香港科技大學
THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

Hydrogen-Powered Aircraft

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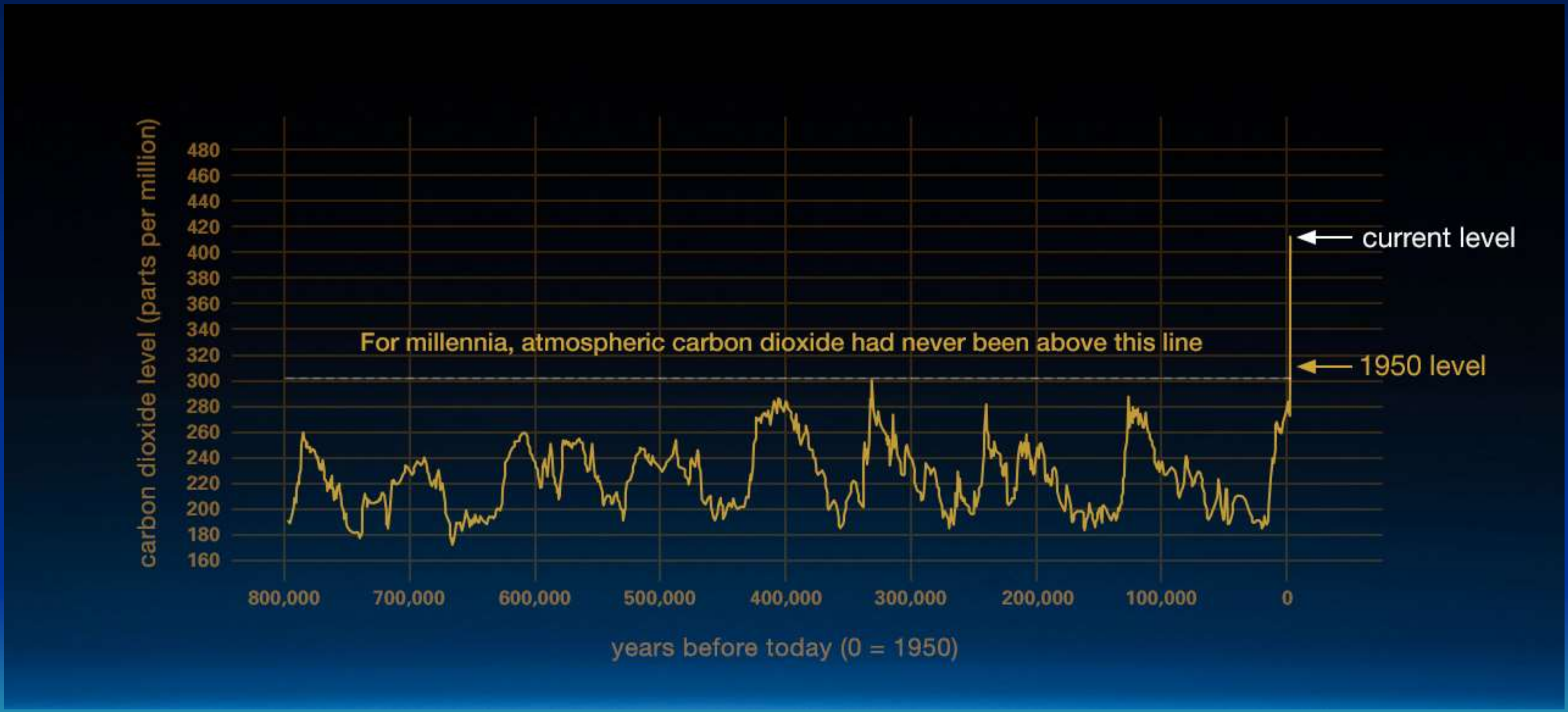
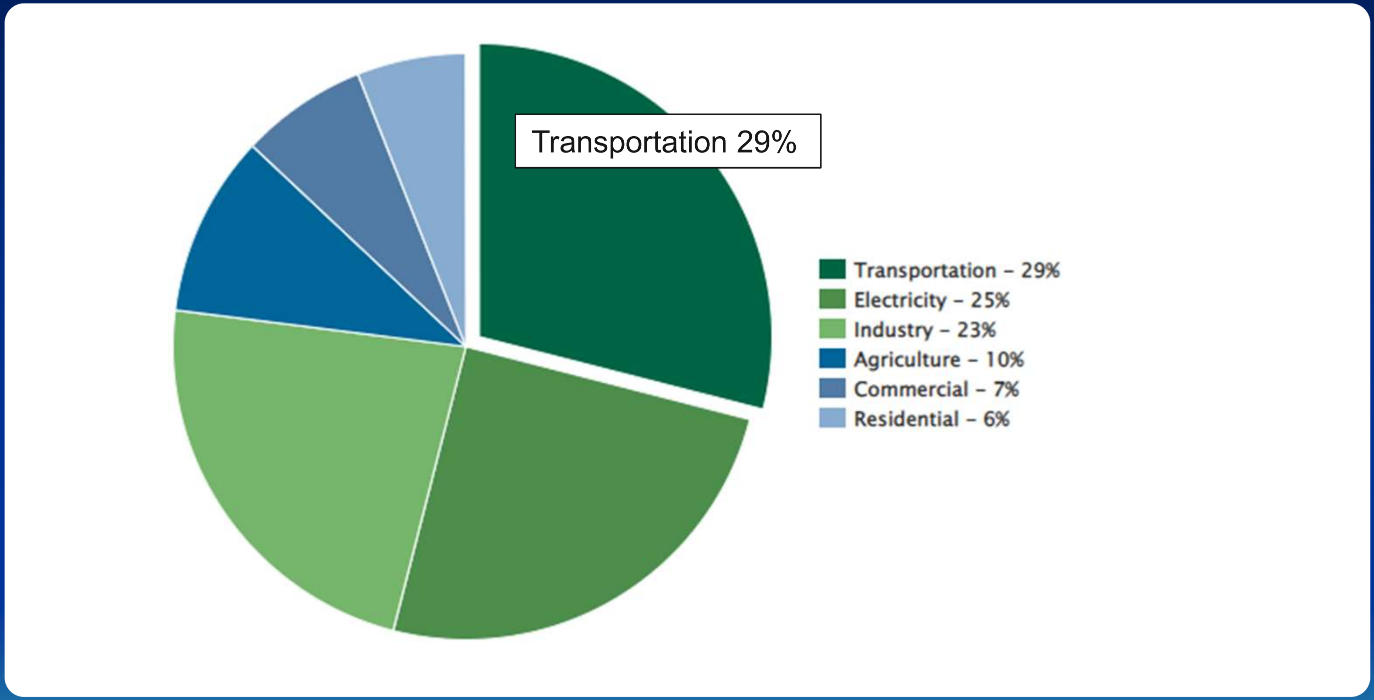
- Need for Zero-Carbon Economy
- Hydrogen vs. Batteries
- History of Hydrogen-powered Propulsion
- Hydrogen Generation, Distribution and Storage
- Applications of Hydrogen Energy
- The Future of Hydrogen
- Conclusions

The Relentless Rise of CO_2

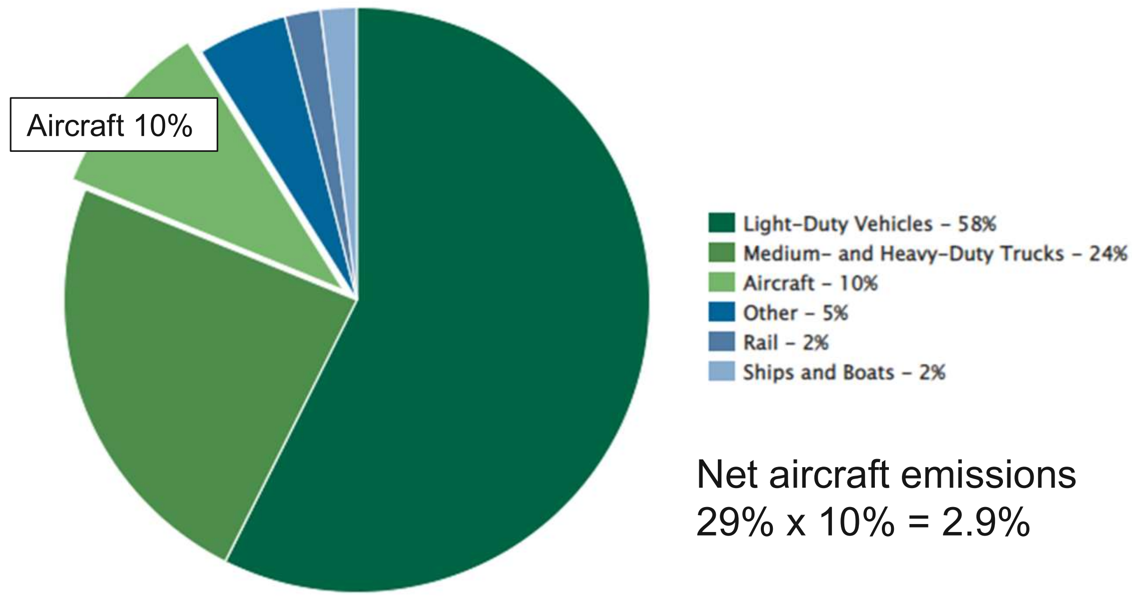


https://climate.nasa.gov/climate_resources/24/graphic-the-relentless-rise-of-carbon-dioxide/

2019 U.S. GHG Emissions by Sector



2019 U.S. Transportation Sector GHG Emissions by Source



Net aircraft emissions
29% x 10% = 2.9%

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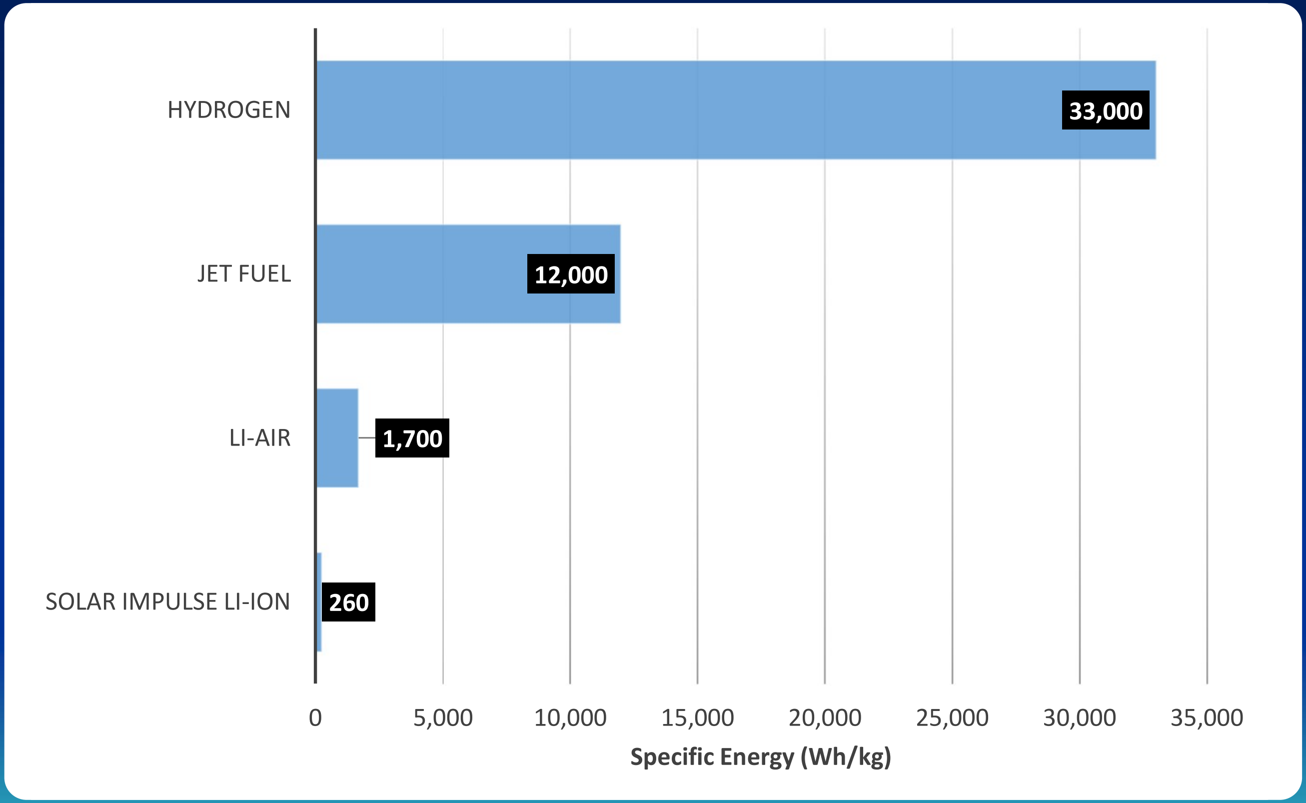
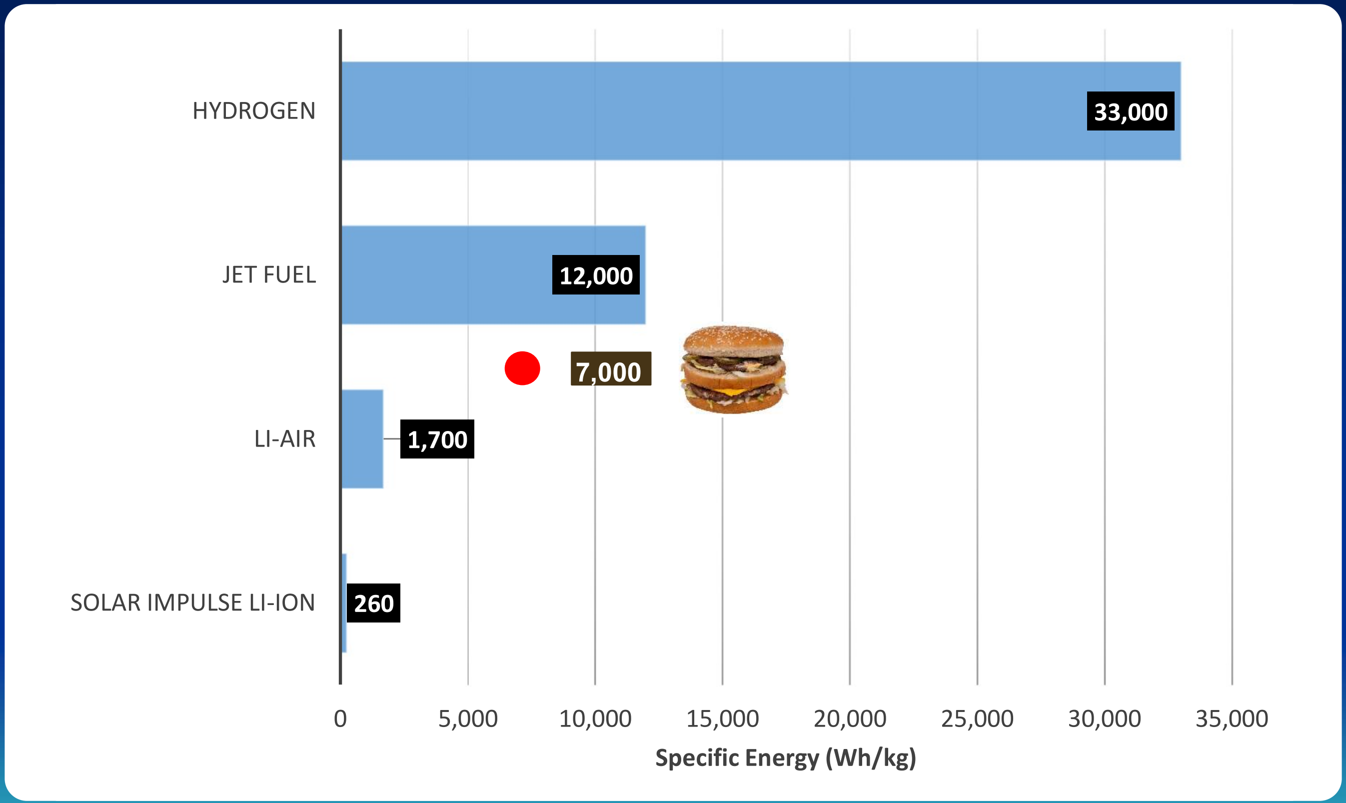
Energy/Unit Weight is Important



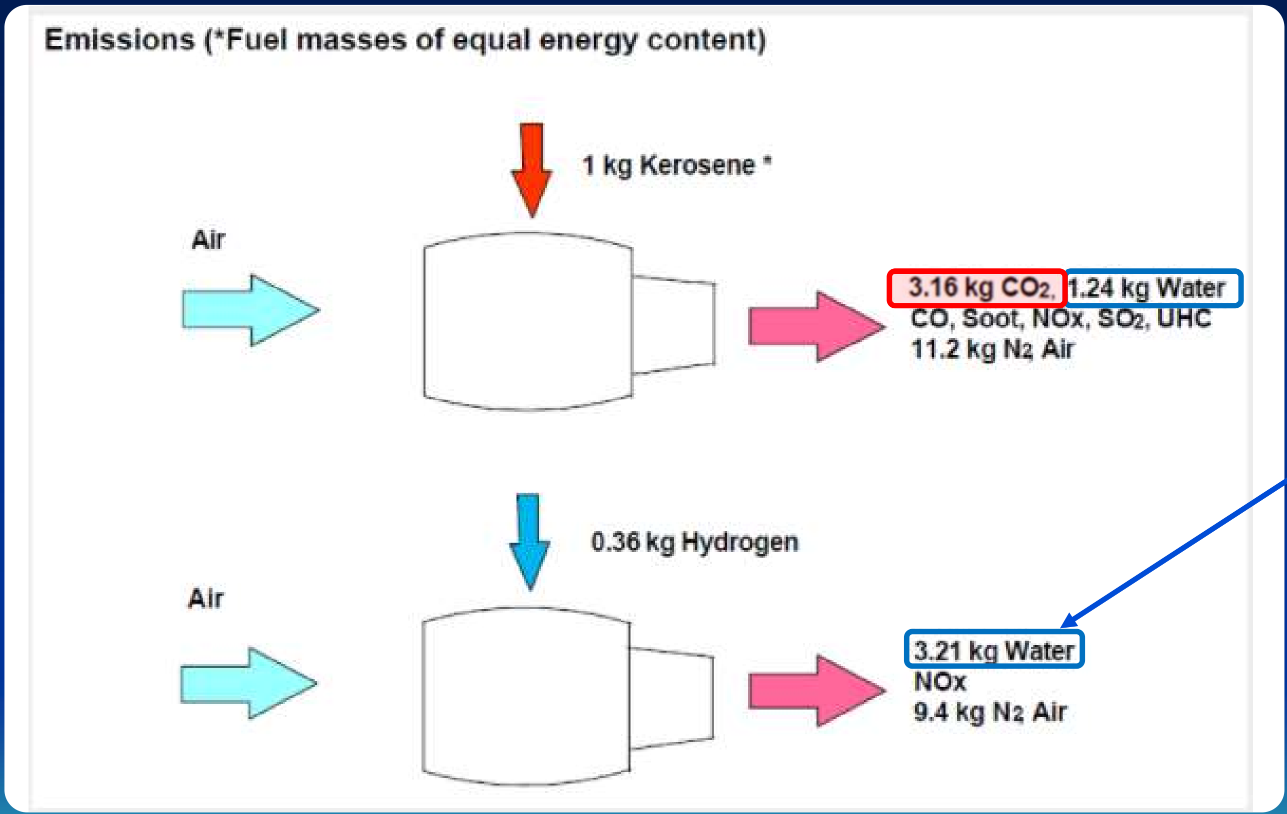
ADAC
Aircraft Design & Consulting

Energy/Unit Weight is Important



https://en.wikipedia.org/wiki/Big_Mac

Jet fuel vs. H_2 Emissions



Compared with jet-fueled engine:

- No CO_2
- 2.6 x water vapor results in increased condensation trails, which may contribute to increased global warming

Source: Airbus Cryoplane study

Understanding Condensation Trails

A NASA DC-8 with a fast forward scattering spectrometer probe followed a DLR A320 ATRA on nine flights over Germany in 2018 to measure ice particle concentrations. Credit: DLR/NASA/Florian Friz

Keith Button, Curbing Contrails, AIAA Aerospace America 2021-05

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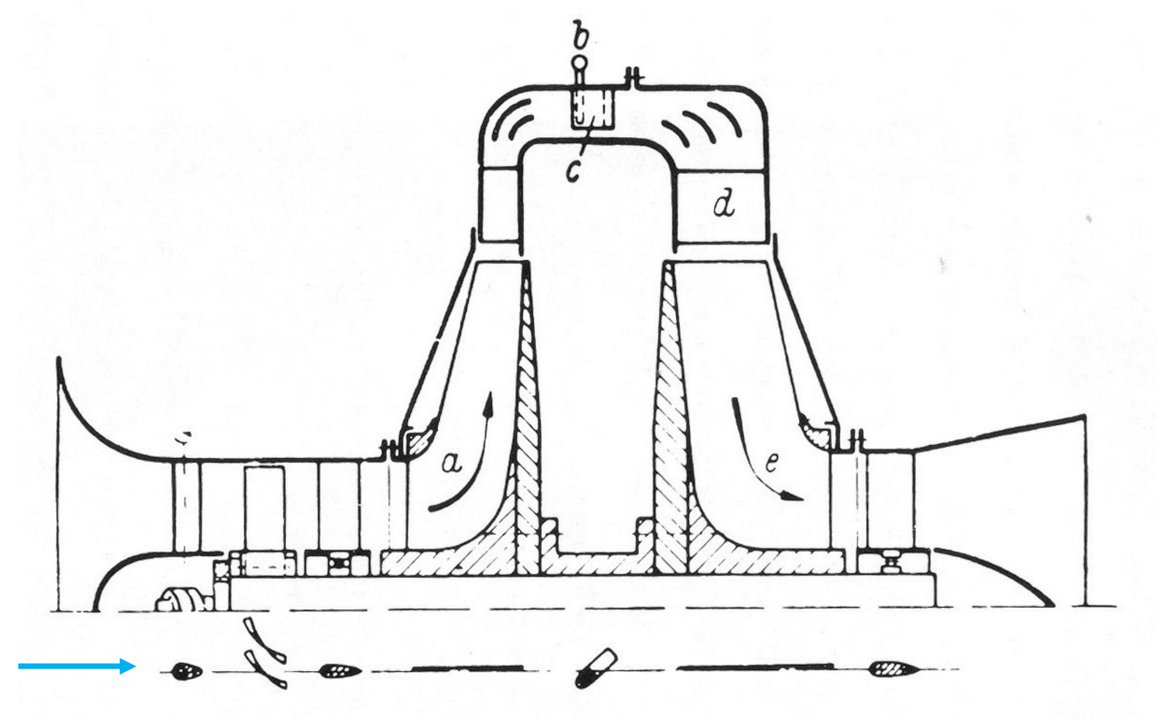
He S-1 Turbojet

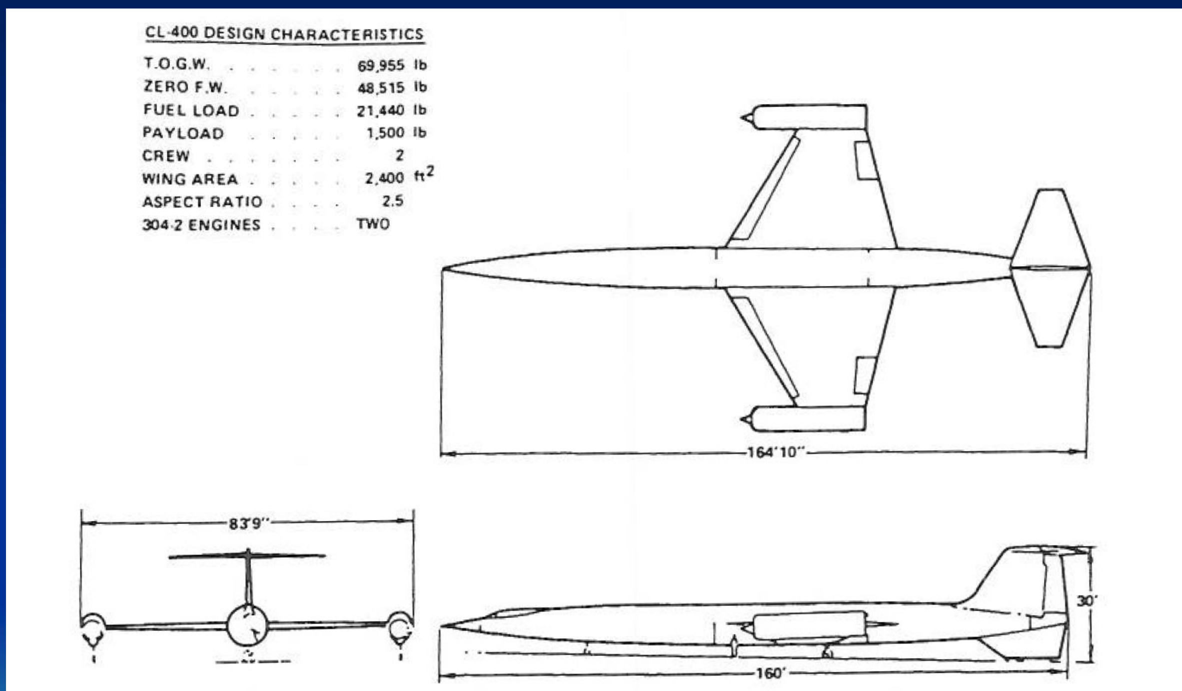
- Built in 1936, tested in April 1937
- Manufacturer: Heinkel-Hirth Mortorenbau
- Designer: Hans von Ohain
- Single-stage centrifugal compressor
- Gaseous hydrogen-powered
- Rotor radius: ~ 30 cm (1 ft)
- Thrust: ~ 250 lb (1,100 N)



IGV/blade/stator/injector sections

ADA505106 AMCs Future - Sustainable Air Mobility. A.D. Reiman.pdf

Lockheed CL-400



- 1954-1958
- Design Mach 2.5 @ 100,000 ft
- Not built, in part because of lack of H_2 infrastructure
- Demonstrated that H_2 could be handled as safely and easily as hydrocarbon fuel

ADA505106 AMCs Future - Sustainable Air Mobility. A.D. Reiman.pdf

Safety of Hydrogen vs. JP-8

For most issues of practical importance, hydrogen is safer than JP-8

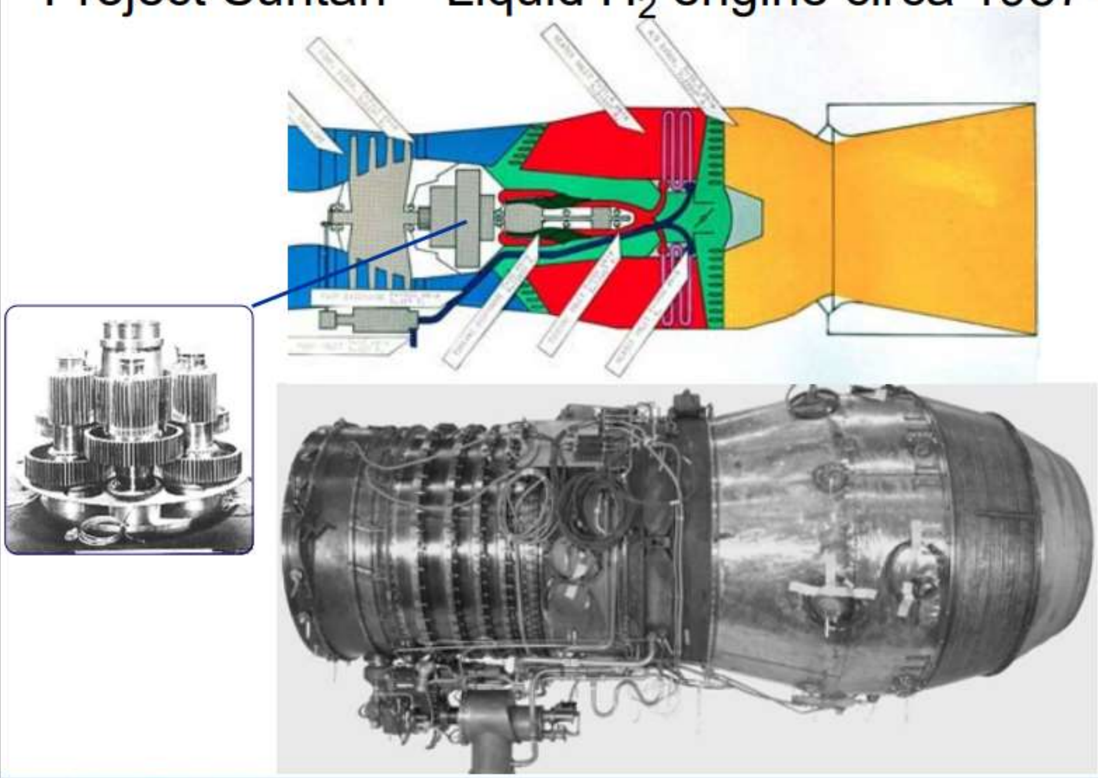
Source: Reiman, A.D., “AMC’s Hydrogen Future: Sustainable Air Mobility”, Air Force Institute of Technology, AFIT/IMO/ENS/09-13, June 2009

Hydrogen vs JP-8

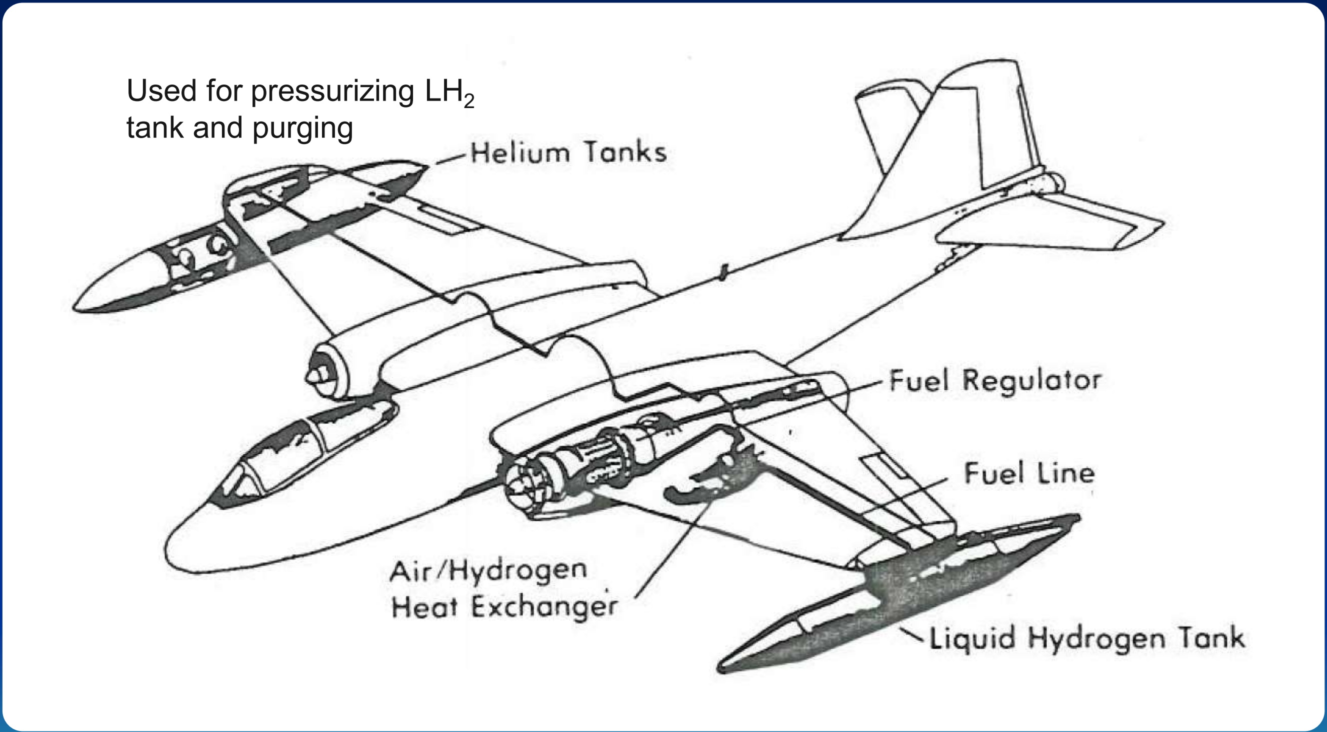
Safety		
Item	**Information**	**Advantage**
Detonation	Gun shot tests into liquid hydrogen tanks failed to result in detonation. Heavy impact tests of liquid hydrogen tanks failed to result in detonation. Detonation of a perfect mixture of hydrogen and air only takes place with a strong detonator, but it is improbable that a perfect mixture of hydrogen and air will occur at the time of a strong detonation. JP-8 has a lower detonability limit in air as a percentage of volume than hydrogen. (Brewer, 1991)	Hydrogen
Emissivity	Hydrogen has a lower emissivity than JP-8 making the thermal radiation during a fire less. If a large hydrogen spill occurs outside an aircraft, remain inside for the heat will not be likely to enter the fuselage due to the low emissivity. (Brewer, 1991)	Hydrogen
Frost Bite	Contact with minute amounts of liquid hydrogen can lead to severe frost bite, while JP-8 poses no frostbite hazard. (Praxair, 2007)	JP-8
Fuel Spills	Hydrogen evaporates much more rapidly than JP-8 and if ignited burns quicker than JP-8. A 12,600 kg hydrogen fuel spill will dissipate in 32 seconds, while a similar volume of JP-8 would take closer to 13 minutes. (Brewer, 1990)	Hydrogen
Ignition Temperature	Hydrogen has a higher autoignition temperature than JP-8, but a lower temperature in an air mixture. A lit cigarette will not ignite in pure hydrogen although it could light a hydrogen-air mixture. A lit cigarette could ignite JP-8. (Brewer, 1991)	JP-8
Invisible Flame	Hydrogen can be a burn hazard due to invisible flame, while JP-8 has a visible flame. (Praxair, 2007)	JP-8
Suffocation	The high diffusion rate of hydrogen can rapidly replace the oxygen in an unventilated room leading to possible suffocation, while JP-8 poses a lesser suffocation hazard. (Praxair, 2007)	JP-8
Toxicity	JP-8 is a liver toxin, kidney toxin, nerve toxin, blood toxin, lung aspiration hazard and a reproductive fetotoxin, while hydrogen is not toxic. (Dfdl, 2001).	Hydrogen

P&W Hydrogen Fueled Aircraft Engine

Project Suntan – Liquid H_2 engine circa 1957-58



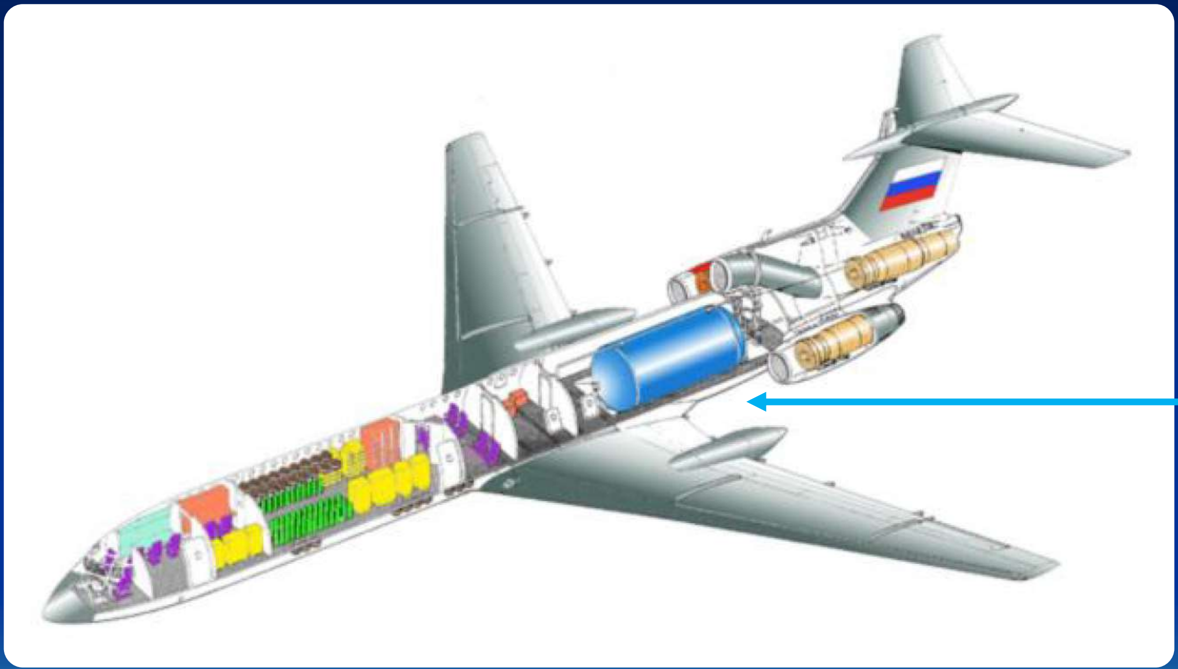
Martin B-57 Canberra



ADA505106 AMCs Future - Sustainable Air Mobility. A.D. Reiman.pdf

- First flight 1955
- NACA Lewis Flight Propulsion Laboratory
- Standard B-57 with Wright J65 engine
- Mach 0.75 @ 50,000 ft
- Switched from JP-4 to H_2
- 21 minutes on H_2
- Switched back to JP-4

LH_2-powered Tu-155



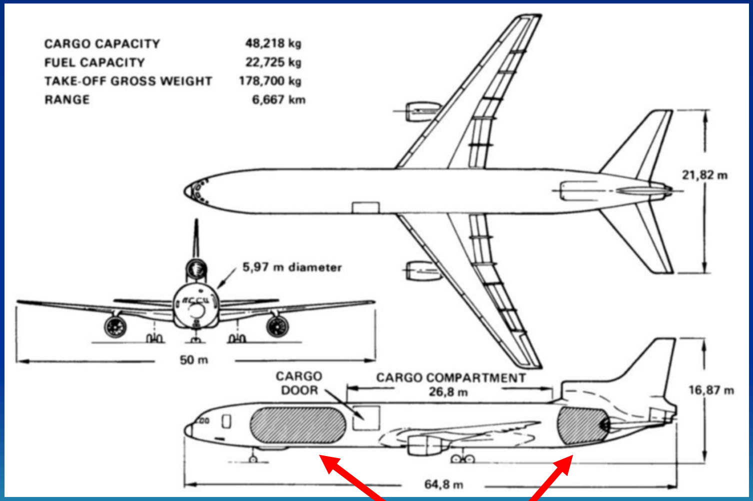
- First flight: 1988-04-15
- Fuel: LH_2 (later LNG for #3 engine only)
- Propulsion: 3 x Kuznetsov NK-8-2 (later replaced #3 with NK-88)
- NK-8-2 can also burn jet fuel
- LH_2 tank diameter 3.1 m (10 ft 2 in), length 5.4 m (17 ft 8 in), AMG6 Al alloy
- 50 mm (2 in) foamed polyurethane lagging

https://leehamnews.com/2020/07/24/bjorns-corner-the-challenges-of-hydrogen-part-1-background/

LH_2-powered L-1011

- Circa 1976
- No carbon footprint
- Energy/unit weight (specific energy) of H_2 about 3 x that of jet fuel (excluding weight of cryogenic tank)
- Requires about 4.2 x volume for same energy
- Problems are mostly institutional

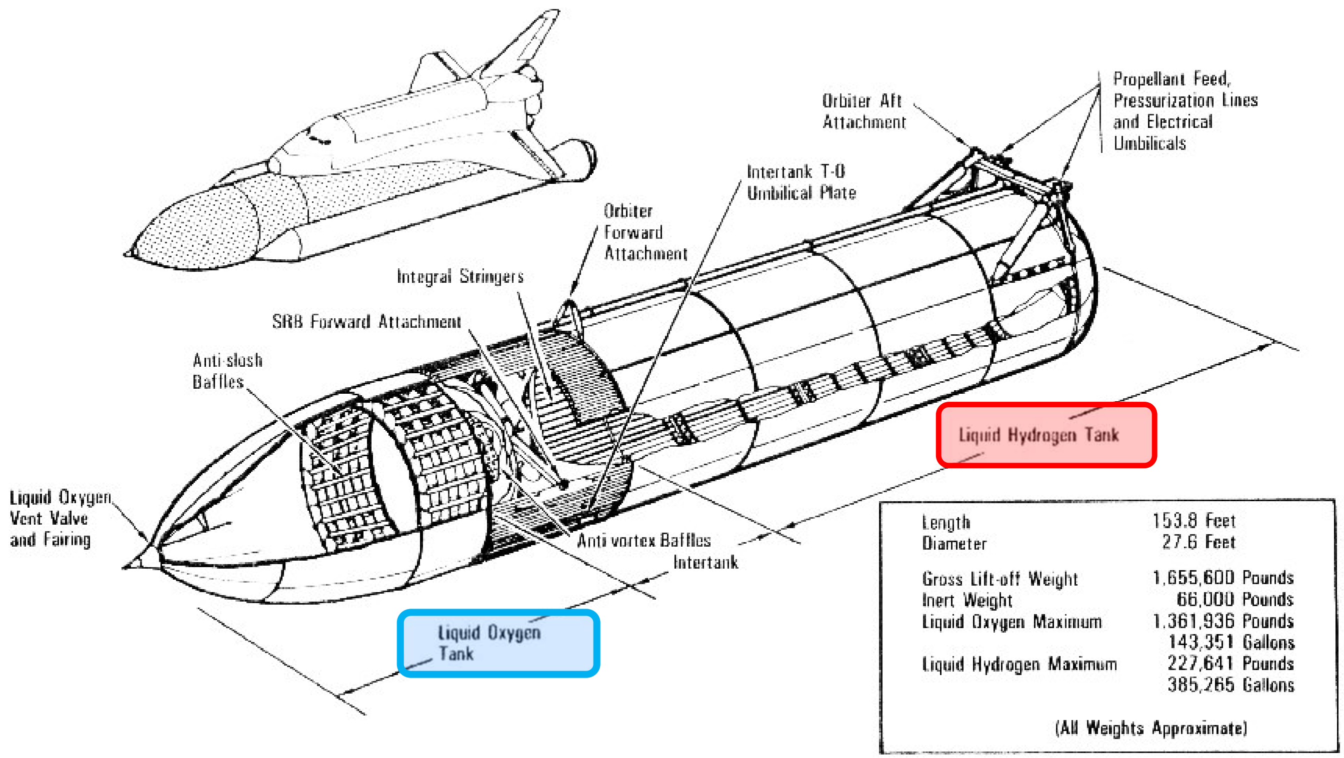
Lockheed L1011-500 with 40 ft stretch to fuselage for fore and aft cryogenic tanks



Source: Lockheed

For infrastructure study by Dan Brewer see https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19770003090.pdf

Space Shuttle Main Tank

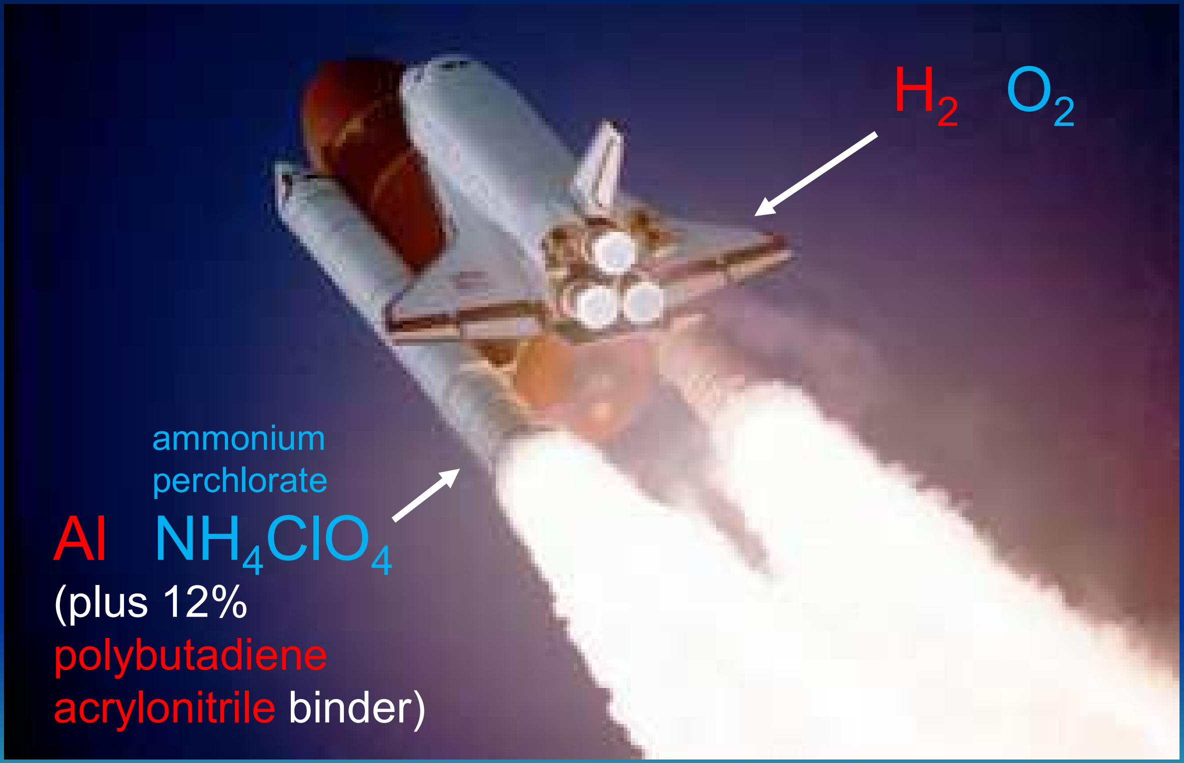


Lightweight External Tank

Source:science.ksc.nasa.gov

Space Shuttle Initial Ascent

SRB products of combustion
- Al_2O_3 (aluminium oxide)
- $AlCl_3$ (aluminium chloride, anti-perspirant)
- H_20
- N_2



Source: nasa

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Hydrogen Challenges

- Production
  - Either methane reformation
    - Cost of methane
    - Cost of reformation
    - Cost of disposal of CO_2
  - Or electrolysis
    - Cost of electricity
    - Cost of electrolysis
- Cost of H_2 distribution and storage
- Cost and energy of H_2 liquefaction
- No existing infrastructure

Typical Hydrogen Production

Step 1 Steam-methane reforming reaction

$CH_4 + H_2O$ (+ heat) $\rightarrow CO + 3H_2$

Or partial oxidation of methane reaction (produces less H_2)

$2CH_4 + O_2 \rightarrow 2CO + 2H_2$ (+ heat)

Step 2 Water-gas shift reaction

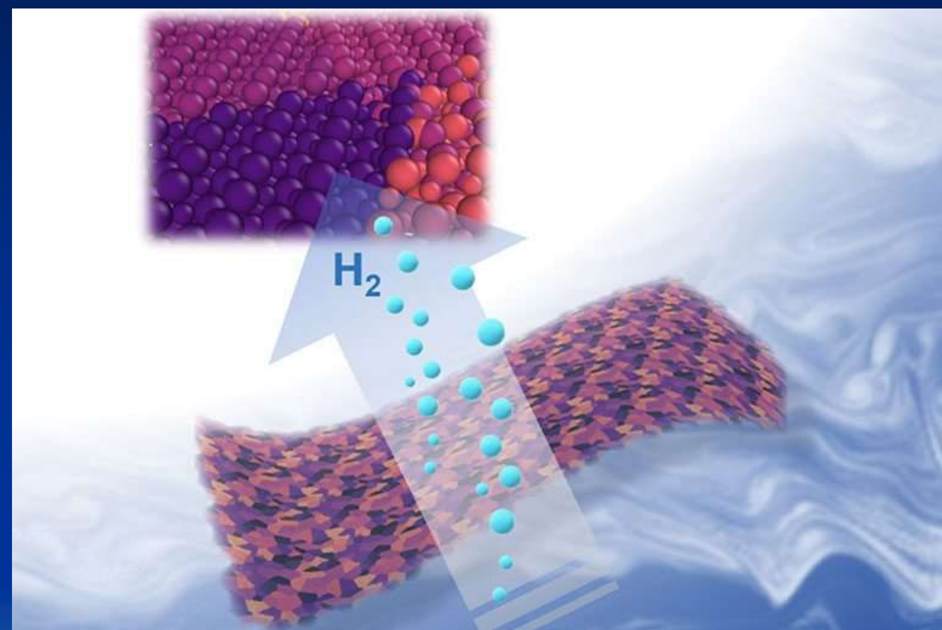
$CO + H_2O \rightarrow CO_2 + H_2$ (+ small heat)

Total GHG approx. halved

https://energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming

Electrocatalytic H_2 Generation

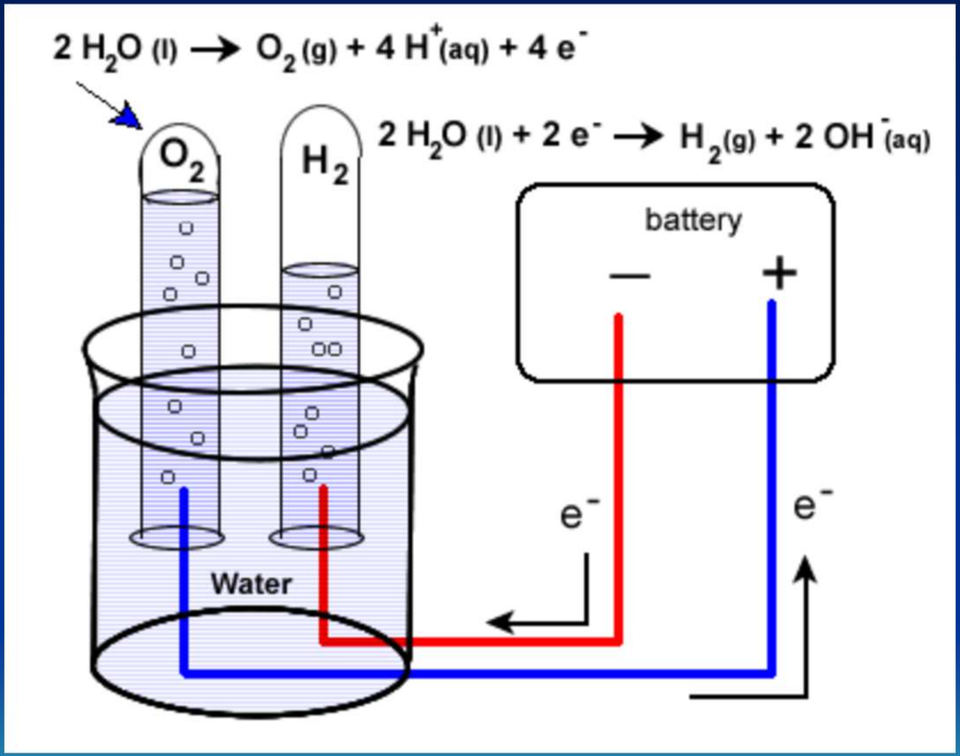
- In water-gas shift reaction
- Nanometer-thin sheets of metal carbide as catalyst
  - molybdenum
  - tungsten
  - cobalt



https://scitechdaily.com/researchers-use-gelatin-to-make-powerful-new-hydrogen-fuel-catalyst/

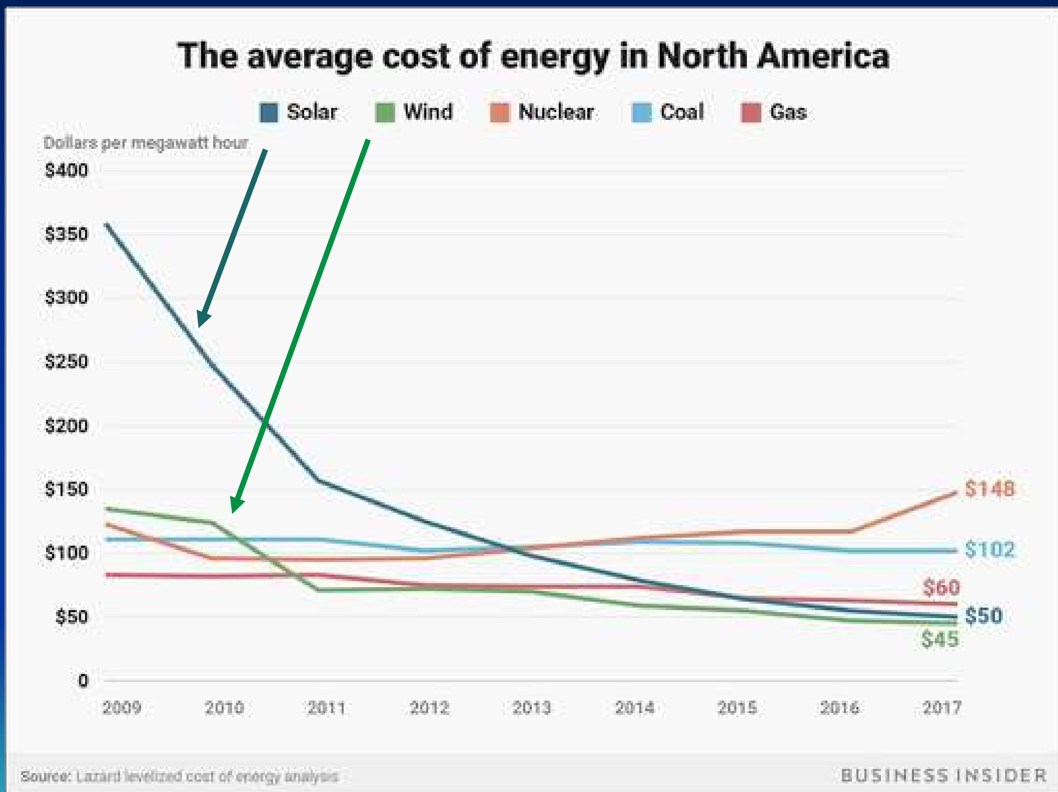
Co-authors on the study are Lujie Yang, Buxuan Li and Minsong Wei of UC Berkeley, J. Nathan Hohman and Chenhui Zhu of Lawrence Berkeley National Lab; Wenshu Chen and Jiajun Gu of Shanghai Jiao Tong University; Xiaolong Zou and Jiaming Liang of the Shenzhen Institute; and Mohan Sanghasadasa of the U.S. Army RDECOM AMRDEC

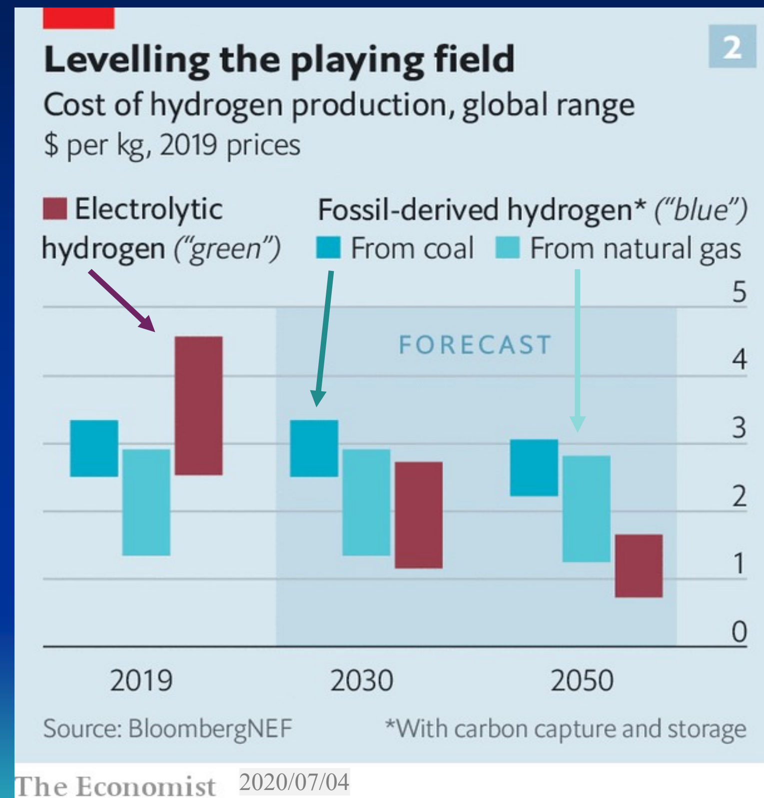
Electrolysis of Water

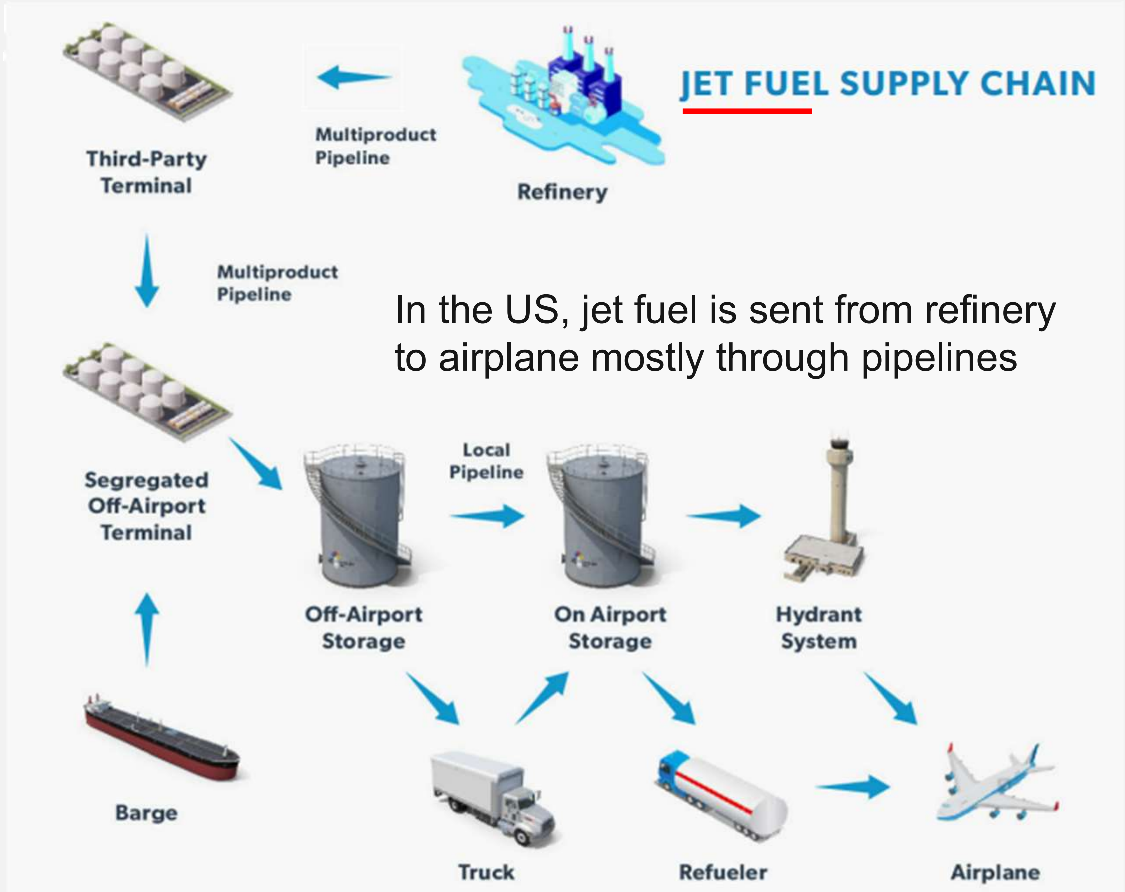


https://sites.prairiesouth.ca/legacy/chemistry/chem30/6_redox/redox3_3.htm

Electrolytic Hydrogen will get Cheaper







In the US, jet fuel is sent from refinery to airplane mostly through pipelines

https://www.airlines.org/wp-content/uploads/2018/01/jet-fuel-1.pdf

https://www.airlines.org/wp-content/uploads/2018/01/jet-fuel-1.pdf

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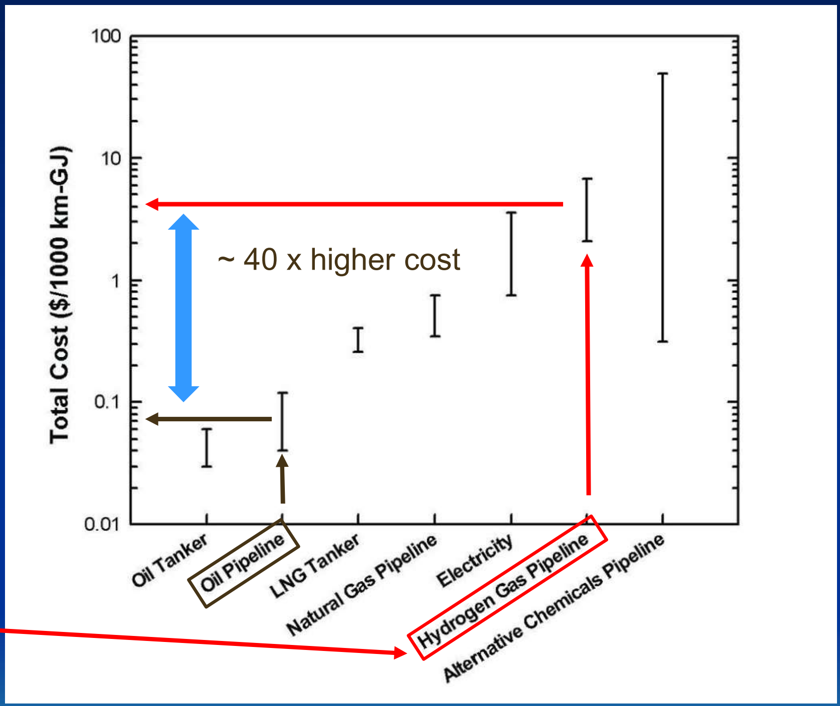
- Cost and energy of H_2 liquefaction
- No existing infrastructure



Can you use jet fuel pipelines for hydrogen?

- In theory, yes – but
  - If sent at low pressure above atmospheric, then it won't leak*, but energy flow rate is too small
  - If sent at high pressure above atmospheric, hydrogen is likely to leak
  - If sent as liquid, then pipes would have to be thermally insulated

*In the UK, "town gas" (used up until 1967)
made from coal was 50% H_2, 35% CH_4, 10% CO, 5% C_2H_4

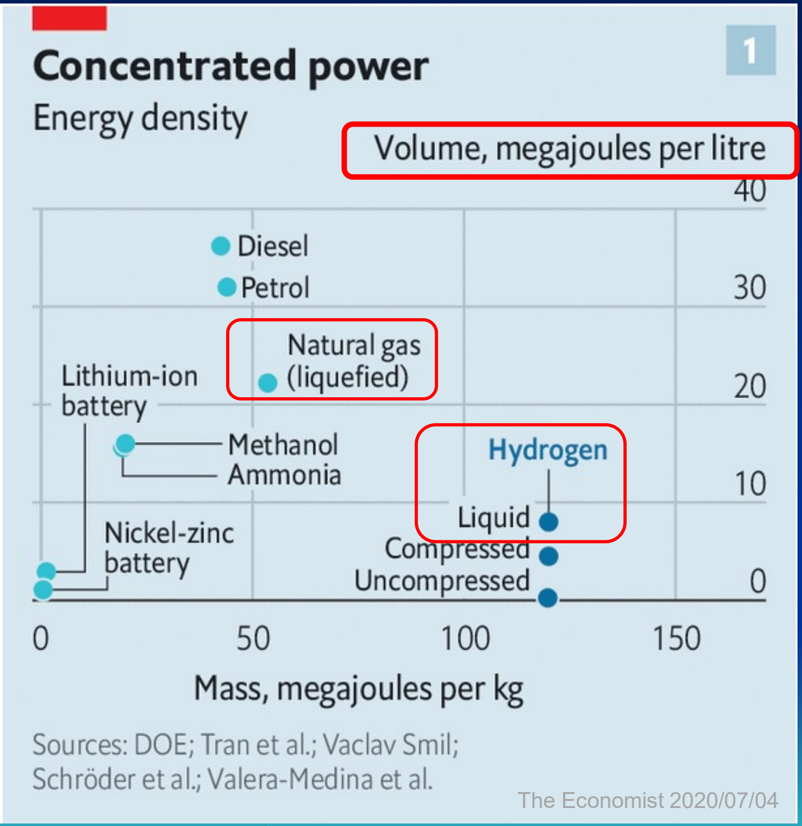
The Economist 2020/07/04

Hydrogen Transmission

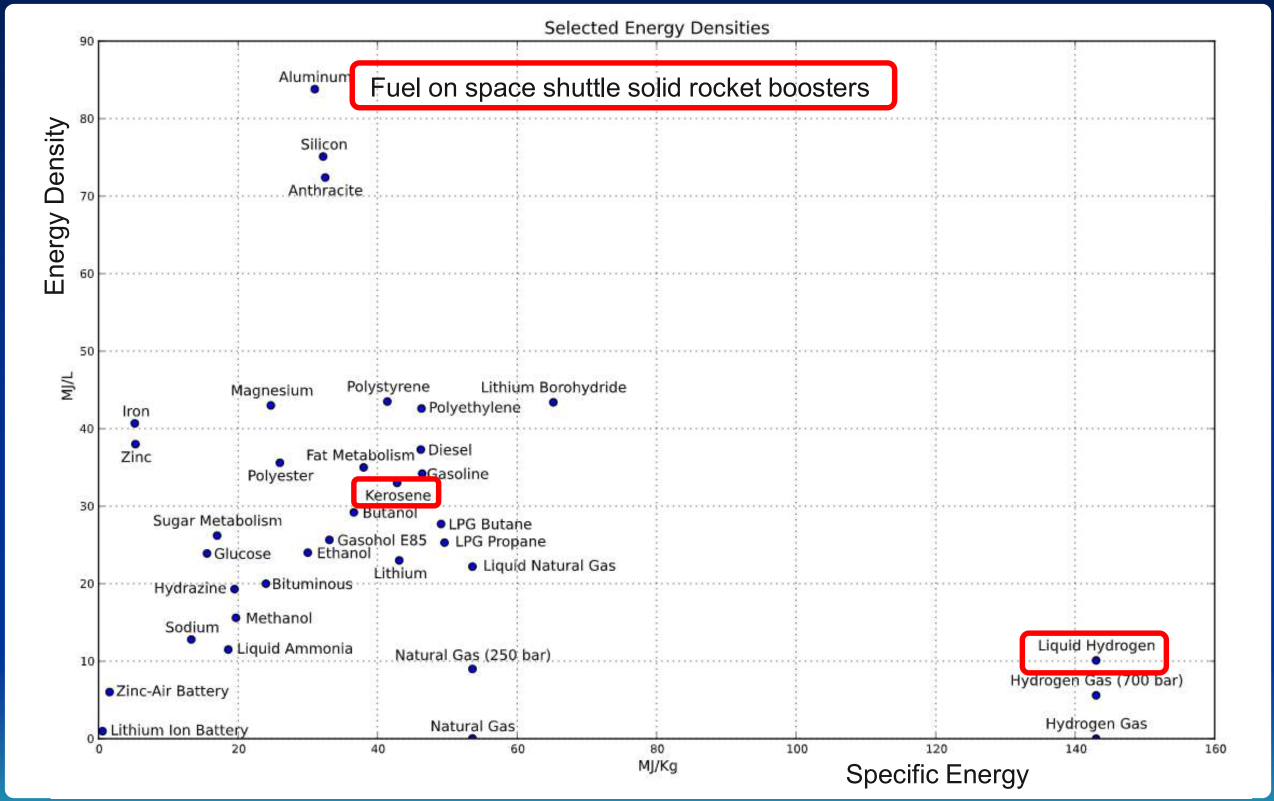
Even if liquified, for same flow velocity, energy flow rate (MJ/L x L/s)* is less than half that of LNG (but viscosity of LNG is higher than that of LH_2)

Probably better to produce H_2 locally using electrolysis

* watts

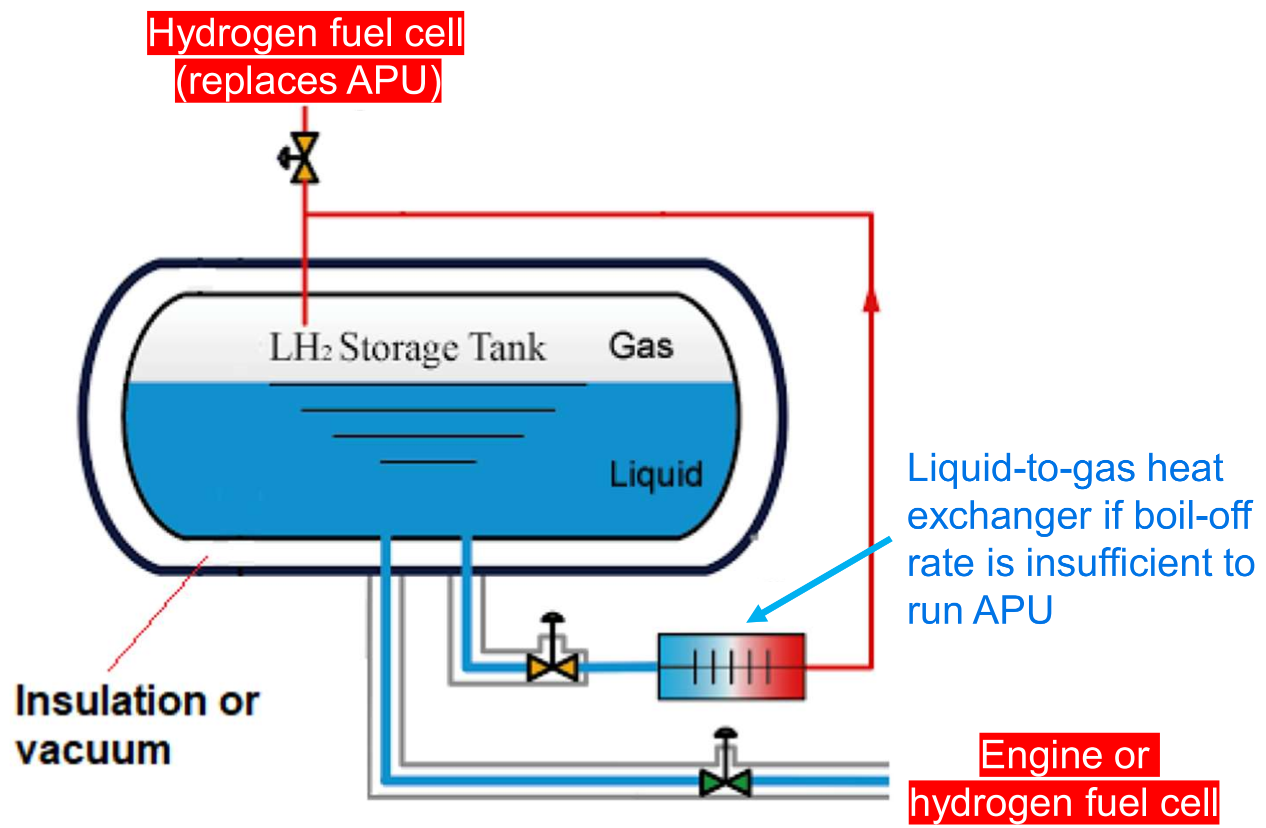


Energy Storage



https://en.wikipedia.org/wiki/Hydrogen-powered_aircraft

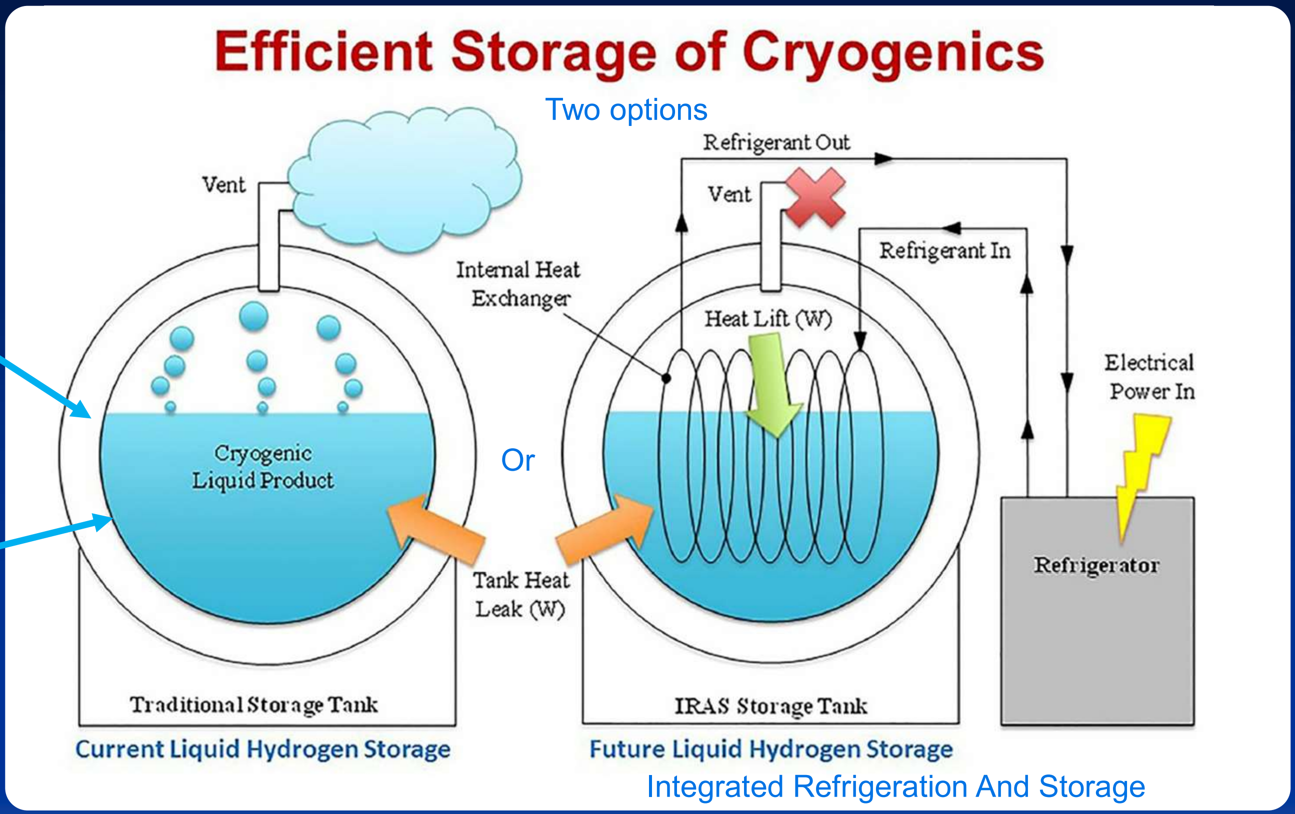
Typical Airplane LH_2 Tank



Vacuum and/or foam insulation

Aluminium tank

Maintain temp < 20K



IRAS system complexity and weight only pays off for missions > 15 hours

Reducing Distribution Cost

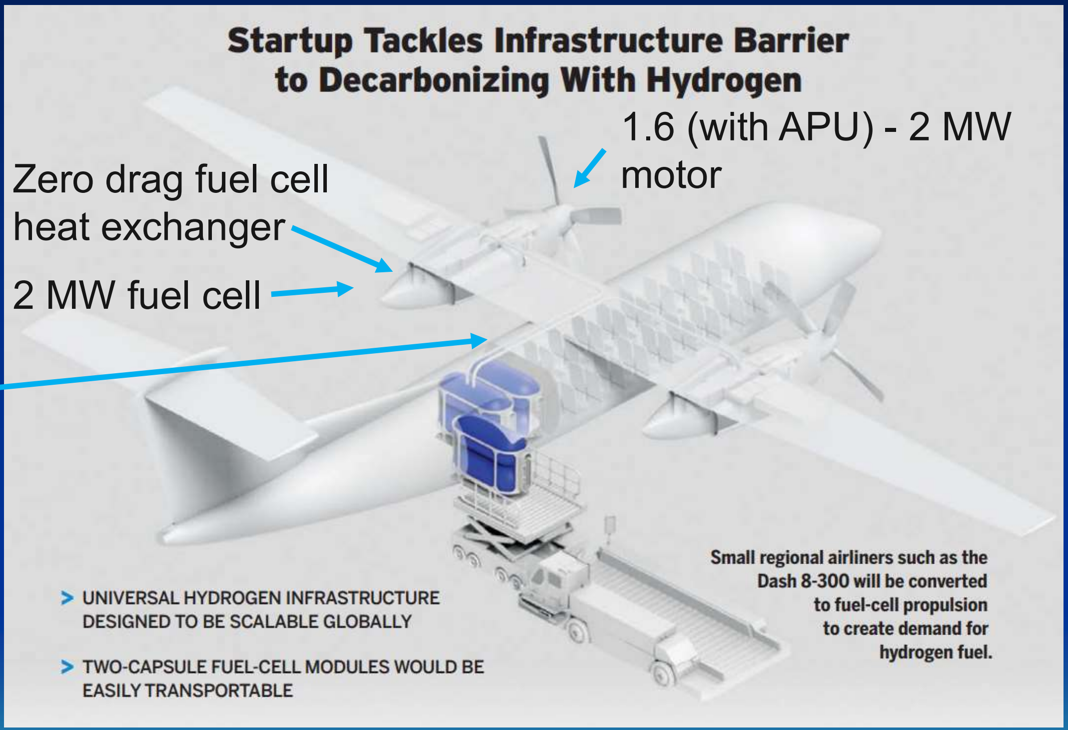
- 2020-09 Startup company Universal Hydrogen
  - 850 bar high pressure gas tanks, or
  - LH_2 tanks (40 hour dwell time between production and consumption)

Interchangeable gaseous or liquid-hydrogen capsules will be transported and stored on aircraft in easy-to-handle modules.

https://aviationweek.com/sites/default/files/2020-09/AWST_200914.pdf

Universal Hydrogen

- For Dash 8-300
  - 400 nmi range with gaseous H_2 tanks
  - 550 nmi range with LH_2 tanks
  - (Fleet average currently 300 nmi)
  - Fuel tank lines through dorsal fin, external to pressure hull
- Pax seats reduced from 50 to 40
- Maintenance costs 25% lower

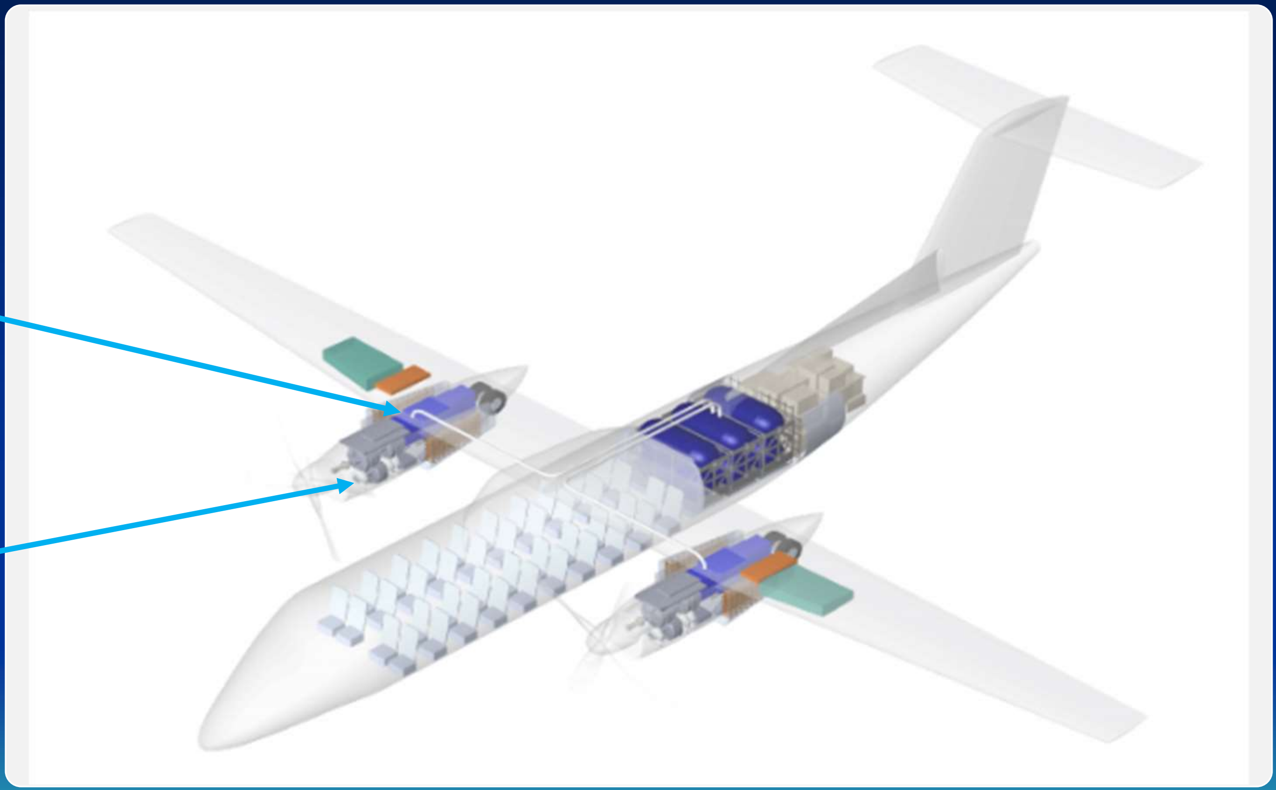


https://aviationweek.com/sites/default/files/2020-09/AWST_200914.pdf

Universal Hydrogen

Fuel cells by Plug Power

Electric motors by Magni-X



https://aerospaceamerica.aiaa.org/departments/hydrogen-evangelist/

H_2-powered Britten-Norman Islander

Low-cost application of H_2 propulsion

https://www.greencarcongress.com/2021/03/20210330-fresson.html

https://www.greencarcongress.com/2021/03/20210330-fresson.html

- Pods contain compressed H_2 tanks
- Fuel cells in rear of engine nacelles

- Project of Cranfield Aerospace
- First flight planned 2023
- Entry into service: early 2025

- Endurance: 1 hour, with 45 minutes reserves
- Projected use by Loganair (includes world's shortest scheduled flight of 1.5 minutes)

Scottish islands have cheap electricity for electrolysis of water, thanks to wind farms

Nacelles with Integrated Fuel Tanks

- Removable pods include
  - Propeller
  - Electric Motor
  - Power electronics
  - LH_2 tank
  - Cooling system
  - Auxiliary equipment

Source: Leeham Company LLL

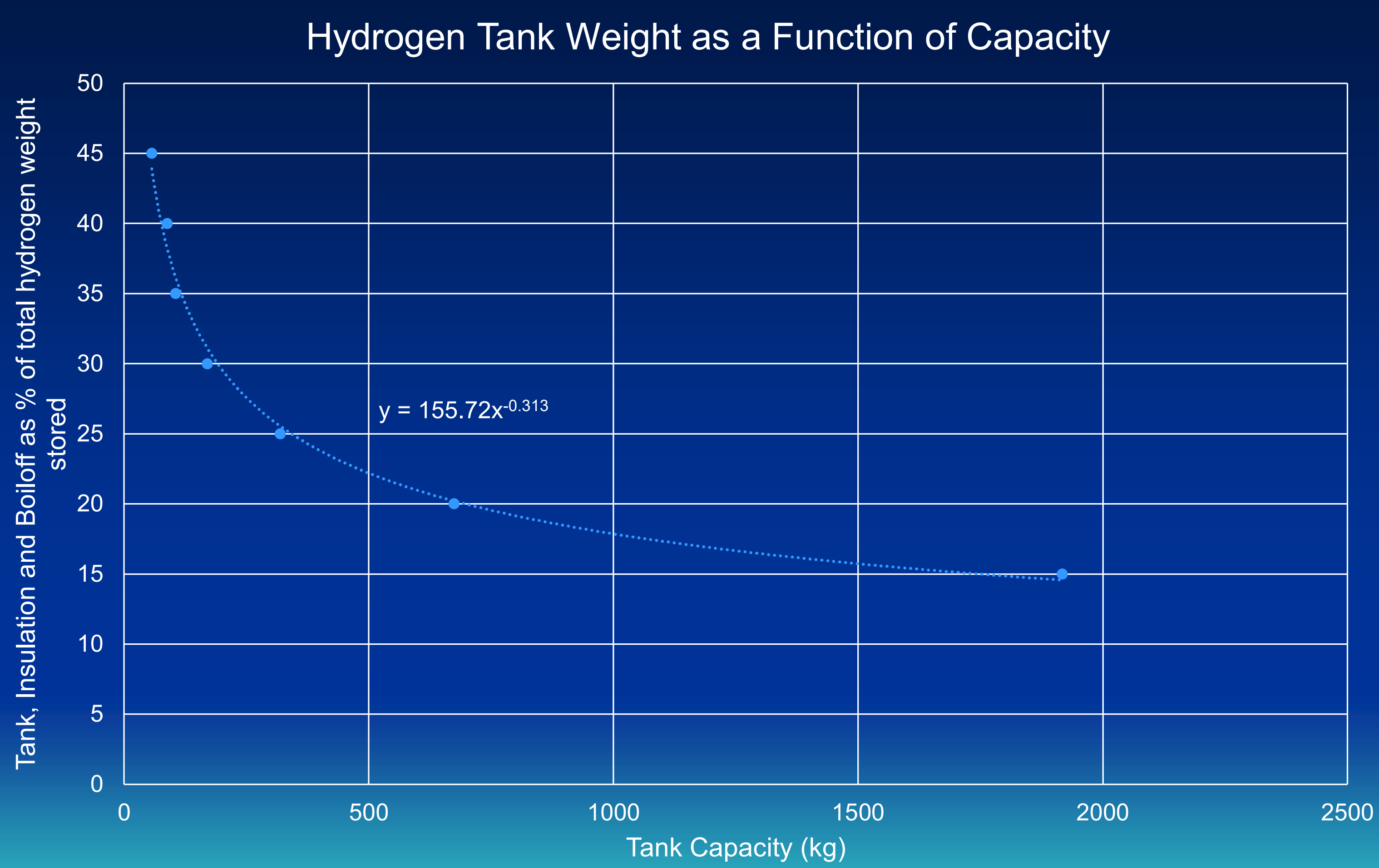
Comparative Weight Analysis – Nacelle Pods

For ATR72-600 80 seats, engines develop 4 MW at takeoff. Fuel needed for max range of 800 nmi is 2,000 kg with 500 kg reserves (all weights in table shown in kg, values from Bjorn Fehrm, with mods (in red), "The challenges of hydrogen, Part 30. Integrated Nacelles)"

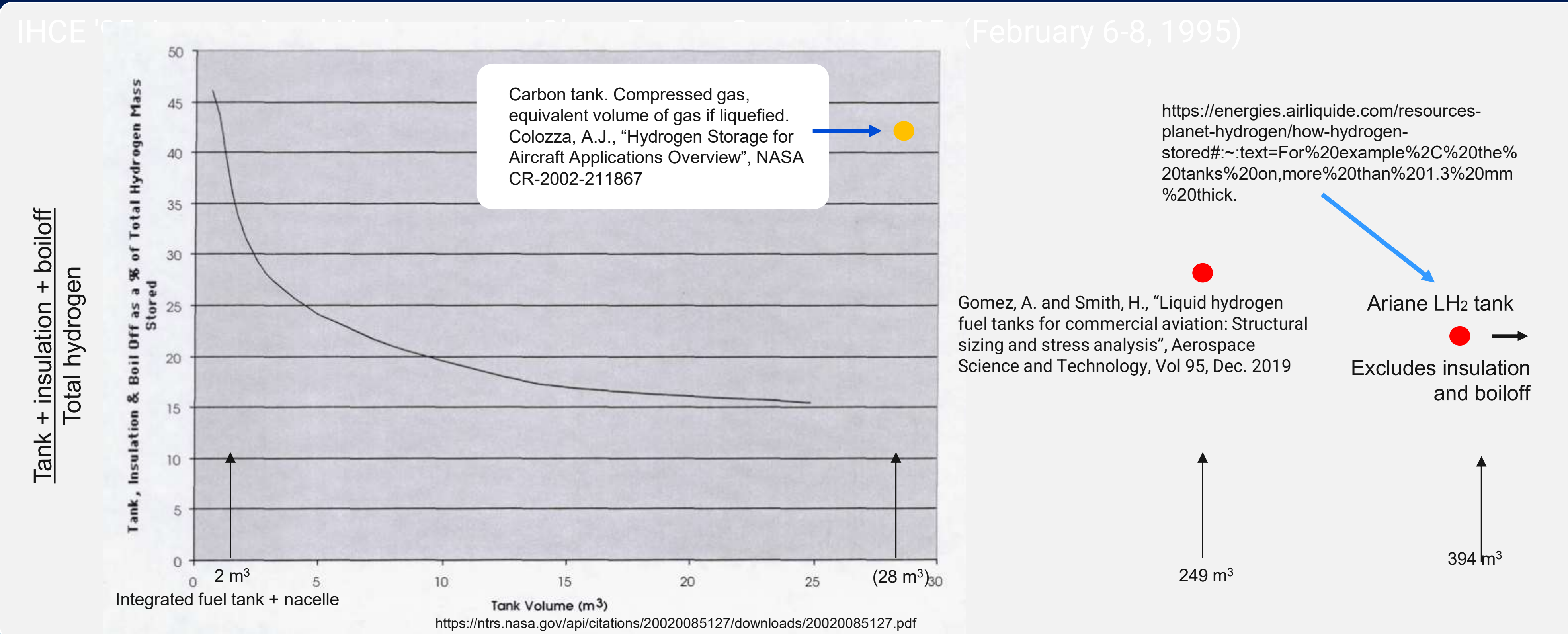
	Jet fuel	Burn LH_2	Fuel cell
Electric motor			300
Turboshaft	500	500	
Inverter			200
Fuel cell			2100
Fuel	2,500	850	700
Tanks		2400	2100
Tank sealing, pumps, valves	500	250	250
Total	**3,500**	**4,000**	**5,650**

Weight of tanks plus additional nacelle structure

For small tanks, maybe better to user compressed gaseous H_2


Hydrogen Tank Weight as a Function of Capacity
Tank, Insulation and Boiloff as % of total hydrogen weight stored
0
5
10
15
20
25
30
35
40
45
50
0
500
1000
1500
2000
2500
Tank Capacity (kg)
y = 155.72x-0.313

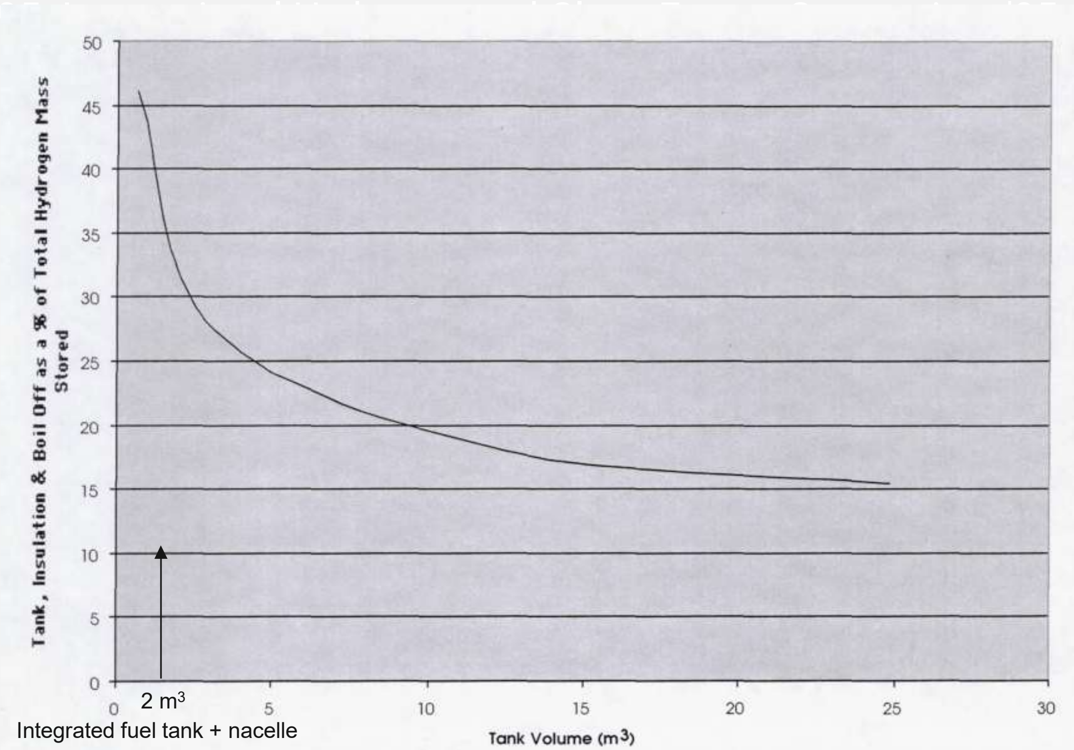
Square-Cube Law in effect



Square-Cube Law in effect

IHCE '95 … (February 6-8, 1995)

Tank + insulation + boiloff / Total hydrogen



Integrated fuel tank + nacelle

https://ntrs.nasa.gov/api/citations/20020085127/downloads/20020085127.pdf

https://energies.airliquide.com/resources-planet-hydrogen/how-hydrogen-stored#:~:text=For%20example%2C%20the%20tanks%20on,more%20than%201.3%20mm%20thick.

Gomez, A. and Smith, H., "Liquid hydrogen fuel tanks for commercial aviation: Structural sizing and stress analysis", Aerospace Science and Technology, Vol 95, Dec. 2019

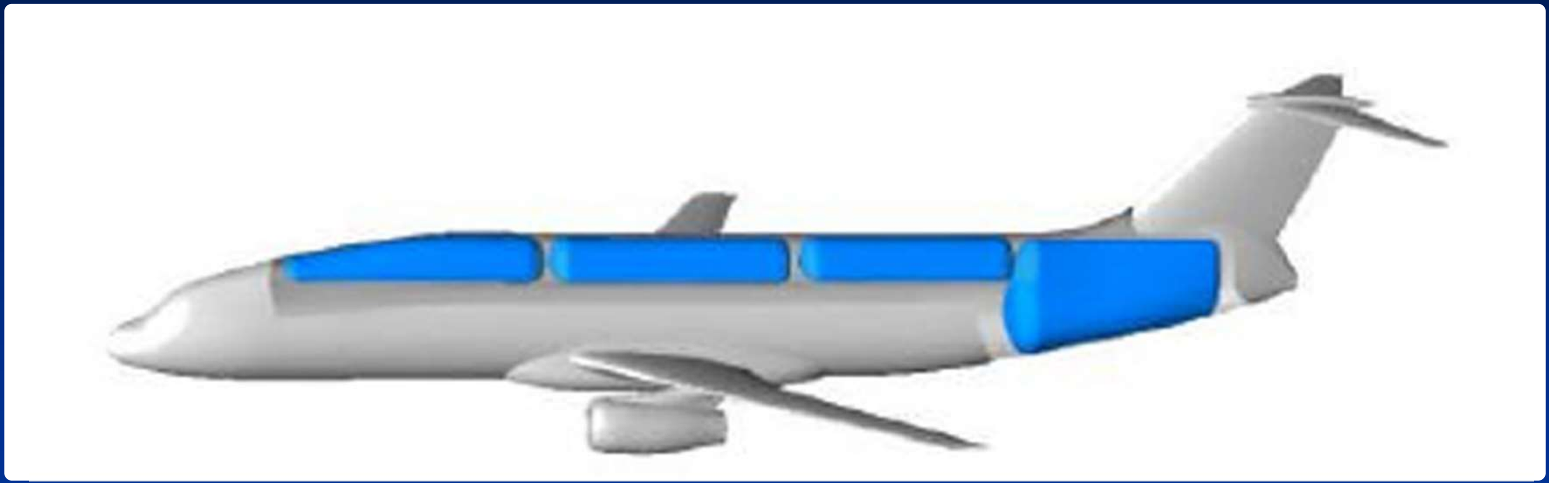
249 m^3

Ariane LH_2 tank

Excludes insulation and boiloff

394 m^3

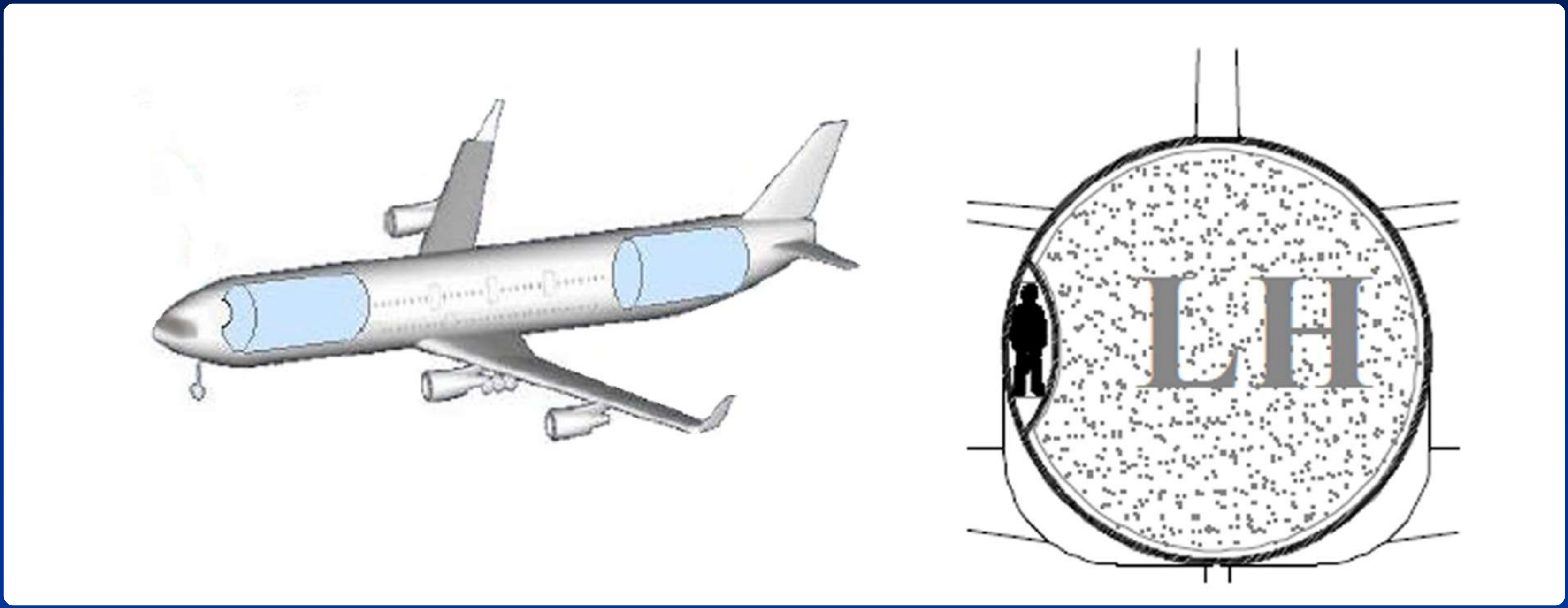
Tank Location – Short/Medium Range



© Leehamnews.com-Bjorns Corner The challenges of Hydrogen Pat 6 Tank placement.pdf

Combine aft tank with expanded fuselage crown

Tank Location – Long Range



Forward and aft tanks with passageway for flight deck crew

Tank Location – Short Haul

For relatively low fuel fraction, ok to put tanks in aft location

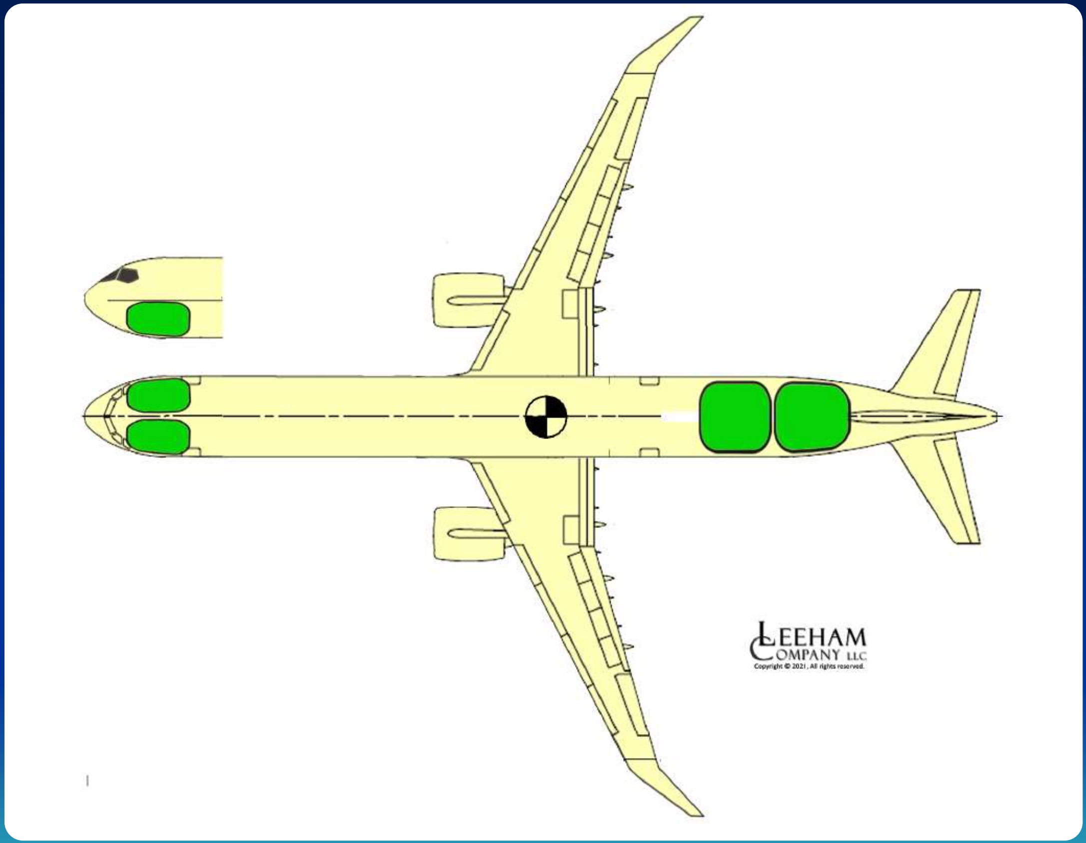
Empty tank is still quite heavy, so wing must be moved aft to rebalance

Airbus ZEROe Program

Credit: Airbus

Reducing CG Travel

- Total fuel load of 4.1 t
- 1/3 of fuel in cheek tanks
- Moment arms of forward and aft tanks about aircraft CG are approximately equal
- Move nose landing gear forward under weather radar
- Move avionics bay to cockpit crown

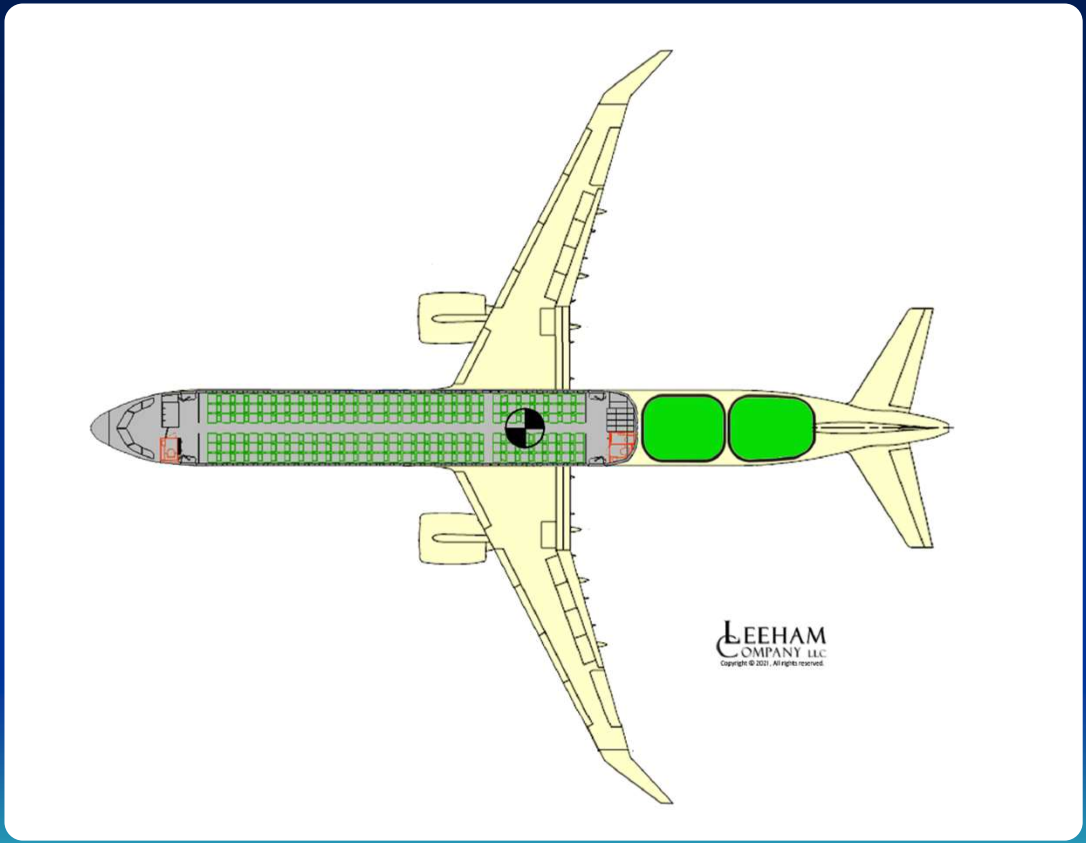


Source: © Leeham Company LLC

LH$_2$-powered A-320

6-abreast, single aisle
160 seats, high density

Assume typical 800 nm flight segment

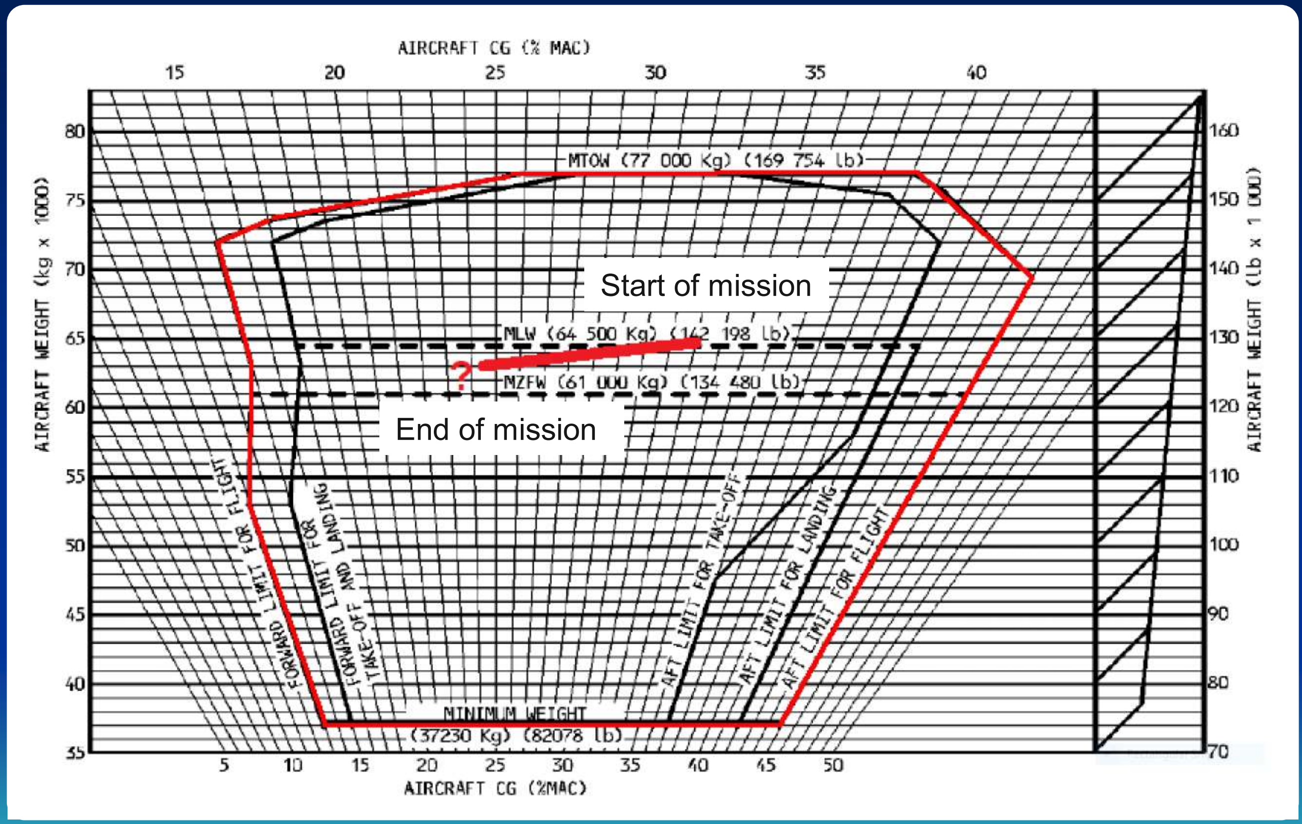


Source: © Leeham Company LLC

LH$_2$-powered A-320 c.g. travel

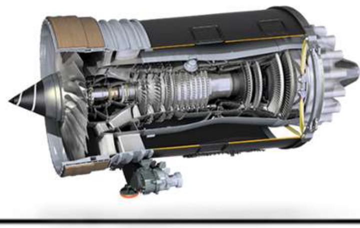
- Direct combustion of H_2
- C.g. envelope for A320 →
- Assume 800 nmi stage length
- From forward tank, assume 1.4 t of LH$_2$ consumed during flight
- Assume c.g. at 33% MAC at start of flight
- C.g. moves forward as fuel is burned
  - Increases trim drag

Source: leehamnews.com – Bjorn's Corner
"The Challenges of Hydrogen Part 18"



Credit: Airbus

Comparative SFC of Kerosene and Hydrogen



Rolls-Royce BR710-48

	Value			
	SLS, ISA+10C		Cruise (11 km, $M_0 = 0.8$), ISA	
	Kerosene	Hydrogen	Kerosene	Hydrogen
F_n (kN)	66.28	66.28	8.67	8.67
SFC (g/kN s)	11.273	3.979	17.910	6.365
W_2 (kg/s)	197.00	197.00	70.16	70.11
W_{fuel} (kg/s)	0.747	0.264	0.155	0.055
TET (K)	1507.9	1470.9	1103.7	1089.5
SEC (kJ/kN s)	485.88	477.46	772.02	763.81
SFC_{CH}/SFC_{H_2}	2.833		2.814	
SEC_{CH}/SEC_{H_2}	1.018		1.011	
$(SFC_{CH} - SFC_{H_2})/SFC_{CH}$ (%)	64.71		64.71	
$(W_{fuel\ CH} - W_{fuel\ H_2})/W_{fuel\ CH}$ (%)	64.71		64.71	
$(SEC_{CH} - SEC_{H_2})/SEC_{CH}$ (%)	1.73		1.06	

Corchero, G. and Montanes, “An approach to the use of hydrogen for commercial aircraft engines” Universidad Politecnica de Madrid

https://oa.upm.es/5938/1/Monta%C3%B1ez_07.pdf

Safety of Hydrogen vs. JP-8

For most issues of practical importance, hydrogen is safer than JP-8

Source: Reiman, A.D., "AMC's Hydrogen Future: Sustainable Air Mobility", Air Force Institute of Technology, AFIT/IMO/ENS/09-13, June 2009

Hydrogen vs JP-8

Safety

Item	Information	Advantage
Detonation	Gun shot tests into liquid hydrogen tanks failed to result in detonation. Heavy impact tests of liquid hydrogen tanks failed to result in detonation. Detonation of a perfect mixture of hydrogen and air only takes place with a strong detonator, but it is improbable that a perfect mixture of hydrogen and air will occur at the time of a strong detonation. JP-8 has a lower detonability limit in air as a percentage of volume than hydrogen. (Brewer, 1991)	Hydrogen
Emissivity	Hydrogen has a lower emissivity than JP-8 making the thermal radiation during a fire less. If a large hydrogen spill occurs outside an aircraft, remain inside for the heat will not be likely to enter the fuselage due to the low emissivity. (Brewer, 1991)	Hydrogen
Frost Bite	Contact with minute amounts of liquid hydrogen can lead to severe frost bite, while JP-8 poses no frostbite hazard. (Praxair, 2007)	JP-8
Fuel Spills	Hydrogen evaporates much more rapidly than JP-8 and if ignited burns quicker than JP-8. A 12,600 kg hydrogen fuel spill will dissipate in 32 seconds, while a similar volume of JP-8 would take closer to 13 minutes. (Brewer, 1990)	Hydrogen
Ignition Temperature	Hydrogen has a higher autoignition temperature than JP-8, but a lower temperature in an air mixture. A lit cigarette will not ignite in pure hydrogen although it could light a hydrogen-air mixture. A lit cigarette could ignite JP-8. (Brewer, 1991)	JP-8
Invisible Flame	Hydrogen can be a burn hazard due to invisible flame, while JP-8 has a visible flame. (Praxair, 2007)	JP-8
Suffocation	The high diffusion rate of hydrogen can rapidly replace the oxygen in an unventilated room leading to possible suffocation, while JP-8 poses a lesser suffocation hazard. (Praxair, 2007)	JP-8
Toxicity	JP-8 is a liver toxin, kidney toxin, nerve toxin, blood toxin, lung aspiration hazard and a reproductive fetotoxin, while hydrogen is not toxic. (Dfdl, 2001).	Hydrogen

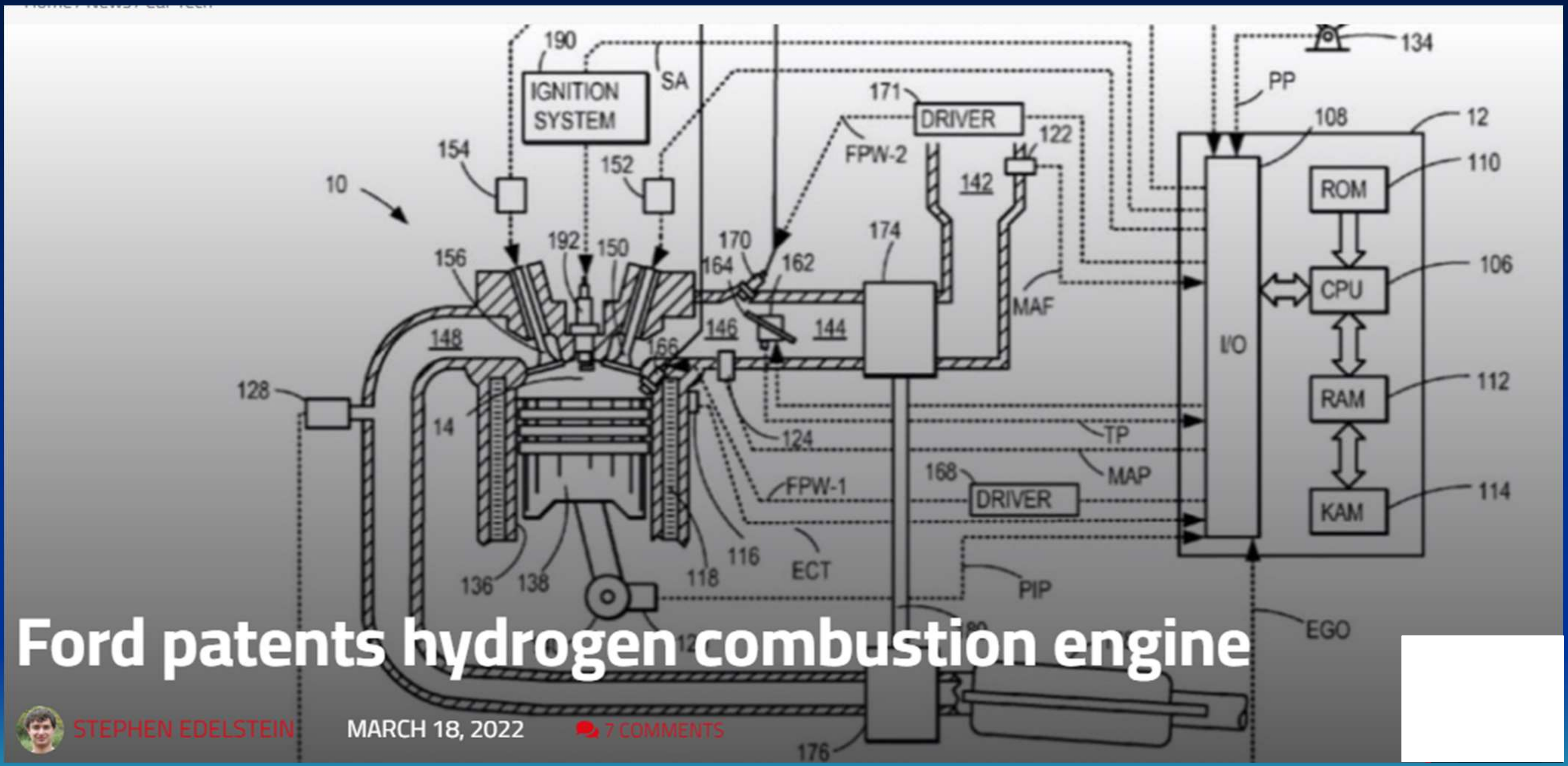
- Need for Zero-Carbon Economy
- Hydrogen vs. Batteries
- History of Hydrogen-powered Propulsion
- Hydrogen Generation, Distribution and Storage
- Applications of Hydrogen Energy
- The Future of Hydrogen
- Conclusions

- Applications of Hydrogen Energy
  - Burn it directly with atmospheric O_2 (or LO_2) (rocket, gas turbine, or reciprocating engine)
  - Combine it with atmospheric O_2 (or LO_2) in fuel cell to generate electricity
  - Hybrid of direct burn and fuel cell
  - Hybrid of battery and fuel cell

Boeing Phantom Eye

Source: ainonline.com

- LH_2 fuel
- 2 x Ford 2.3 litre gasoline engines
- Multiple turbochargers
- First flight June 2012
- Program terminated Aug 2016
- Claimed performance up to 4 days at up to 65,000 ft
- Payload 450 lb
- Cruise speed 150 kt
- Possibility did not meet performance goals

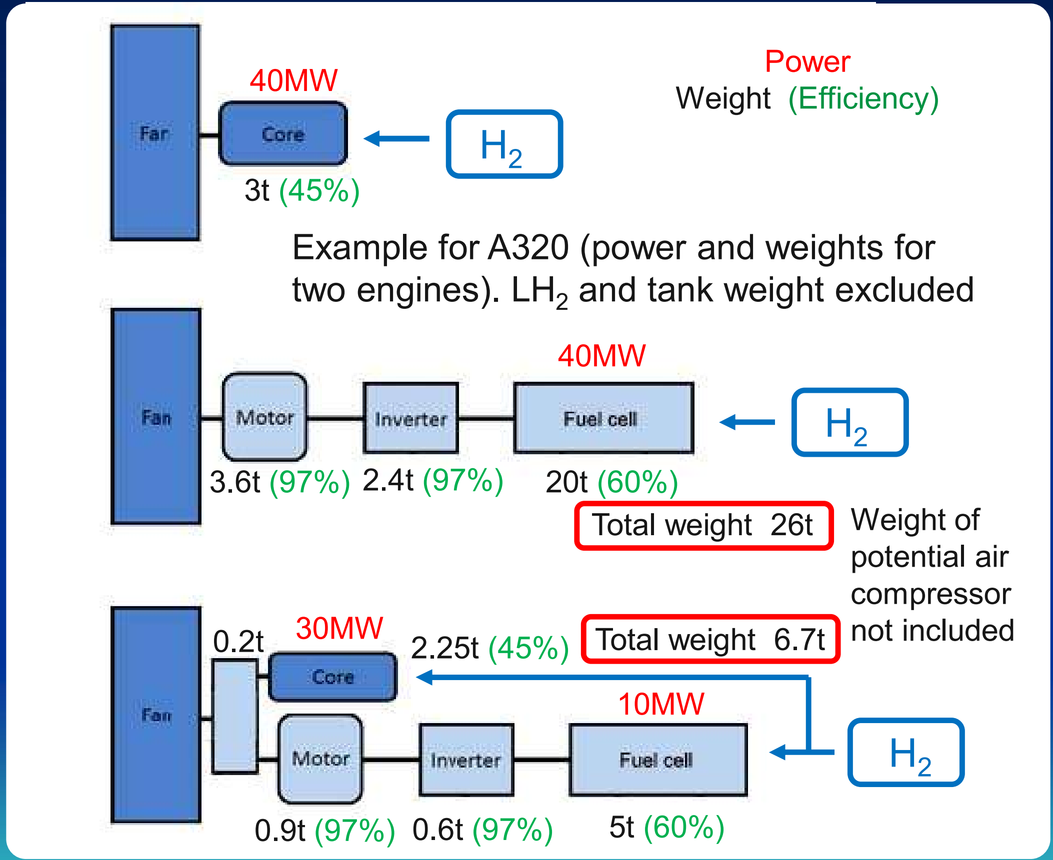

Home / News / Car Tech
IGNITION SYSTEM
DRIVER
DRIVER
I/O
ROM
CPU
RAM
KAM
Ford patents hydrogen combustion engine
STEPHEN EDELSTEIN
MARCH 18, 2022
7 COMMENTS

H_2 Turbofan Options – Current Technology

Direct combustion of H_2 in conventional gas turbine

Combine H_2 with atmospheric O_2 in fuel cells to generate electrical power (maybe works for very long range)

Size electric power train for cruise, size core for extra power at takeoff



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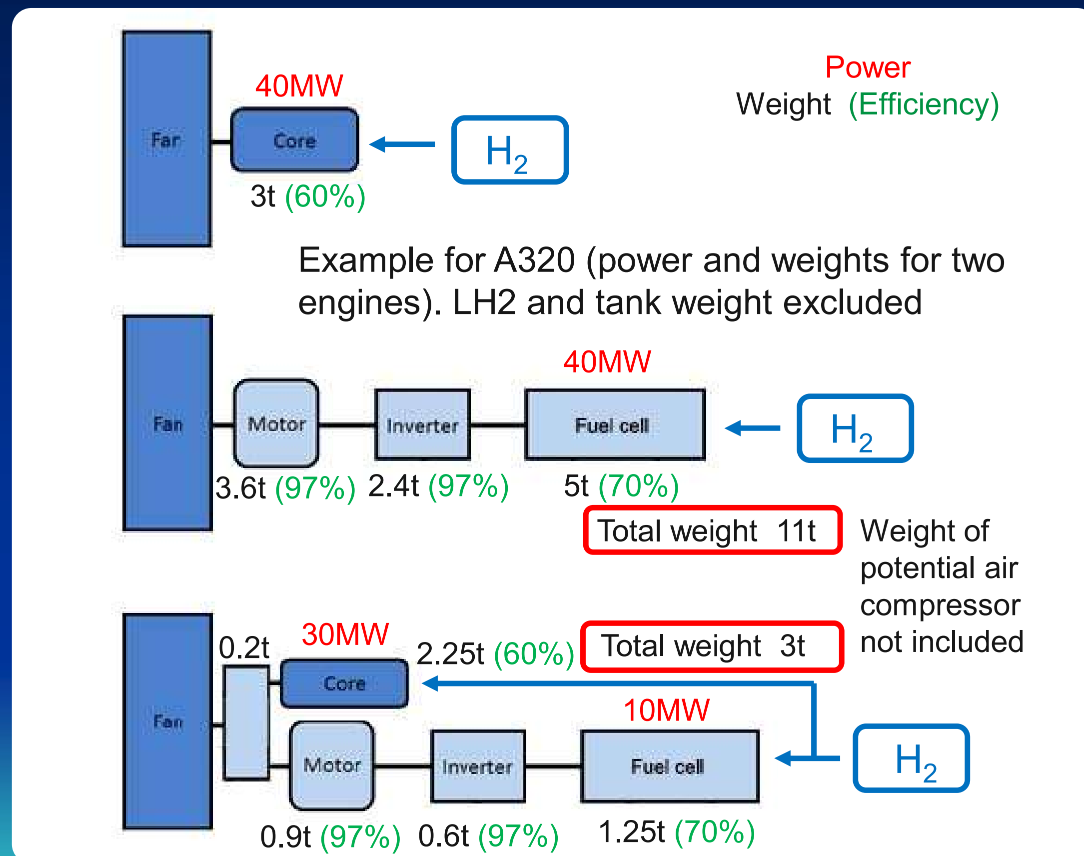
H_2 Propulsion Options – Future Technology

Direct combustion of H_2 in conventional gas turbine

Combine H_2 with atmospheric O_2 in fuel cells to generate electrical power

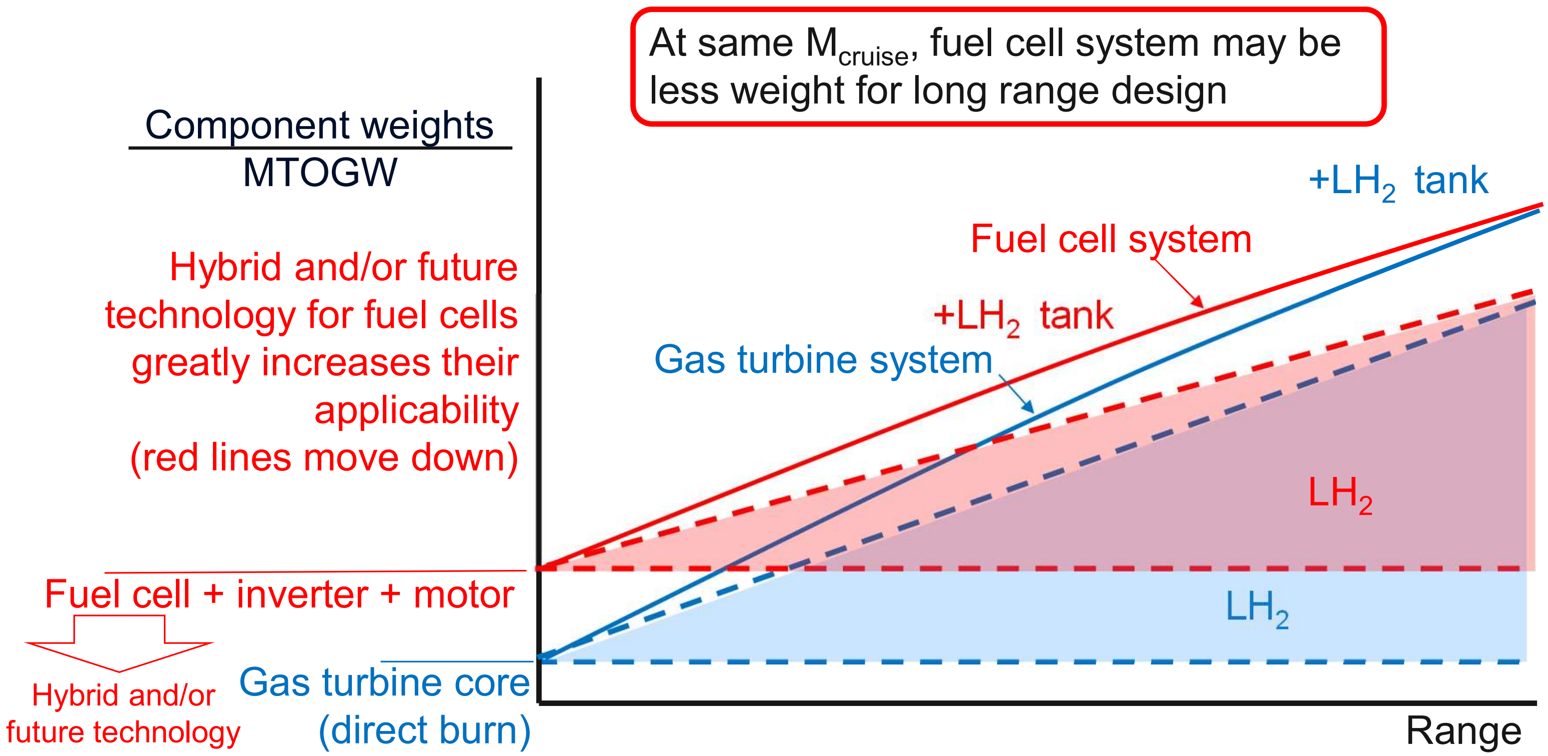
(maybe best for very long range)

Size electric power train for cruise, size core for extra power at takeoff



Fuel cell kW/kg from Kadyk, et al., "Analysis and Design of Fuel Cell Systems for Aviation", Energies 2018,11,375, 6 Feb 2018

Jet Propulsion Relative Weights



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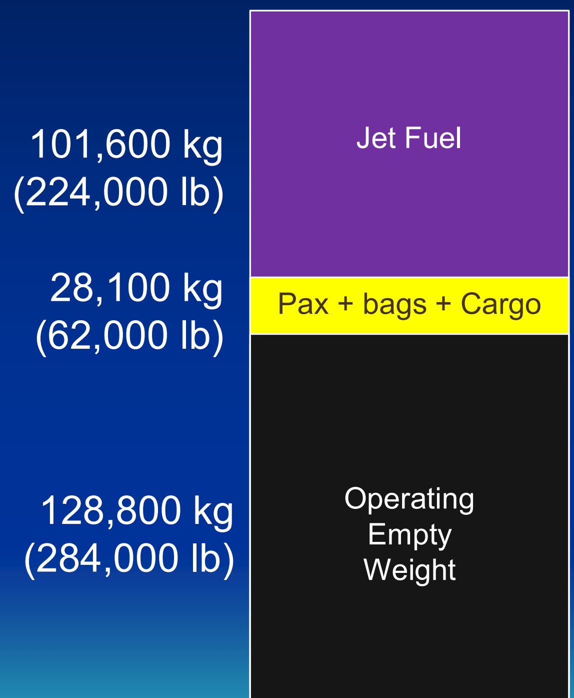
  - Burn it directly with atmospheric O_2 (or LO_2) (rocket, gas turbine, or reciprocating engine)
  - Combine it with atmospheric O_2 (or LO_2) in fuel cell to generate electricity
  - Hybrid of direct burn and fuel cell
  - Hybrid of battery and fuel cell

Boeing 787-9 Typical Long Stage Length Weight Breakdown

Takeoff Gross Weight =
254,000 kg (560,000 lb)



LAX – SIN is 14,000 km (7,560 n mi)
Scheduled block time: 17 hr 55 min

LH_2-powered Airbus A310

- 2000-2002 study by consortium led by Airbus
- Larger wetted area: energy consumption increases 9% -12%
- OWE increases ~ 23%
- MTOGW varies from –ve 14.8% to +ve 4.4% depending on config.
- Increase in DOC of 4%-5% due to fuel only
- No fundamental technical roadblocks

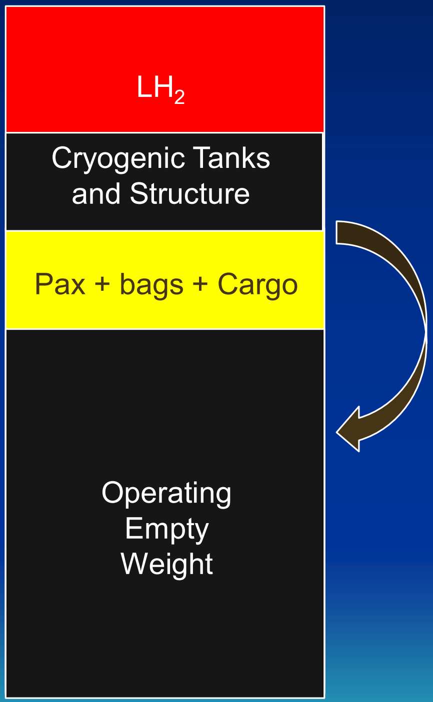
http://planetforlife.com/h2/h2vehicle.html

Airbus A310 H_2 Cryoplane Concept

LH_2-powered Airbus A310

- Trade reduced LH_2 weight for increased cryogenic tank and structural weight
- Not so much change in weight on long range flights

http://planetforlife.com/h2/h2vehicle.html



LH$_2$-powered Dornier 328JET

https://en.wikipedia.org/wiki/Fairchild_Dornier_328JET#/media/File:Tyrolean_Jet_Services_Do-328-300_OE-HTJ.jpg

https://leehamnews.com/2020/02/07/bjorns-corner-why-e-in-eplane-shall-stand-for-environment-part-8/#more-32511

- Do-328JET first flight on 1998-01-20
  - Jet-fuelled turbofans
- Only 110 aircraft manufactured

- DASA* study in 1995
- Direct burn of LH$_2$ in modified turbofans

*DASA = merger of Daimler-Benz + Messerschmitt-Bölkow-Blom + MTU

Hydrogen-Powered Dornier 328 Secures German Funding

April 05, 2022

DLR-led project will fly a Dornier 328 modified with a hydrogen hybrid-electric propulsion system.
Credit: DLR

https://aviationweek.com/air-transport/aircraft-propulsion/hydrogen-powered-dornier-328-secures-german-funding

Direct Combustion

- Generates NO_x
- Generates more water vapor than jet fuel

Source: www.aero-news.net

Burn vaporized LH_2 in jet engines using atmospheric O_2

EU Clean Sky Program

- Clean Sky 2 started in 2014
  - Goal 20-30% reduction in CO_2 with TRL 6 in 2024
  - €4 billion ($4.5 billion)
  - E.g. – Breakthrough Laminar Aircraft Demonstrator in Europe (BLADE) (> 60 flight hours) →
- Clean Sky 3 goal is 80% reduction in CO_2 by 2050
  - Budget not yet set
  - Entry into service 2030-35
  - Reach TRL 6 by 2025-27

Credit: Airbus/S. Ramadier


ZEROe Hydrogen combustion demonstrator
A380 multimodal test platform
with its capacity to store large hydrogen tanks
Hydrogen combustion engine
located along the rear fuselage
4 liquid hydrogen tanks
stored in a caudal position
Liquid hydrogen distribution system
flightlab
ZEROe demonstrator
AIRBUS

- CFM (GE + Safran) will modify GE Passport engine
  - 79-84 kN thrust
  - OPR 45
  - BPR 5.6
  - Twin shaft
- 4 x 100 kg tanks of LH_2

FlyZero – Direct Burn Test Requirements

Major tests

Hydrogen gas turbine architectures are applicable to all market segments considered in FlyZero: regional, narrowbody and midsize.

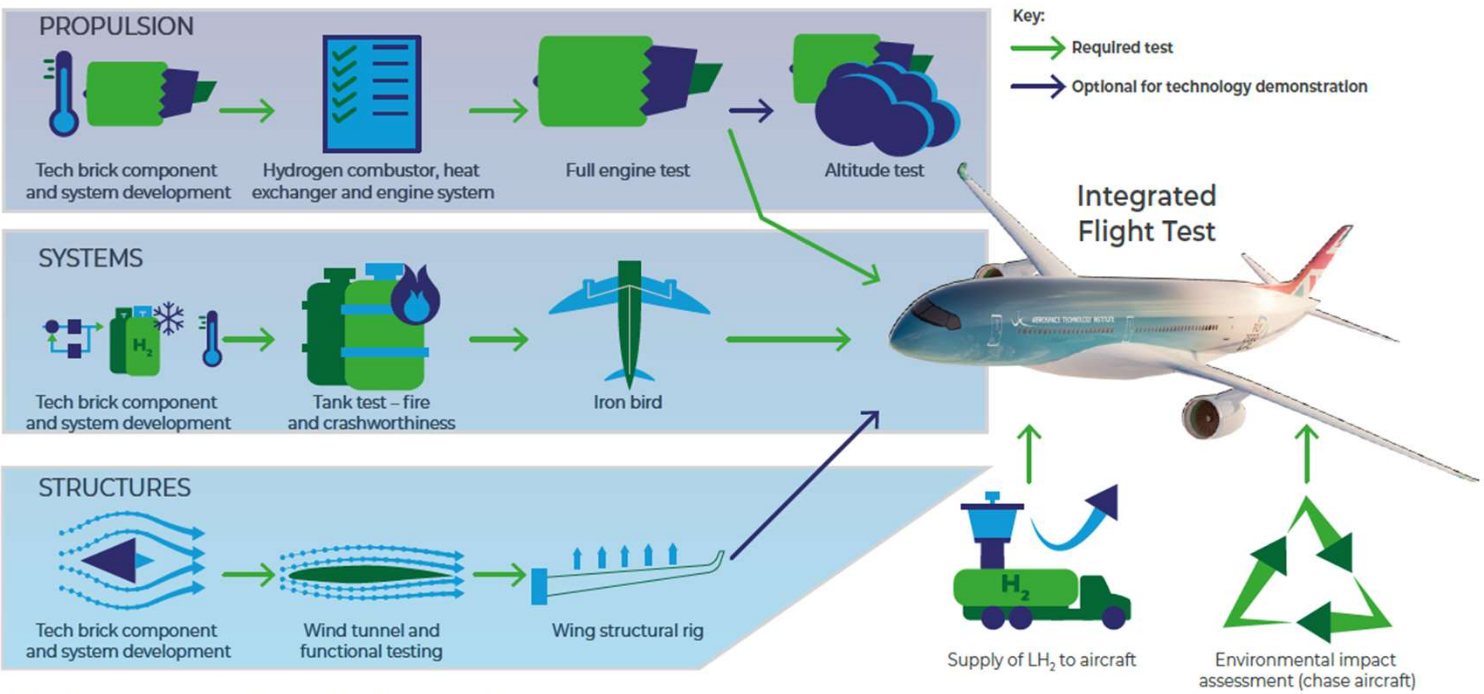


Figure 9 – Hydrogen gas turbine aircraft architecture - major tests.

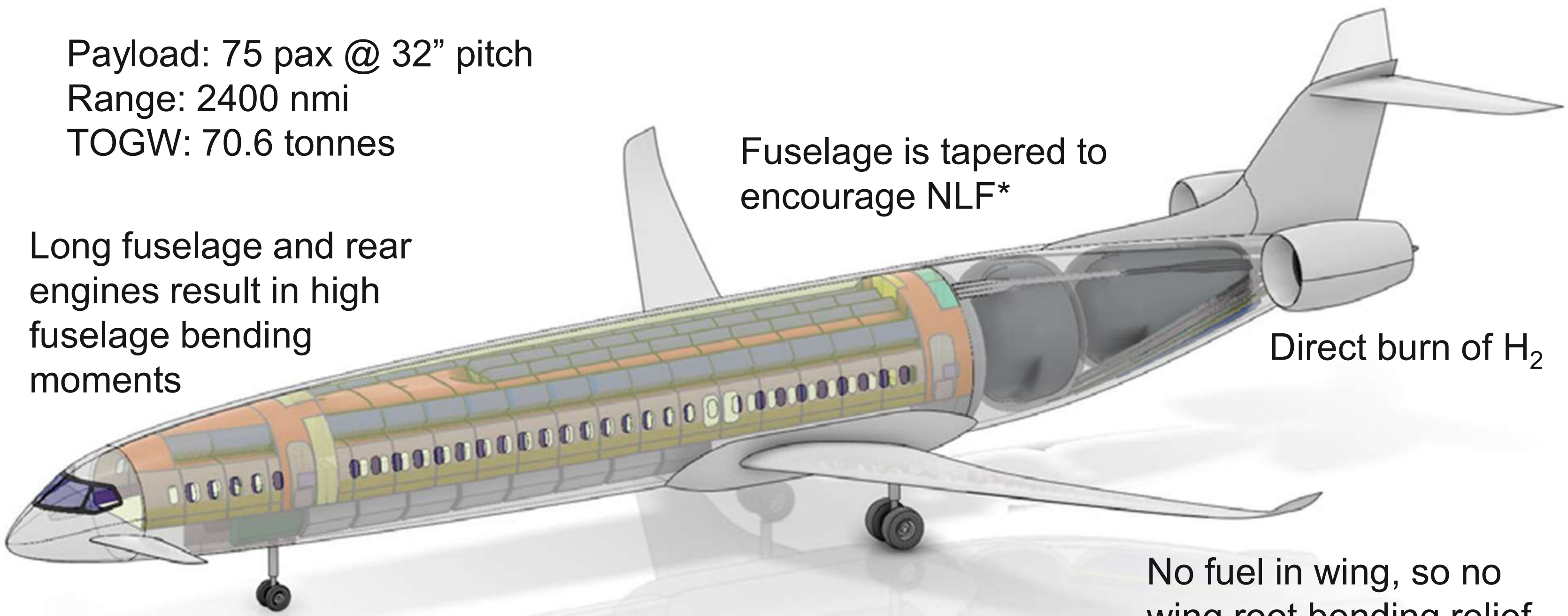
FlyZero – A320 Replacement

*NASA report CR3970 ‘Design of Fuselage Shapes for Natural Laminar Flow‘

Payload: 75 pax @ 32” pitch
Range: 2400 nmi
TOGW: 70.6 tonnes

Long fuselage and rear engines result in high fuselage bending moments

Fuselage is tapered to encourage NLF*



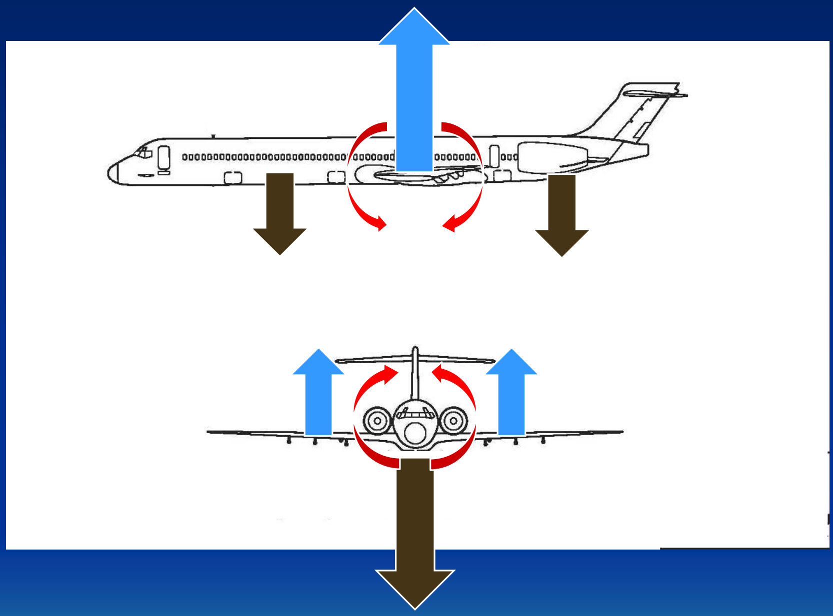
Direct burn of H_2

No fuel in wing, so no wing root bending relief

https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIN-REP-0007-FlyZero-Zero-Carbon-Emission-Aircraft-Concepts.pdf

Fuselage And Wing Root Bending

- Engines mounted on rear fuselage induce additional wing and fuselage bending
- Made worse by
  - Stretched fuselage
  - Heavier engines



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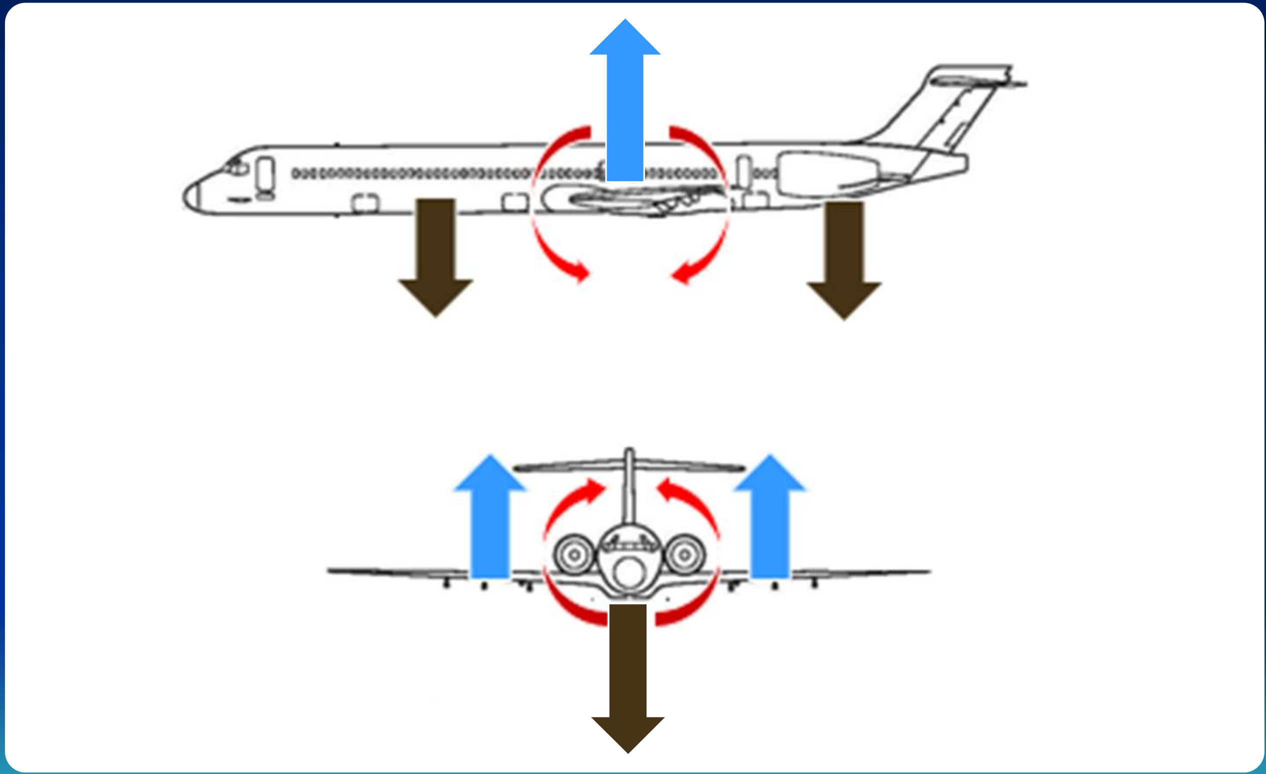

- Number of DC-9s and MD-80s still operating ~ 126
- Number of 737 and A320s operating ~ 11,000

FlyZero – A320 Replacement

Narrowbody Aircraft Mission Data		Reference A320neo	Baseline A320-2030	Concept FZN-1E
Fuel Type		Jet A-1	SAF	LH_2
Payload	No. of Pax @ seat pitch (in.)	180 @ 32"	180 @ 32"	180 @ 32"
	Cargo (kg)	-	-	-
	Total Payload (kg)	19,400	18,795	18,795
Max. Take-Off Weight (MTOW) (tonnes)		79.0	70.6	70.7
Operating Empty Weight (tonnes)		44.9	41.5	48.0
Design Mission	Range (nmi)	2,495	2,400	2,400
	Total Mission Fuel Mass inc. reserves (kg)	14,753	10,312	3,903
	Block Time (hrs)	6.0	5.8	5.8
	Block Fuel Mass (kg)	12,184	8,439	3,283
	Block Fuel Energy (MJ)	523,912	388,194	374,262
	Energy Intensity (MJ/ASNM)	1.13	0.899	0.866
Typical Mission	Range (nmi)	850	850	850
	Total Mission Fuel Mass inc. reserves (kg)	6,638	4,902	1,800
	Block Time (hrs)	2.4	2.4	2.4
	Block Fuel Mass (kg)	4,306	3,187	1,241
	Block Fuel Energy (MJ)	185,158	146,602	141,747
	Energy Intensity (MJ/ASNM)	1.17	0.96	0.92

Fuel fraction
3.903/70.7
= 0.055

FlyZero – A320 Replacement

Narrowbody Aircraft Mission Data		Reference A320neo	Baseline A320-2030	Concept FZN-1E
Fuel Type		Jet A-1	SAF	LH_2
Payload	No. of Pax @ seat pitch (in.)	180 @ 32"	180 @ 32"	180 @ 32"
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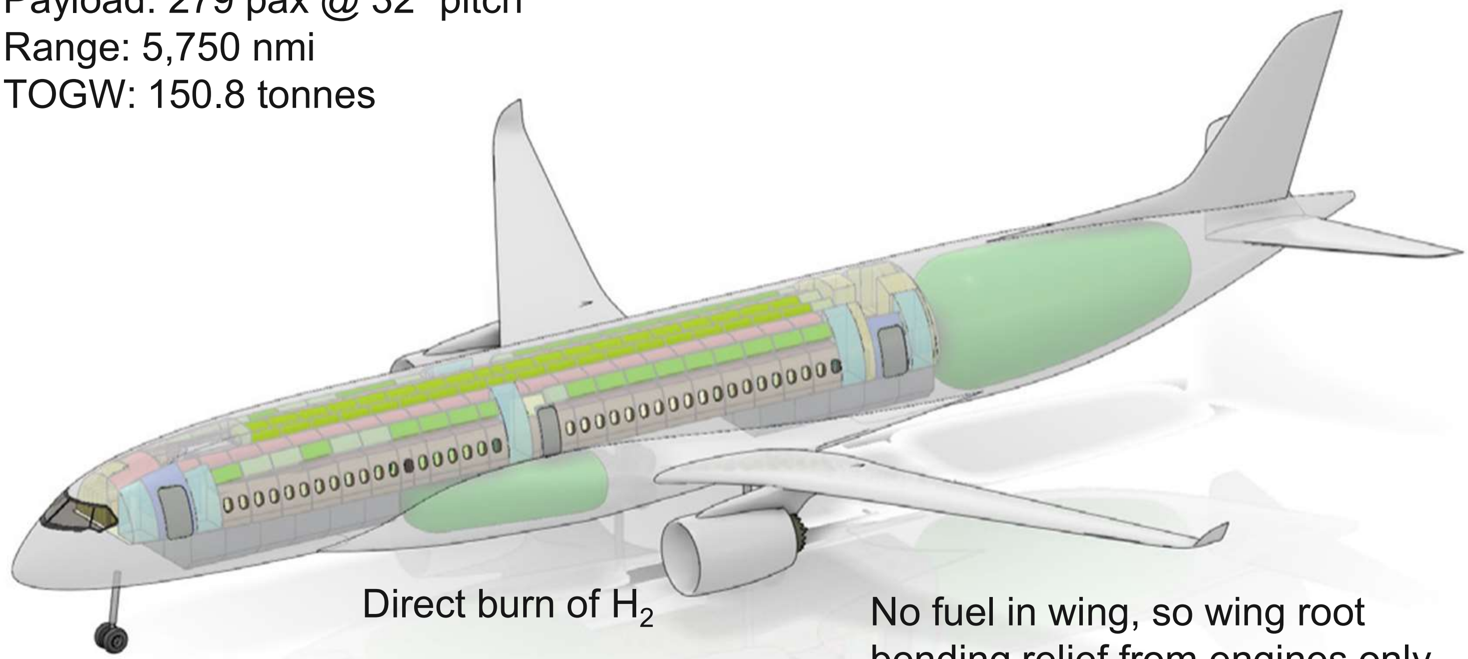
ΔOEW
= 48.0 – 41.9
= 3.1t

ΔOEW/Fuel
= 3.1/3.9 = 1.7

This value made worse by putting engines on rear fuselage

FlyZero – 767-200ER Replacement

Payload: 279 pax @ 32” pitch
Range: 5,750 nmi
TOGW: 150.8 tonnes



Direct burn of H_2

No fuel in wing, so wing root bending relief from engines only

https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIN-REP-0007-FlyZero-Zero-Carbon-Emission-Aircraft-Concepts.pdf

FlyZero – 767-200ER Replacement

Midsize Aircraft Mission Data		Reference B767-200ER	Baseline B767-2030	Concept FZM-1G
Fuel Type		Jet A-1	SAF	LH_2
Payload	No. of Pax @ seat pitch (in.)	242 @ 32"	279 @ 32"	279 @ 32"
	Cargo (kg)	10,190	0	0
	Total Payload (kg)	35,600	29,250	29,250
Max. Take-Off Weight (MTOW) (tonnes)		179.2	170.0	150.8
Operating Empty Weight (tonnes)		82.4	96.5	104.8
Design Mission	Range (nmi)	5,273	5,750	5,750
	Total Mission Fuel Mass inc. reserves (kg)	61,440	44,375	16,743
	Block Time (hrs)	11.9	12.5	12.7
	Block Fuel Mass (kg)	54,910	40,383	15,151
	Block Fuel Energy (MJ)	2,361,130	1,857,613	1,727,214
	Energy Intensity (MJ/ASNM)	1.69	1.16	1.08
Typical Mission	Range (nmi)	3,700	3,700	3,700
	Total Mission Fuel Mass inc. reserves (kg)	42,085	28,672	11,104
	Block Time (hrs)	8.5	8.4	8.4
	Block Fuel Mass (kg)	36,190	25,138	9,677
	Block Fuel Energy (MJ)	1,556,170	1,156,348	1,103,178
	Energy Intensity (MJ/ASNM)	1.74	1.12	1.07

Fuel fraction
16.743/150.8
= 0.111

FlyZero – 767-200ER Replacement

Midsize Aircraft Mission Data		Reference B767-200ER	Baseline B767-2030	Concept FZM-1G
Fuel Type		Jet A-1	SAF	LH_2
Payload	No. of Pax @ seat pitch (in.)	242 @ 32"	279 @ 32"	279 @ 32"
	Cargo (kg)	10,190	0	0
	Total Payload (kg)	35,600	29,250	29,250
Max. Take-Off Weight (MTOW) (tonnes)		179.2	170.0	150.8
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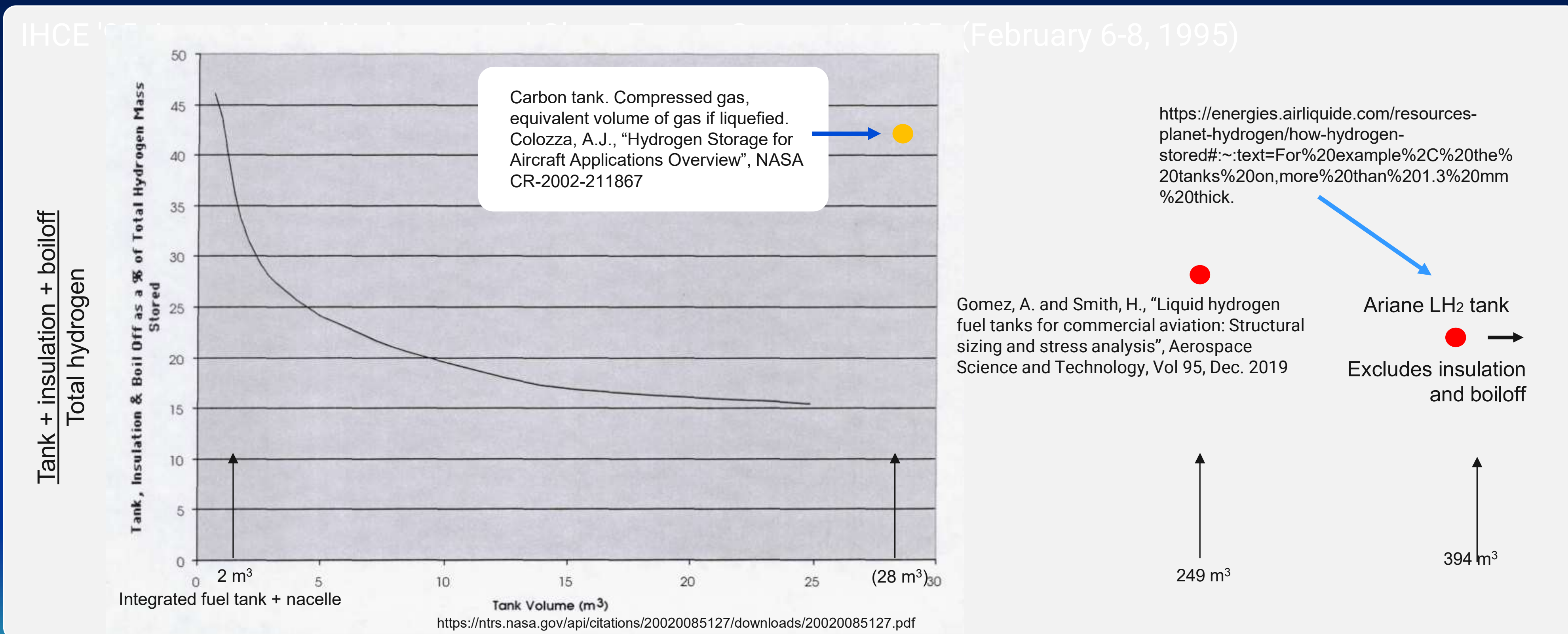
	Block Fuel Energy (MJ)	1,556,170	1,156,348	1,103,178
	Energy Intensity (MJ/ASNM)	1.74	1.12	1.07

ΔOEW
= 104.8-96.5
= 8.3t

ΔOEW/(fuel weight)
= 8.3/16.7 = 0.5

Reasonable value to use for initial sizing for transport aircraft with engines on wing

Square-Cube Law in effect

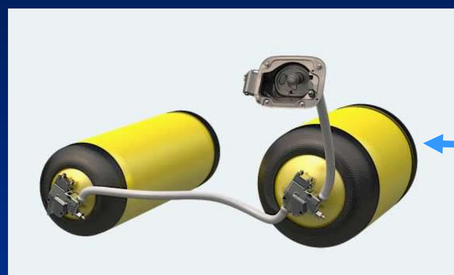


- Areas where direct burn may be inferior
  - When multiple propulsors can be used for lift augmentation, drag reduction, or S&C
  - For short-haul turboprops flying at lower Mach numbers and shorter field length requirements
  - When propulsors are small and become very inefficient due to Reynolds Number effects (e.g., light aircraft)
  - When higher efficiency of electric motors outweighs weight of fuel cell* and inverter for long range aircraft

*can expect significant decrease in fuel cell weight in future

- Applications of Hydrogen Energy
  - Burn it directly with atmospheric O_2 (or LO_2) (rocket, gas turbine, or reciprocating engine)
  - Combine it with atmospheric O_2 (or LO_2) in fuel cell to generate electricity
  - Hybrid of direct burn and fuel cell
  - Hybrid of battery and fuel cell

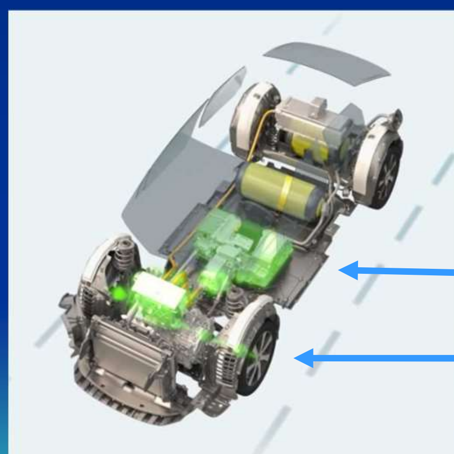
Toyota Mirai



Tanks with H_2 at 70 MPa (10,000 psi)

Cost ~ $58,365 (excluding $5,000 rebate)
Range (2016 model) 312 mi (502 km)

Source:ssl.Toyota.com

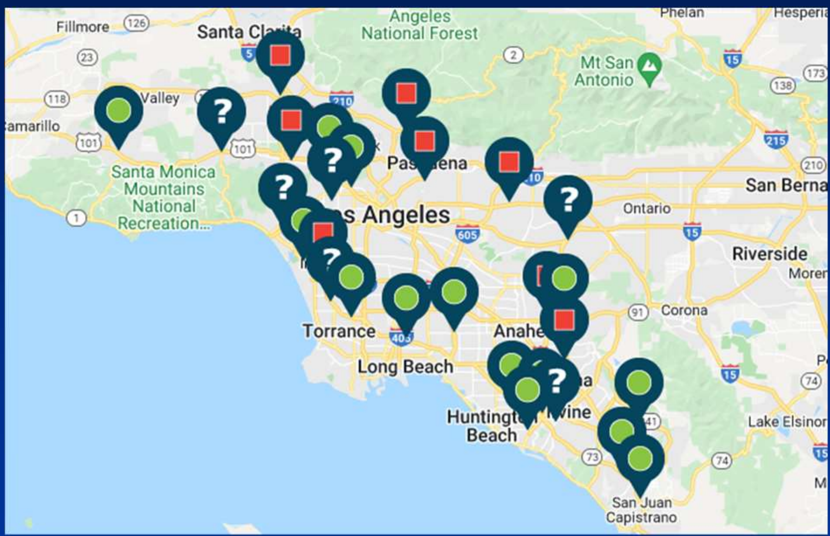


Fuel cell

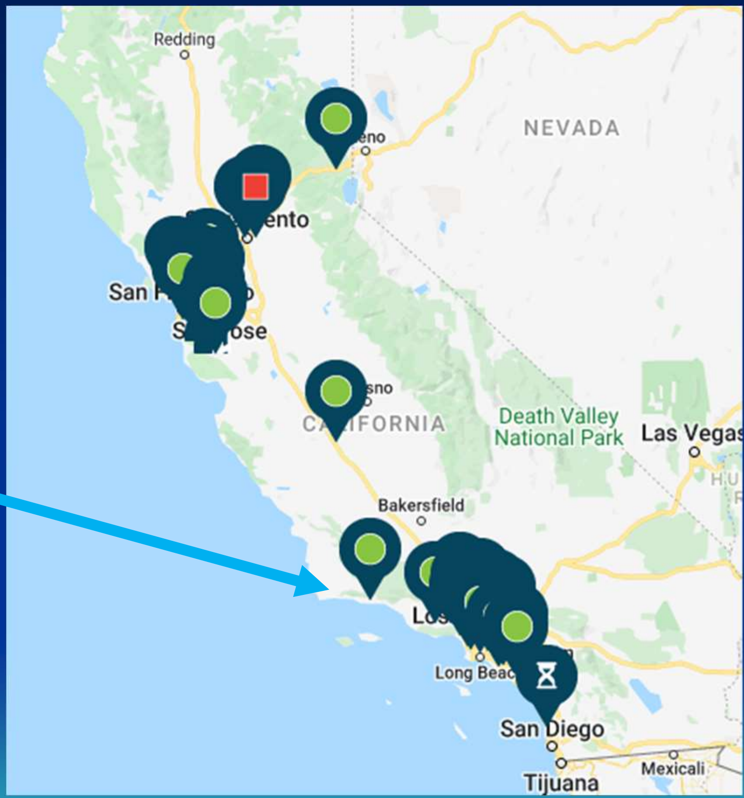
Electric motor

Cost of H_2 ~ 17 ¢/mile
Cost of gasoline ~ 17.2 ¢/mile at $6/gal

Hydrogen Filling Stations in California



As of 2022-04 plenty of filling stations in metropolitan areas

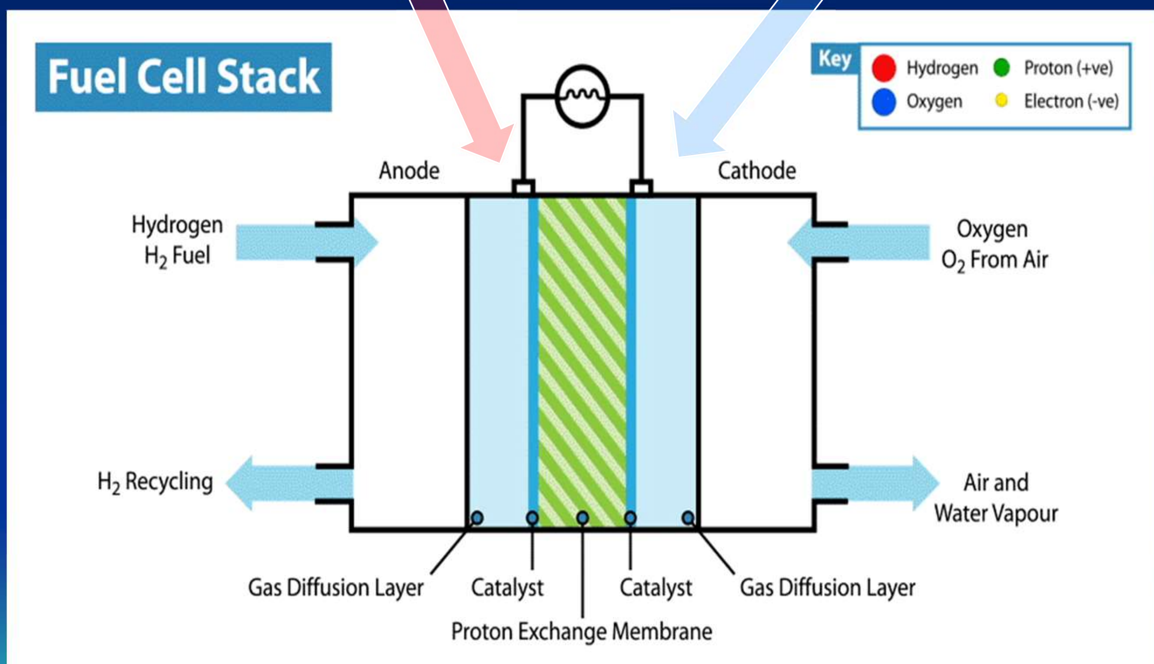


https://cafcp.org/stationmap

ADAC Aircraft Design & Consulting

Fuel Cell Operation

$2H_2 + O_2 \rightarrow 4H + 2O \rightarrow 4p^+ + 4e^- + 2O \rightarrow 2H_2O$



Source: www.intelligent-energy.com/technology/technology-faq/

40-60% energy efficient (compared with i.c. engine efficiency of ~ 25%)

Hydrogen-Powered Trucks

- Trucks initially operating in Port of Los Angeles
- Operations will extend to rest of California

Alaka'i Technologies LH_2 fuel cell-powered VTOL

- MA-based (30 employees)
- Codesigned by BMW-owned Designworks
- 3 x LH_2 fuel cells
- 6 x 100 kW electric motors
- Payload: 456 kg (1000 lb)
- Range: up to 644 km (348 nmi)
- Endurance: up to 4 hours
- Speed: up to 190 km/h (103 kt)
- < 10 minute refueling time

https://www.designboom.com/technology/alakai-technologies-skai-evtol-hydrogen-fuel-cell-flying-car-03-20-2019/
Courtesy of alakai'I technologies

Skai H_2-powered flying taxi

Alaka’i Technologies LH_2 fuel cell-powered VTOL

- LH_2 in 200 or 400 ℓ double-walled SS tanks
- 4-bladed fixed pitch rotors
- Fly-by-light fiber optics-based controls for EMI and lightning protection
- Triple-redundant autopilot
- Redundant 6-rotor configuration
- Redundant fuel cells
- Airframe ballistic parachute

https://www.designboom.com/technology/alakai-technologies-skai-evtol-hydrogen-fuel-cell-flying-car-03-20-2019/
Courtesy of alakai'I technologies

Skai rotor head

Alaka'i Technologies LH_2 fuel cell-powered VTOL

- Seats for 5 people (inc. pilot)
- Or 5 pax with autonomous control or ground-based pilot
- 5G wi-fi

https://www.designboom.com/technology/alakai-technologies-skai-evtol-hydrogen-fuel-cell-flying-car-03-20-2019/
Courtesy of alakai'I technologies

Skai seating arrangement

FlyZero – Fuel Cell Test Requirements

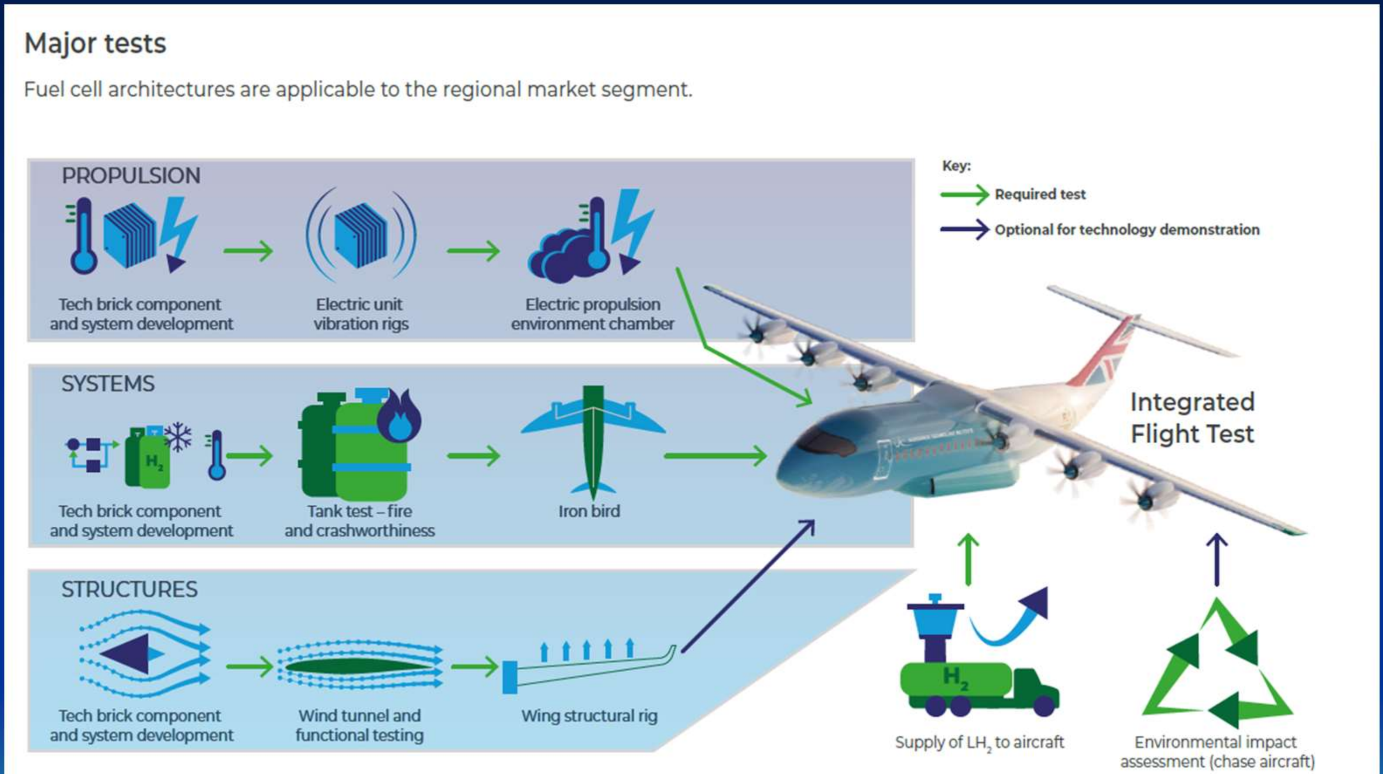


Figure 8 – Hydrogen fuel cell aircraft architecture – major tests.

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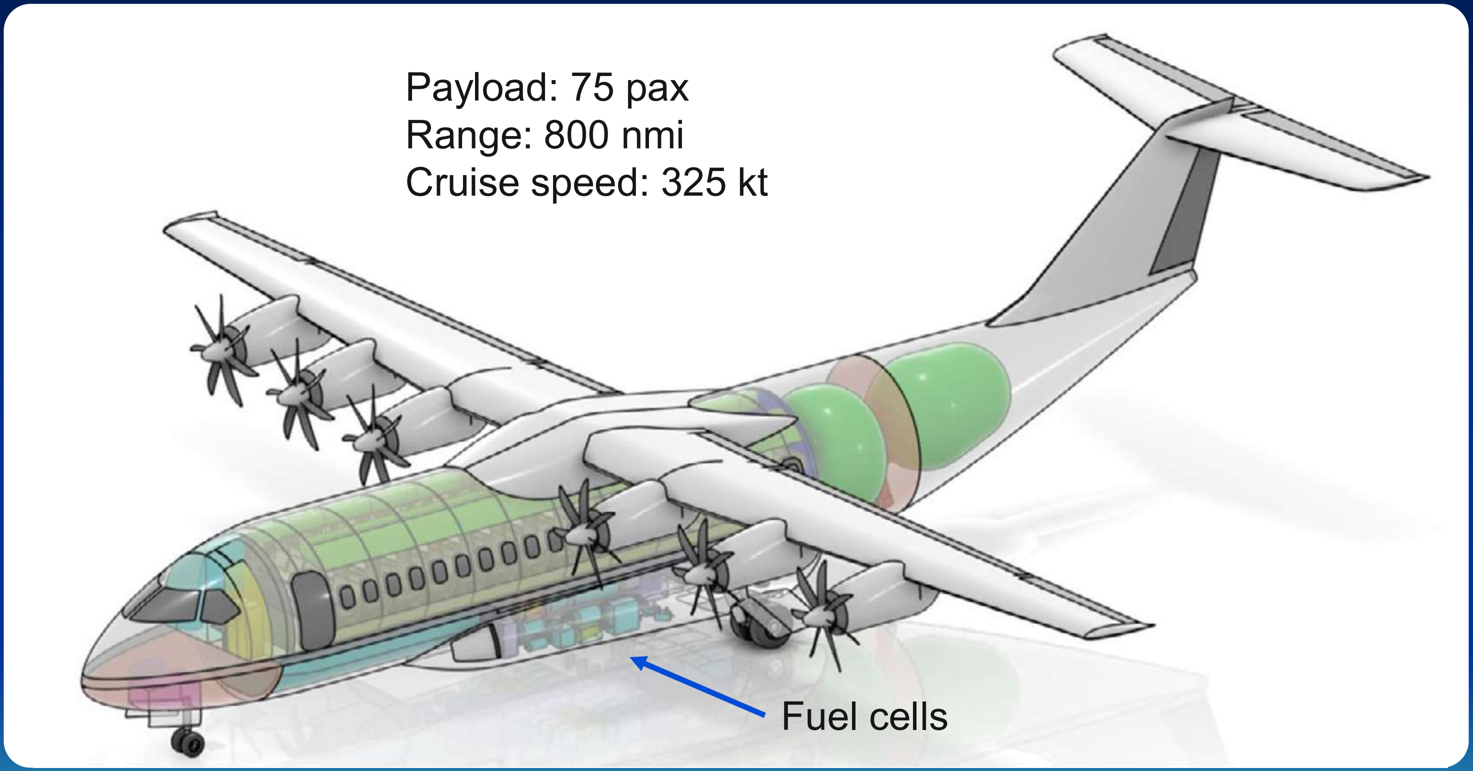
FlyZero - Regional Airliner



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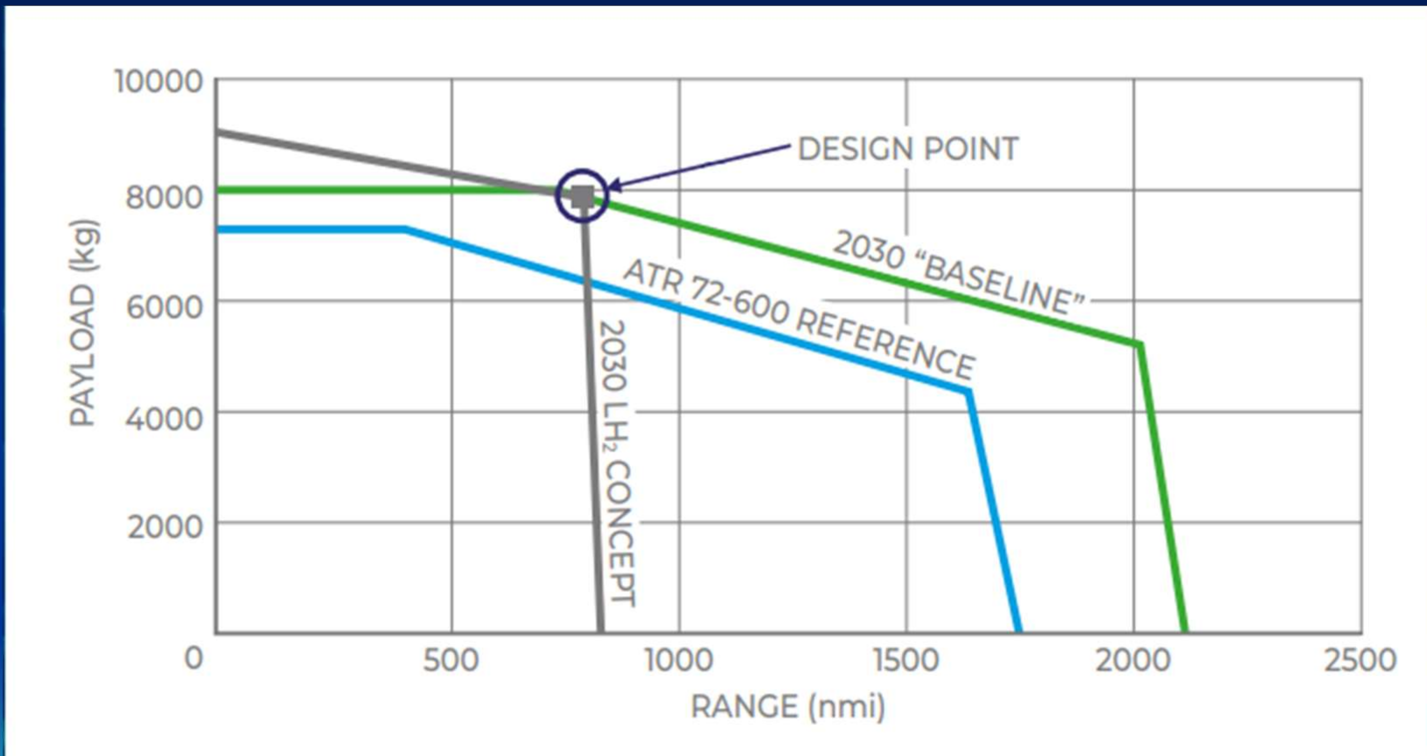
FlyZero – Regional Airliner



https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIN-REP-0007-FlyZero-Zero-Carbon-Emission-Aircraft-Concepts.pdf

FlyZero – Regional Airliner

Regional Aircraft Geometric Data		Reference ATR72-600	Baseline ATR72-2030	Concept FZR-1E
Fuel Type		Jet A-1	SAF	LH_2
Overall Aircraft Length (m)		27.2	28.5	28.0
Fuselage	Length (m)	27.2	27.2	27.0
	Diameter (m)	2.8	2.8	3.5
Wing	Aspect Ratio (-)	12	14	14
	Quarter-Chord Sweep (deg)	1.6	1.8	7.0
	Thickness Root/Tip (%)	18/13	18/13	18/12
	Span (m)	27.1	31.3	31.0
	Area (m^2)	61.0	70.0	70.8
	Loading (kg/m^2)	374	368	407
Propulsors	No. of Propulsors	2	2	6
	Propeller Diameter (m)	3.9	4.0	2.3
	Nacelle Diameter (m)	1.1	1.2	0.96
Empennage	Vertical Area (m^2)	12.5	13.6	11.0
	Horizontal Area (m^2)	11.6	11.9	20.2
	Horizontal Span (m)	7.3	7.4	10.7

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FlyZero – Regional Airliner

Regional Aircraft Performance Data		Reference ATR72-600	Baseline ATR72-2030	Concept FZR-1E
Fuel Type		Jet A-1	SAF	LH_2
Normal Take-off	Aircraft Sea Level Shaft Power (kW)	3,692	4,235	4,400
	Aircraft Power to Weight (kW/kg)	0.162	0.164	0.153
	Field Length (m)	1,240	1,201	1,387
Start of Cruise	Aircraft Propulsive Power (kW)	1,796	2,684	3,115
	Lift to Drag Ratio (-)	16.8	15.5	15.1
	Speed (ktas)	266	325	325
	Altitude (ft)	25,000	25,000	25,000
	SFC (kg/s/N) x 10^{-6}	13.3	12.4	4.6
	EPSFC (kg/kWhe)	0.350	0.267	0.100
Landing	Approach Speed (keas)	111	109	114
	Field Length (m)	1,252	1,205	1,331

https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIN-REP-0007-FlyZero-Zero-Carbon-Emission-Aircraft-Concepts.pdf

FlyZero – Regional Airliner

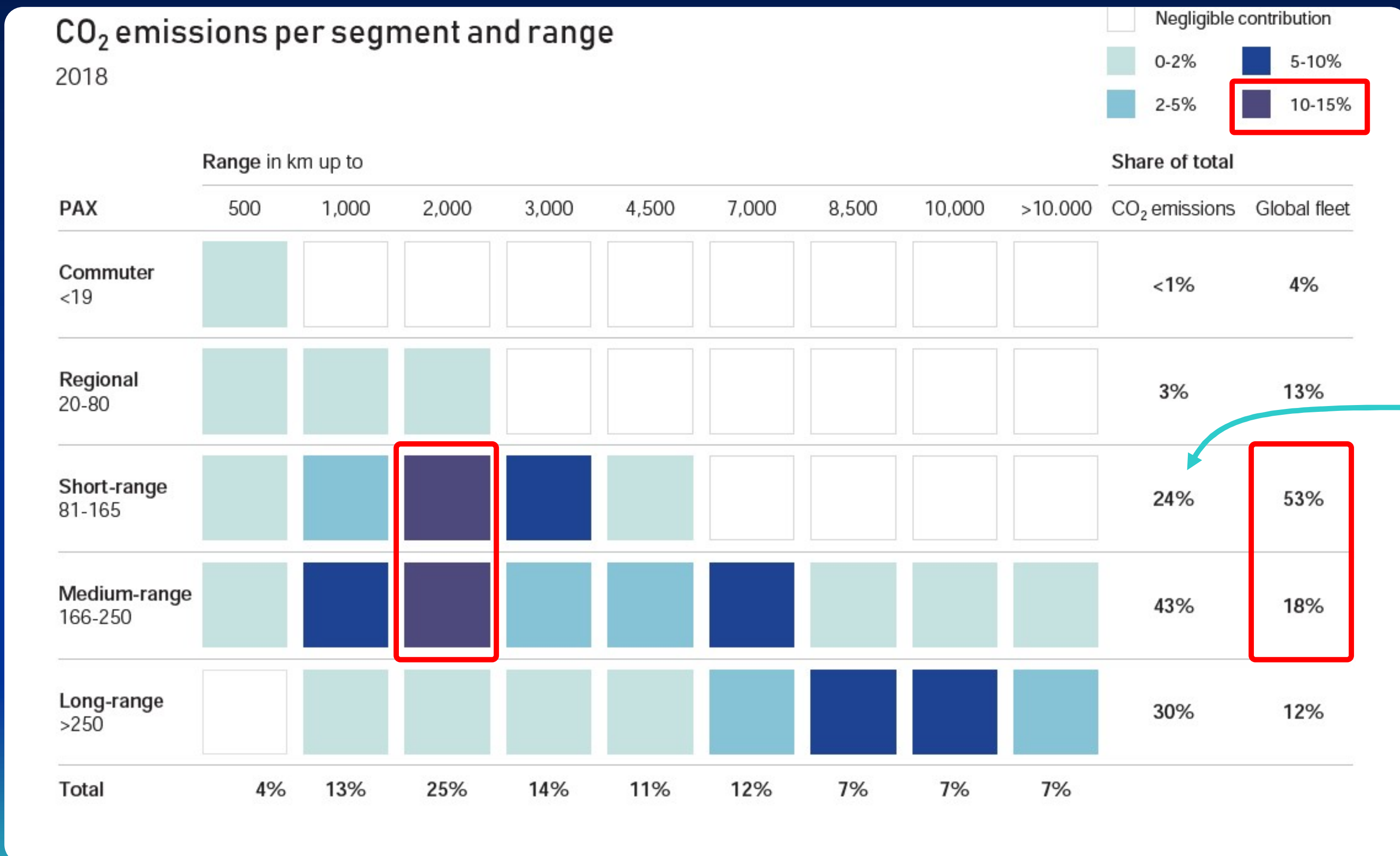
Regional Aircraft Mission Data		Reference ATR72-600	Baseline ATR72-2030	Concept FZR-1E
Fuel Type		Jet A-1	SAF	LH_2
Payload	No. of Pax @ seat pitch (in.)	72 @ 30"	75 @ 30"	75 @ 30"
	Cargo (kg)	0	0	0
	Total Payload (kg)	7,200	7,875	7,875
Max. Take-Off Weight (MTOW) (tonnes)		22.8	25.8	28.8
Operating Empty Weight (tonnes)		13.5	15.0	19.8
Design Mission	Range (nmi)	448	800	800
	Total Mission Fuel Mass inc. reserves (kg)	2,156	2,954	1,158
	Block Time (hrs)	2.1	3.0	2.9
	Block Fuel Mass (kg)	1,381	2,115	877
	Block Fuel Energy (MJ)	59,383	97,308	105,287
	Energy Intensity (MJ/ASNM)	1.84	1.62	1.75
Typical Mission	Range (nmi)	375	375	375
	Total Mission Fuel Mass inc. reserves (kg)	1,974	1,959	730
	Block Time (hrs)	1.9	1.6	1.6
	Block Fuel Mass (kg)	1,208	1,168	470
	Block Fuel Energy (MJ)	51,951	53,708	56,436
	Energy Intensity (MJ/ASNM)	1.92	1.91	2.01

Fuel fraction
1.158/28.8
= 0.040

https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIN-REP-0007-FlyZero-Zero-Carbon-Emission-Aircraft-Concepts.pdf

- Applications of Hydrogen Energy
  - Burn it directly with atmospheric O_2 (or LO_2) (rocket, gas turbine, or reciprocating engine)
  - Combine it with atmospheric O_2 (or LO_2) in fuel cell to generate electricity
  - Hybrid of direct burn and fuel cell
  - Hybrid of battery and fuel cell

Summary of EU-commissioned report



- Range up to 2000 km and 81-250 pax create 67% of CO_2 emissions

Source: EU Hydrogen Powered Aviaition.

ADAC Aircraft Design & Consulting

H_2 Propulsion Options – Future Technology

Direct combustion of H_2 in conventional gas turbine

Combine H_2 with atmospheric O_2 in fuel cells to generate electrical power

(maybe best for very long range)

Size electric power train for cruise, size core for extra power at takeoff

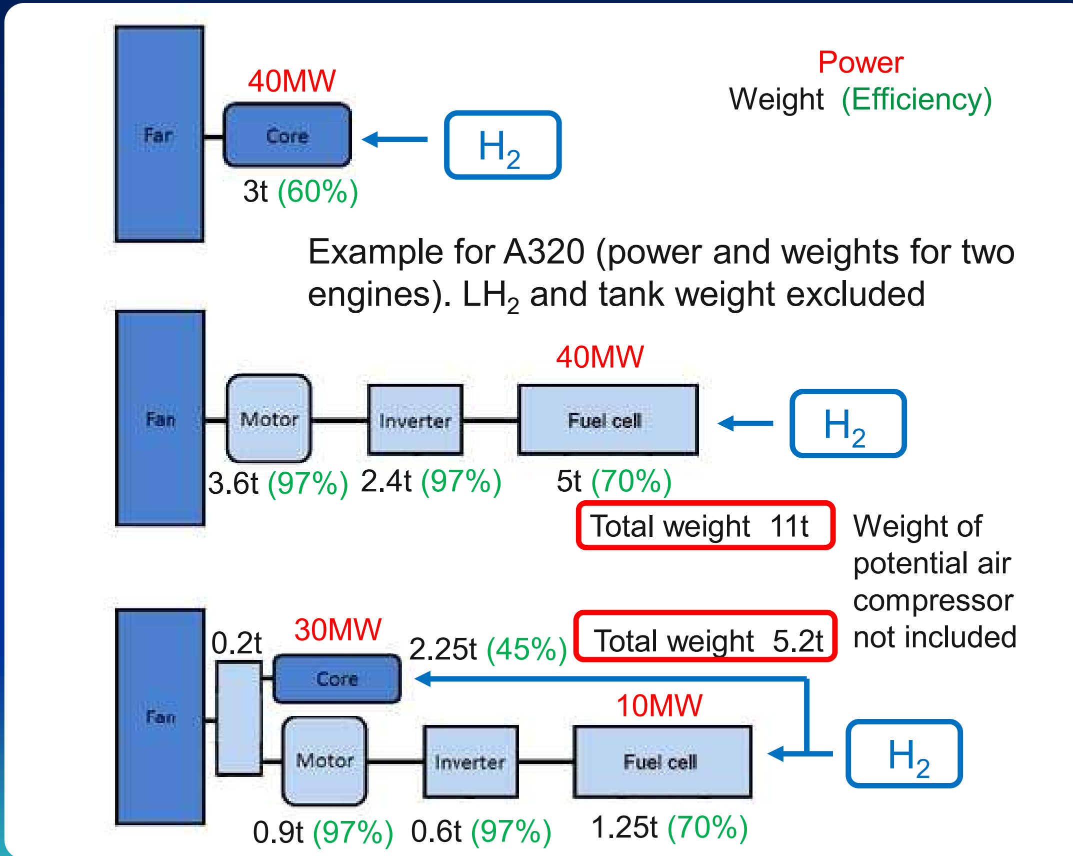


Exhibit 8

Short-range aircraft powered by hybrid H_2 propulsion

Revolutionary aircraft

Design mission: 165 PAX, 2,000 km range, cruise speed Mach 0.72

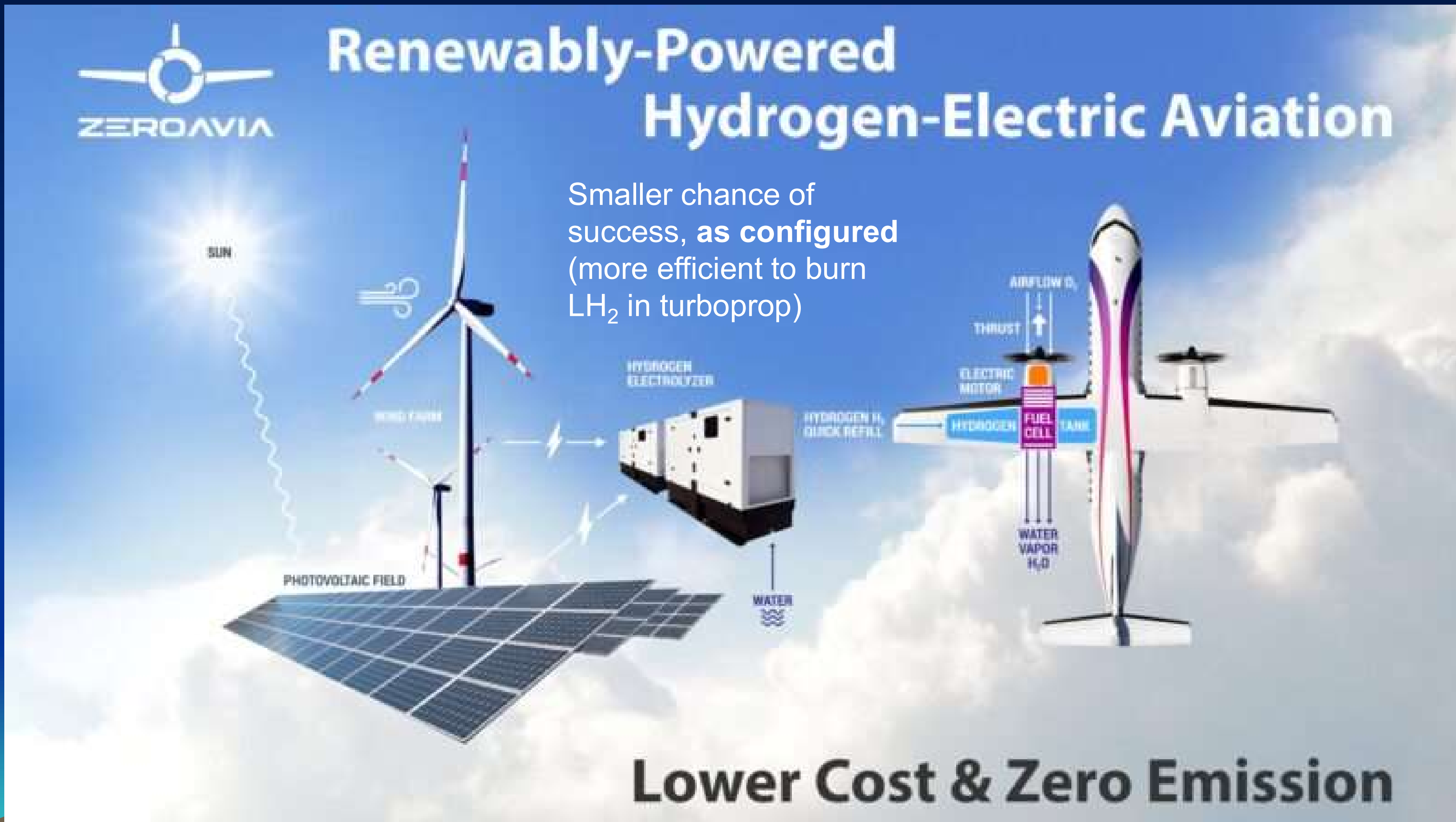
- **2 LH_2 tanks** behind PAX cabin -added weight: 4 tons
- **Fuel cell system (11 MW)** powering electric motors
- **Electric motor** driving main turbine fan shaft during cruise, while H_2 turbine is turned off

Fuel cells justified because of lower M_{cruise}, less sweep, smaller engines

Energy demand[1]	-4%
CO_2 reduction	100%
Climate impact reduction	70-80%
Additional cost	20-30% CASK[2]
Entry into service	15 years
Propulsion power	Hybrid
MTOW[3]	+14%

1. Major assumptions: 35% gravimetric index of LH_2 tank, 91% useable LH_2 fuel, FCS mass 2 kW/kg (incl. cooling) and 60% peak efficiency (LHV), e-motors and PMAD with 97% efficiency, battery with 0.6 kWh/kg, H_2-turbine with 45% cruise efficiency
2. Cost per available seat kilometer
3. Maximum take off weight

McKinsey, Hydrogen-powered aviation, A fact-based study of the hydrogen technolog, economics, and climate impact by 2050, 2020-05



Smaller chance of success, **as configured** (more efficient to burn LH_2 in turboprop)

http://www.smartaviation-apac.com/2020/07/zeroavia-targeting-19-seat-market-with-hydrogen-power/

Hybrid of direct burn and fuel cell

- Applications of Hydrogen Energy
  - Burn it directly with atmospheric O_2 (or LO_2) (rocket, gas turbine, or reciprocating engine)
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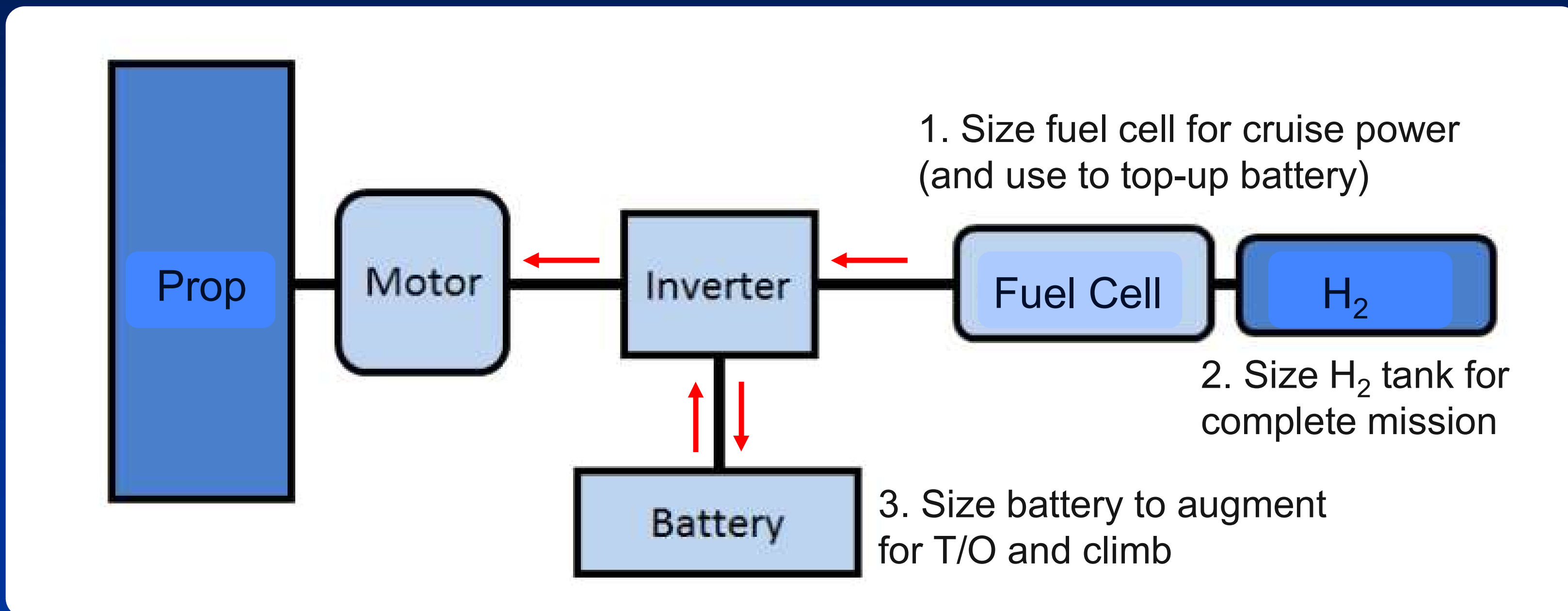
  - Hybrid of battery and fuel cell

DLR/Hydrogenics/Pipistrel HY4



Source: Wikipedia

Weight of battery more than offset by reduction in weight of fuel cell

DLR/Hydrogenics/Pipistrel HY4

Source: hy4.org

- H_2 fuel cell and battery power
- 4 seats
- Range up to 1500 km (810 nmi)
- Cruise speed 145 km/hr (78 kt)
- First flight 2016-09-29

Boeing R&T Europe Dimona (Modified)

- Powered by hydrogen fuel cell and Li batteries (2008)
- Climb: Li battery + fuel cell
- Cruise: 20 minutes on fuel cell
- Cruise at 27 m/sec (51 kt)
- Paris Air Show 2009

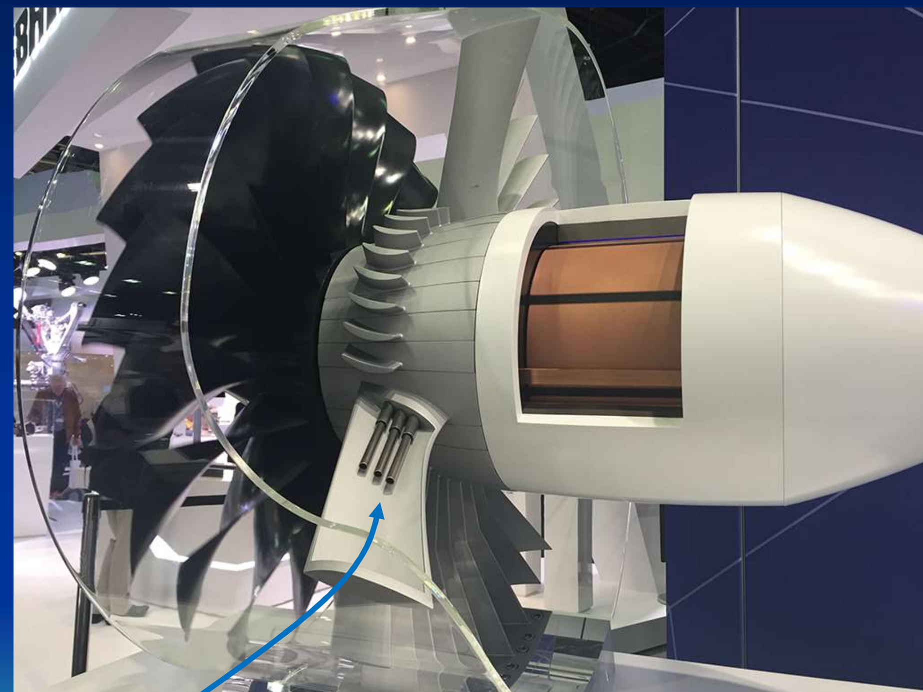
Source: Wikipedia

- Need for Zero-Carbon Economy
- Hydrogen vs. Batteries
- History of Hydrogen-powered Propulsion
- Hydrogen Generation, Distribution and Storage
- Combining Hydrogen and Oxygen
- Applications of Hydrogen Energy
- The Future of Hydrogen
- Conclusions

ASuMED Superconducting Motor

- Advanced Superconducting Motor Experimental Demonstrator
- Developed by Oswald Electromotoren
- High temperature superconductor @ 23 K (- 418 F)
- 1 mW output @ 6,000 rpm
- Specific power 20 kW/kg*
- Overall η 99.9%

* Compare with 5-6 kW/kg for conventional

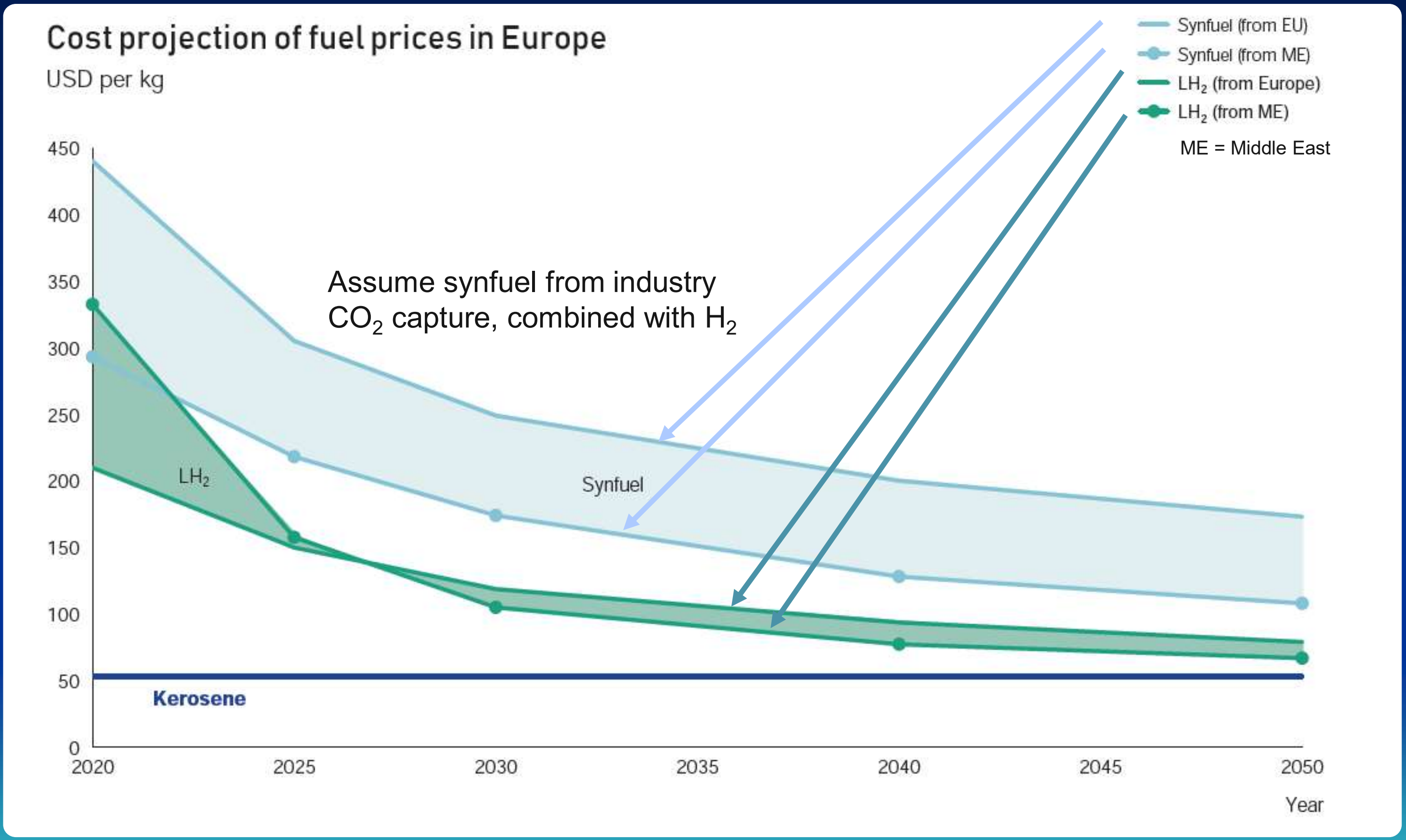


https://aviationweek.com/future-aerospace/full-superconducting-motor-readied-tests

Summary of EU-commissioned report

- Prepared by McKinsey & Company
- Commissioned by Clean Sky 2 Joint Undertaking and Fuel Cells and Hydrogen 2 Joint Undertaking
- Published 2020-05
- H_2 combustion could reduce climate impact by 50–75%
- Fuel cell propulsion by 75-90%

Comparative Cost of Synfuel and LH_2

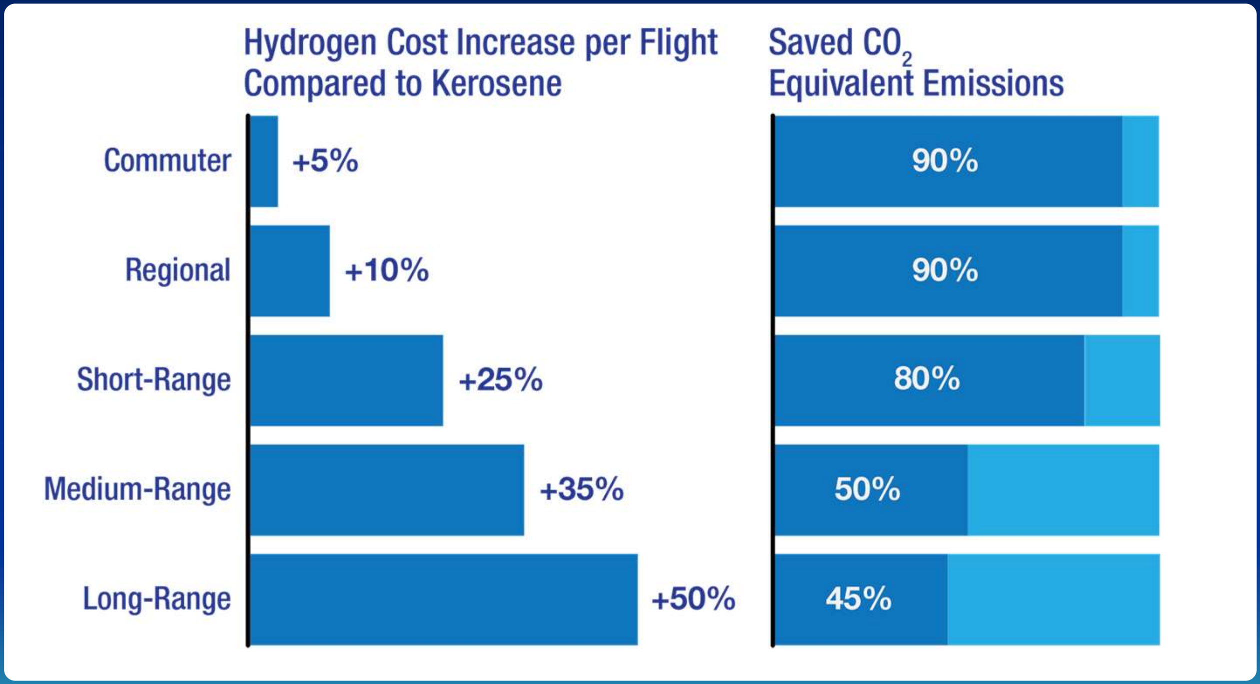


McKinsey, Hydrogen-powered aviation, A fact-based study of the hydrogen technolog, economics, and climate impact by 2050, 2020-05

Hydrogen vs. Kerosene
Aviation Fuel Costs and Emissions in 2040

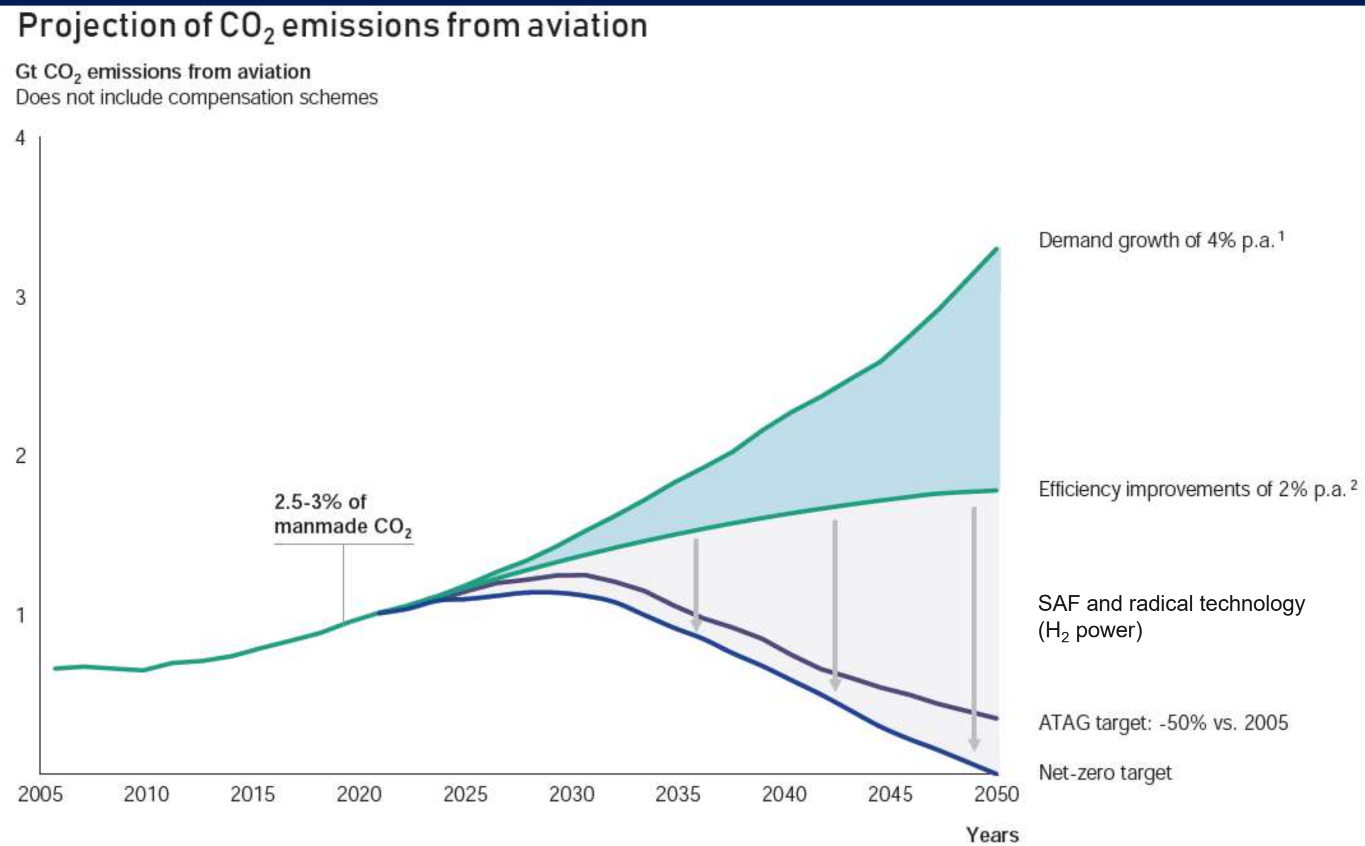
Faury (Airbus CEO)
- Fuel cell
  - Commuter
  - Regional
- Gas turbine (LH_2)
  - Short-Range
  - Medium-Range

McKinsey
- Gas turbine (Synfuel)
  - Long-Range



McKinsey & Co.

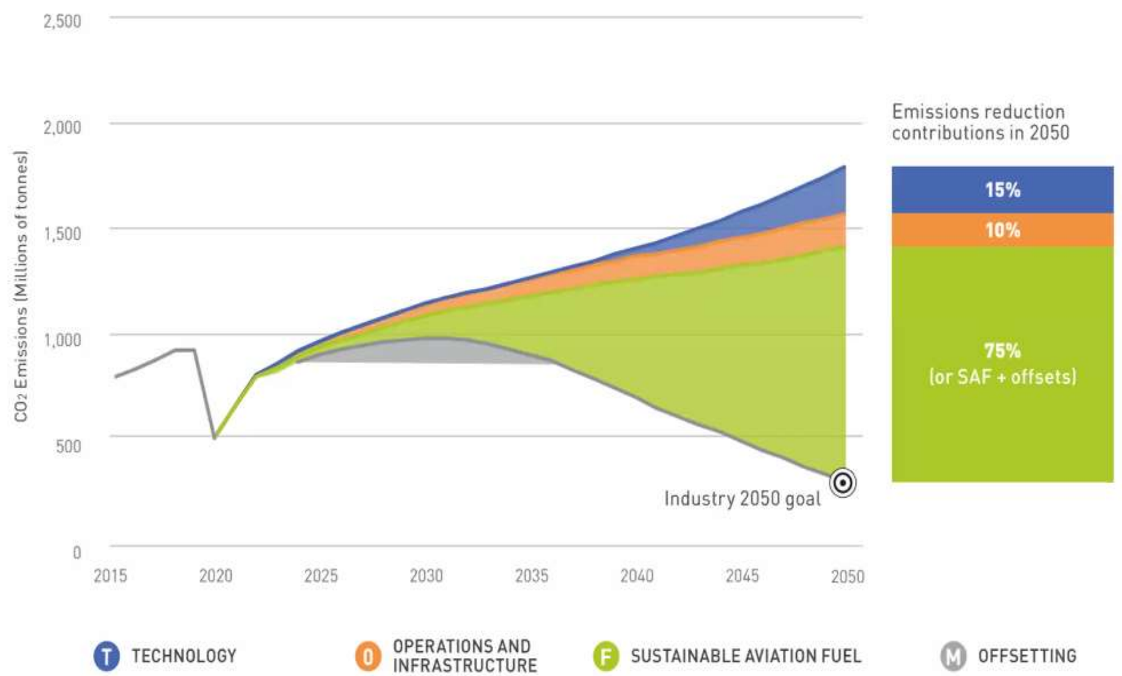
Summary of EU-commissioned report



1. Assumption based on growth projections from ATAG, IATA, ICCT, WWF, UN
2. ICAO ambition incl. efficiency improvements in aircraft technology, operations and infrastructure

McKinsey, Hydrogen-powered aviation, A fact-based study of the hydrogen technolog, economics, and climate impact by 2050, 2020-05

Aggressive Sustainable Fuel Deployment



Source: Waypoint 2050, An Air Transport Action Group Project

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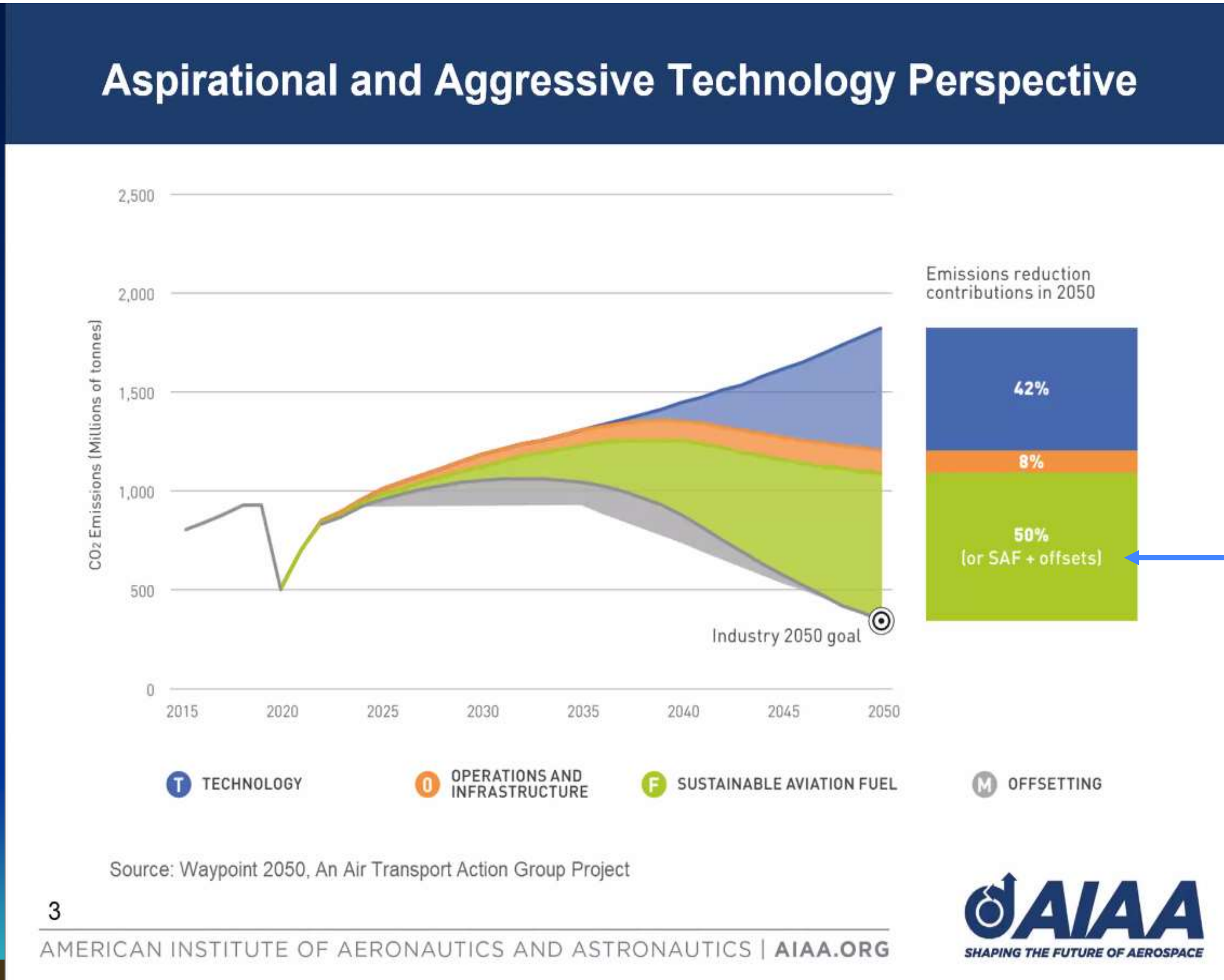
AMERICAN INSTITUTE OF AERONAUTICS AND ASTRONAUTICS | AIAA.ORG

AIAA SHAPING THE FUTURE OF AEROSPACE



Offsets are partly a fraudulent shell game

Note: no explicit mention of H_2-powered aircraft

- Need for Zero-Carbon Economy
- Hydrogen vs. Batteries
- History of Hydrogen Aircraft/Spacecraft Propulsion
- Applications of Hydrogen Energy
- The Future of Hydrogen
- Conclusions

Conclusions

- For VTOL and very short-range aircraft (i.e., small fuel mass fraction), batteries may be preferred
- For H_2, hybrid gas turbine + fuel cell may offer lightest weight for short haul, lower M_{cruise} operations
- For medium and long range, H_2 direct burn is currently best solution
- If fuel cell weight can be reduced, hybrid gas turbine + fuel cell may be preferable for long haul aircraft
- ATAG goal must be achieved, zero net CO_2 is stretch goal

Thanks for your interest

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ADAC
Aircraft Design & Consulting

香港科技大學
THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

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