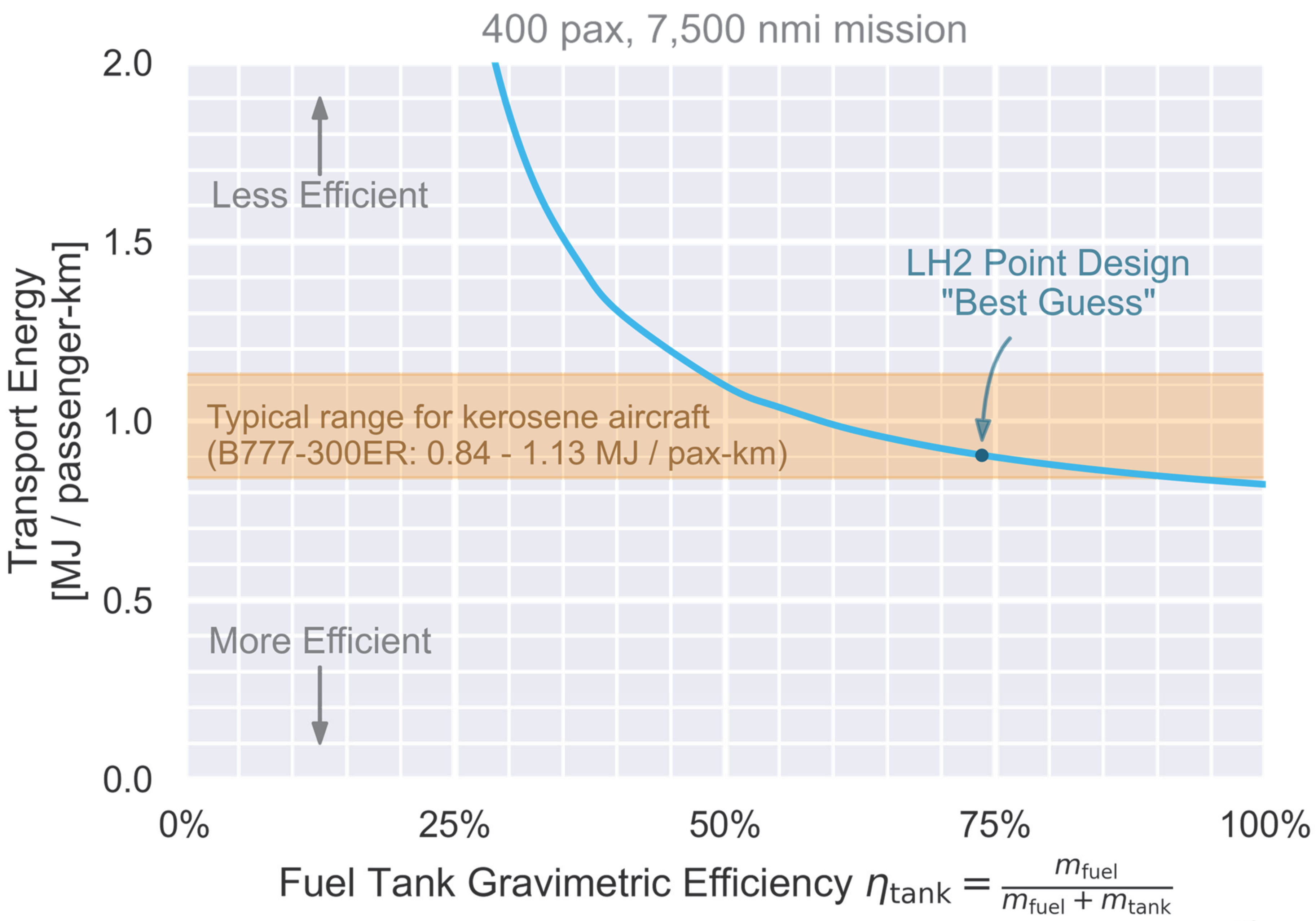
Takeaway 1: LH2 Tank Weight is a Key Metric

Are LH2 or kerosene aircraft more energy-efficient?

It depends, mostly on **tank gravimetric efficiency**

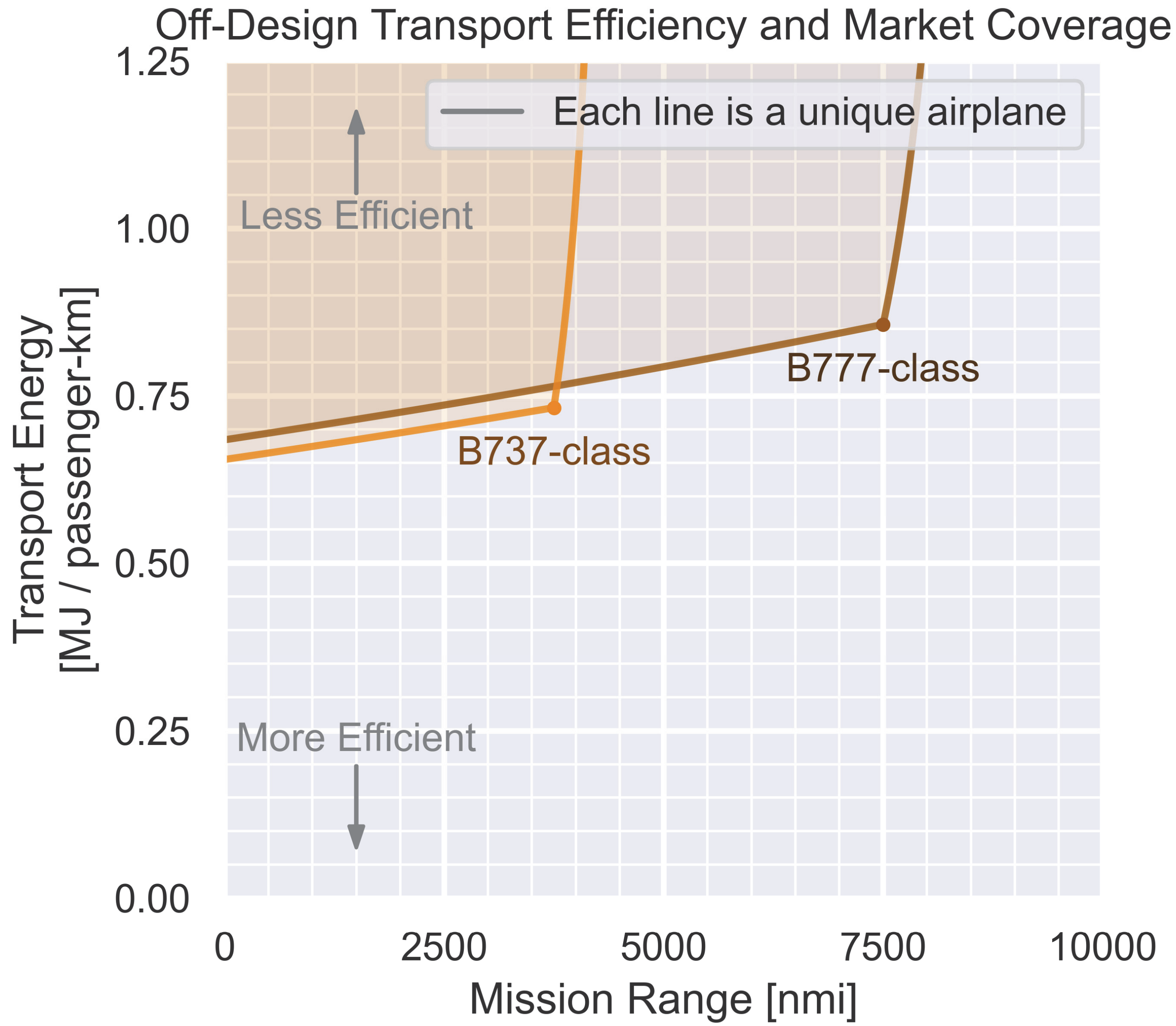
State-of-the-art LH2 tanks have η_{tank} of 50% to 75%

LH2 Tank Fuel Fraction vs. Required Transport Energy

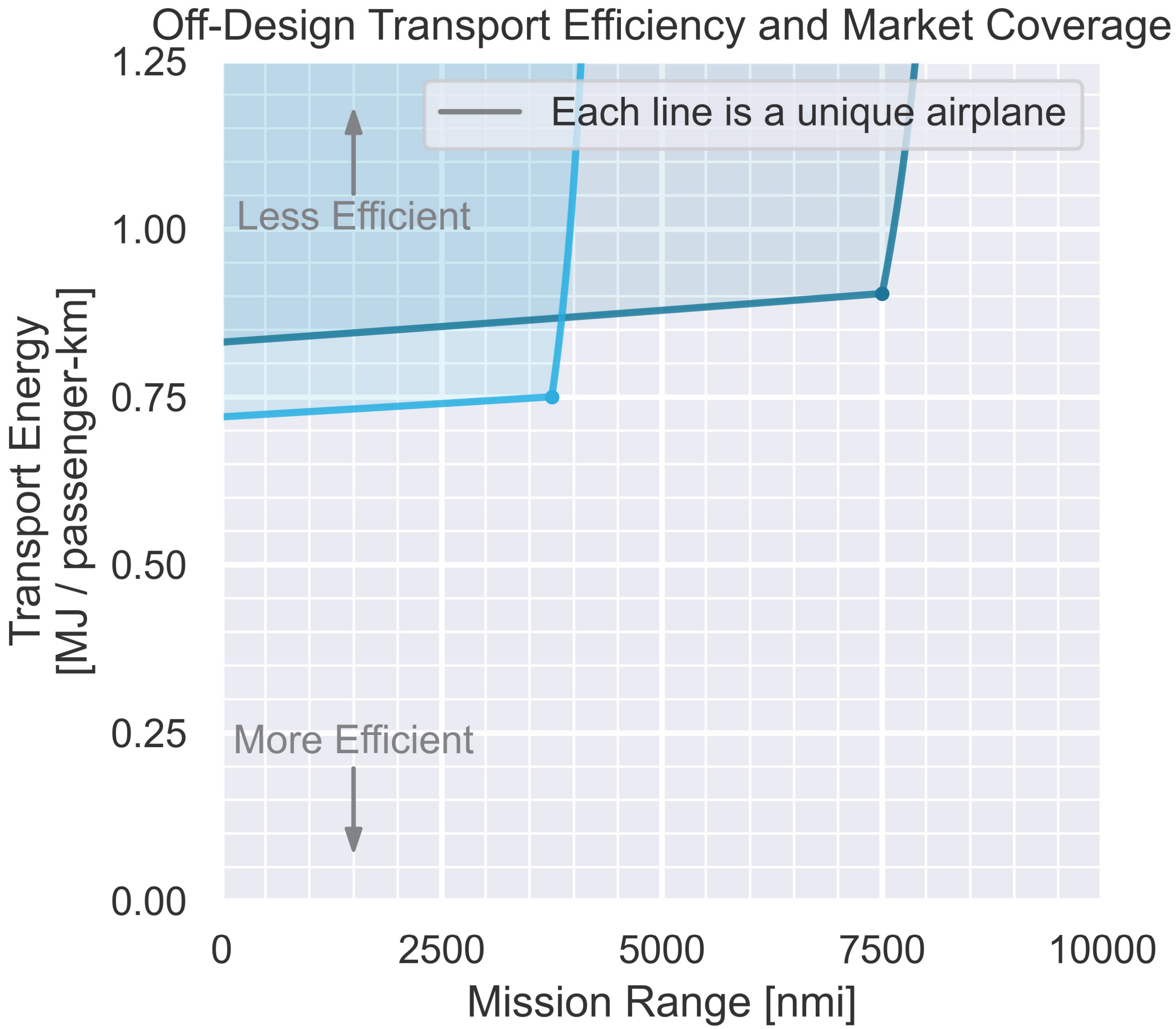


Takeaway 2: Hydrogen wants More Market Segmentation

Kerosene Aircraft Fleet



LH2 Aircraft Fleet



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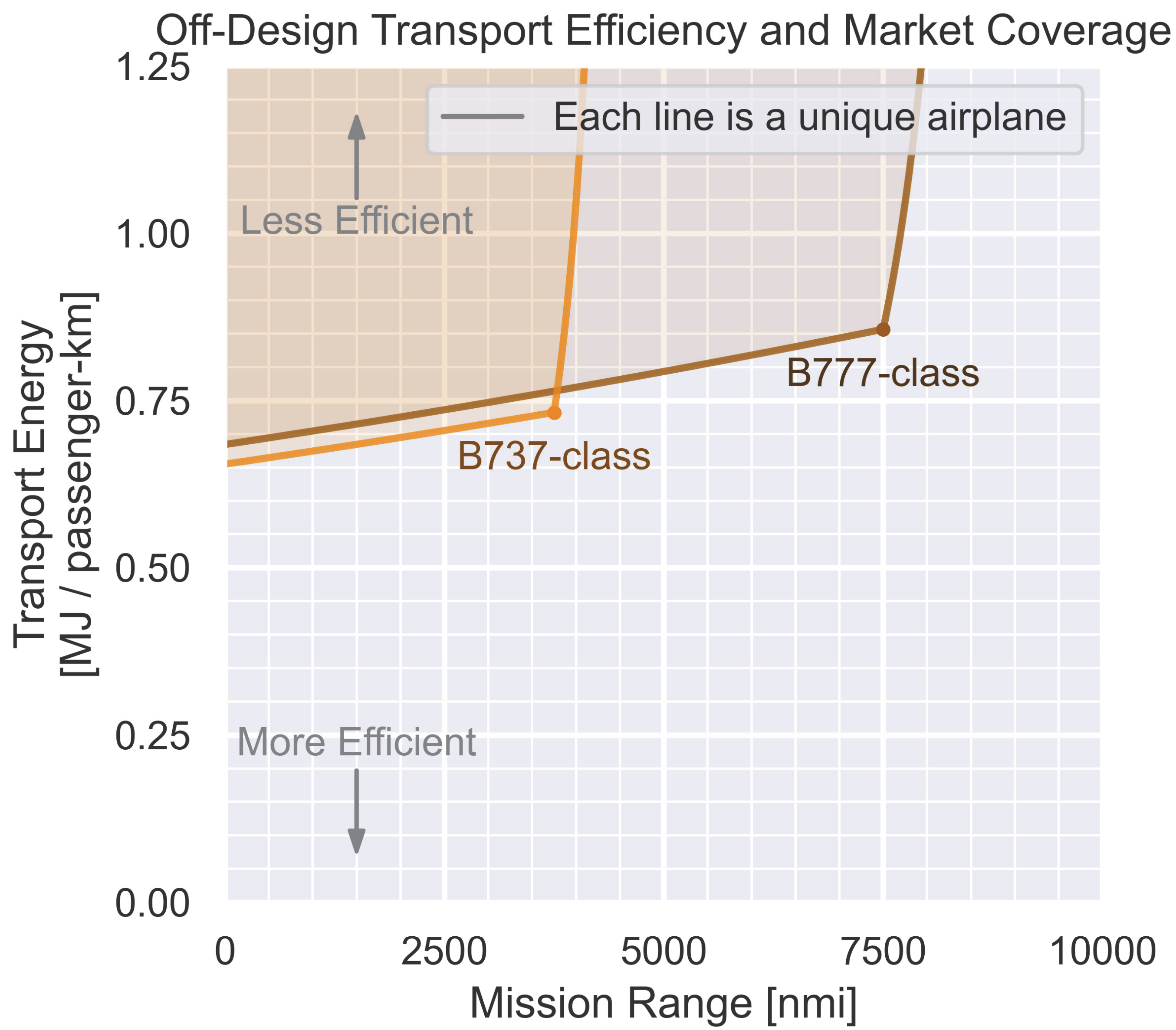
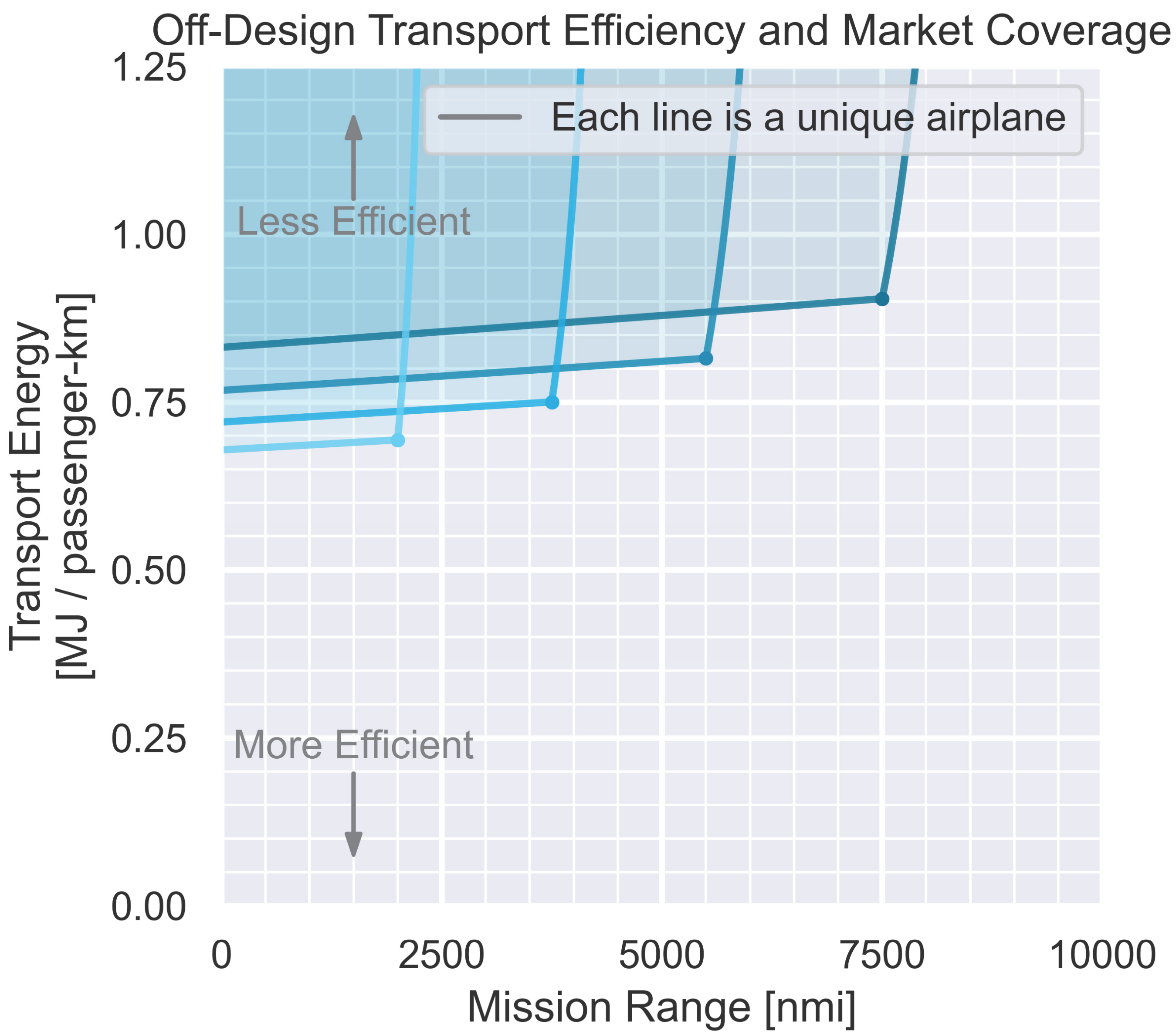
Kerosene Aircraft Fleet



LH2 Aircraft Fleet



Aircraft design point studies are a powerful tool, but we also need to look at the broader story!

Thank You!

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