M3Or1C-04: [Invited] Dual Hydrogen-Jet Fuel Aircraft –A path to low carbon emissions

2023 CEC-ICMC July 12, 2023

Jeff Trudell

NASA Glenn Research Center

Underlined text is a hyperlink

1956 First LH2 powered Flight

- In 1956, a B-57 switched to LH2 powered flight over Lake Erie with existing engines- the first dual hydrogen jet fuel aircraft demonstration

  Requirement for well-insulated, sealed, cryogenic tank and fuel system including infrastructure represent challenges to the designer and now requires flight demonstrations to raise the technology readiness and identify new challenges

- Liquid hydrogen was carried was carried in a tank located under the left wingtip of a B-57 and gaseous helium under the right wingtip.
- When the engine was operating on hydrogen, the JP fuel was recirculated back to its tank. Taking off with conventional fuel and reaching 50,000 ft, the hydrocarbon fuel in one engine was stopped and the flow of GH2 was initiated and increased to the required rate for 21 minutes.

Outline

- 2020 European H2 Aviation Study
- 2021 U. S. Aviation Climate Action Plan and Status
- Dual Hydrogen Jet Fuel Concept
- Dual LH2 Jet Fuel Vision to lower emissions
  - H_2 Hub Locations, excess renewable and off-grid energy, and decentralized microgrids
- Challenges of SAF
- Summary

2020 European Hydrogen Aviation Study

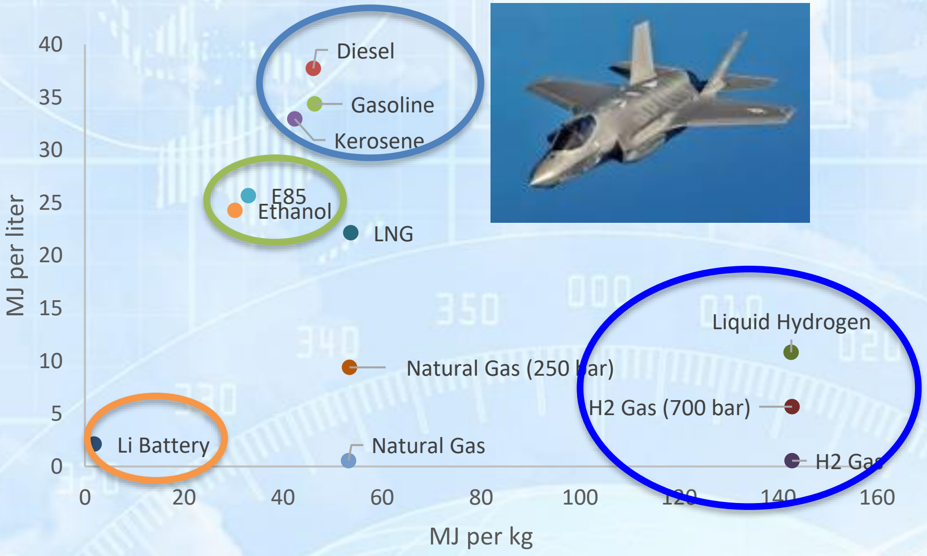
- "H_2 propulsion is best suited for commuter, regional, short and medium {low end} range" - Euro H2 Aviation Study
  - "Consume 25% more energy; 30-40% PAX $ increase", Long (to med) range remain Jet A
  - "Entry into service next 8 to 15 years" {short range <25% of flights}

- US Climate Plan View of the European Study: "do not expect LH2 aircraft to make a significant contribution toward achieving net-zero emissions by 2050.

30 more years to lower emissions with Hydrogen

Hydrogen: Low Energy per Unit Volume

- **100% LH2 powered aircraft requires 4X more fuel volume compared to conventional**
  - Heat Combustion: LH2: (51,590 Btu/lb)/ JP(18,400) = 2.8
  - Density: JP (50.6) /LH2: (4.43 lb/ft3) = 11.4
  - 11.4/2.8 = ~4 times LH2 fuel volume vs conventional
- Low energy per unit volume introduces significant challenges to economically meet the stringent aviation mass, volume and safety requirements
- Examples to follow



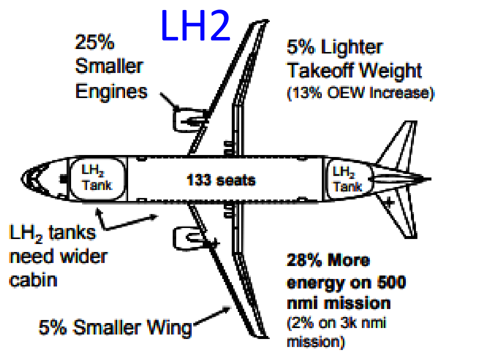


Figure 13.—Hydrogen-powered airplanes need a larger tank, which reduces the fuel efficiency of short-range aircraft.

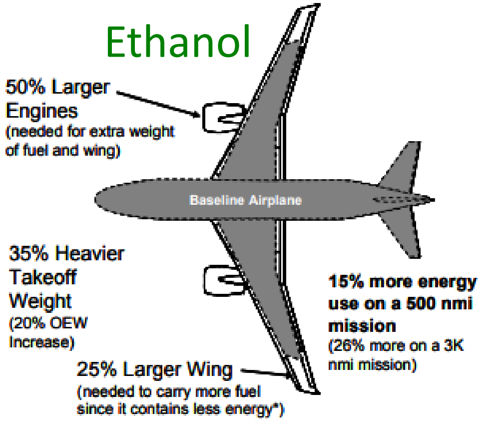
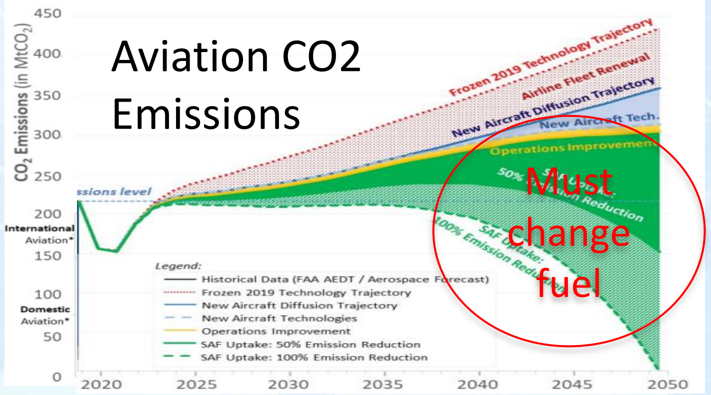


Figure 14.—An ethanol-fueled airplane requires a larger wing and engines, thus reducing the airplane's fuel efficiency.

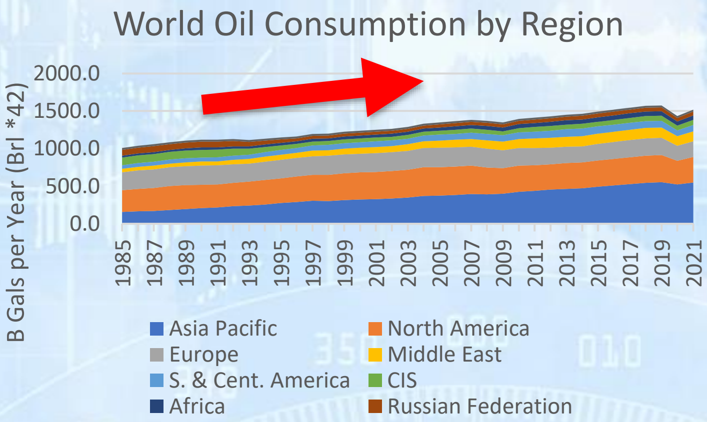
https://ntrs.nasa.gov/api/citations/20060051881/downloads/20060051881.pdf

2021 U.S. Climate Aviation Action Plan

- Achieve 2050 Net-Zero GHG mostly from Sustainable (Synthetic) Aviation Fuel



https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf



World 2021:
~35 Billion barrels * 42 =
~1400 Billion Gals/year

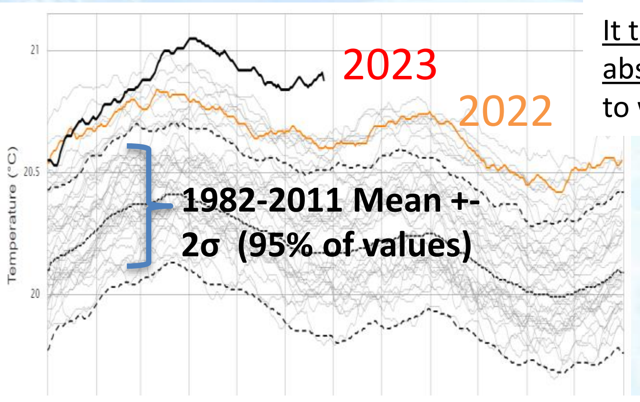
Products Made from Barrel Crude Oil (Gallons) 2009

20 Gas 10 Diesel 4 Jet Fuel
8 Other = 42 gal/barrel

- U.S. –> **Incentives** Europe->**Mandates**
  - $1.25/gal if 50% GHG reduction
  - $3/kg for green H_2 (20 years)
  - ReFuelEU Mandate: 2% SAF 2025, 28% SAF 2050
- US Aviation 18B
- US Gasoline 135B gals
- World Aviation 96B gal

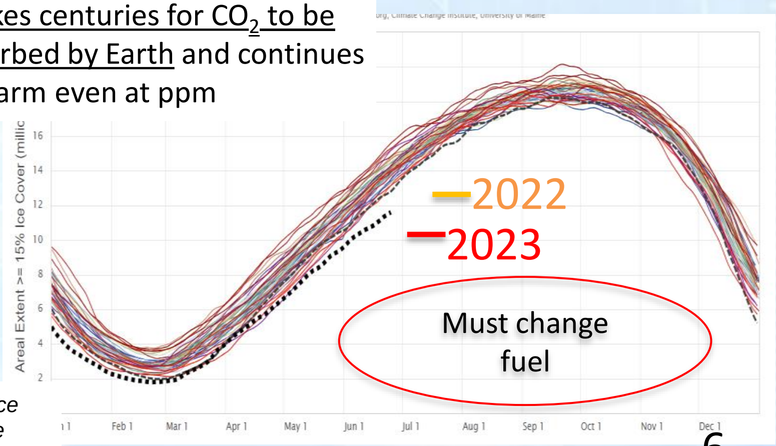
CO2 lbs per gal
Gasoline 19.6 lbs
Diesel 22.4 lbs

Daily Sea Surface Temperature*



Southern Hemisphere Sea Ice Extent*

It takes centuries for CO_2 to be absorbed by Earth and continues to warm even at ppm



*Birkel, S.D. 'Daily 2-meter Air and Sea Surface Temperature, Sea Ice Extent', Climate Reanalyzer (https://ClimateReanalyzer.org), Climate Change Institute, University of Maine, USA. Accessed on June 27, 2023.

Status of SAF Grand Challenge

- 3B gallons per year by 2030 Net Zero by 2050
- 18B 100% commercial jet fuel demand by 2050

- **GAO, May 17, 2023:**

  SAF is used at two large airports, but accounts for less than 0.1% of the jet fuel used by major U.S. airlines.

  Sustainable Aviation Fuel: Agencies Should Track **Progress Toward Ambitious Federal Goals [Reissued** with Revisions May 17, 2023] | U.S. GAO

- Inflation Reduction Act
  - $1.25/gal ***if* 50% reduction in GHG**
  - $3.00/kg for green H_2 (20 yrs)

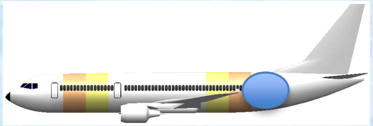
- Ideally, converting US ethanol 18B gal/yr to Jet A at the same price would be 10B gal/yr at 47% less emissions (~60% of Jet A energy)
  - 18B * 0. 60 =~10B gal/year or 60% of quantity goal
  - 0.60*0.47 +0.4*0 =28 % reduction at 1.2x cost of Jet Fuel ideally
  - Does not consider availability of water, other feedstocks

SAF reduces Contrails

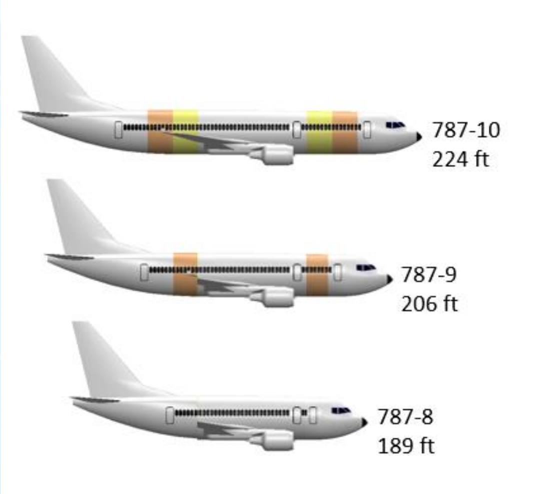
- Global Aviation Net Emissions Net forcing, with uncertainties, now has contrails higher than emissions
  - **Contrails 57.4, (51.8 = CO_2 34.3 + NO_x 17.5) mW/m^2**
  - Jet Engine emits 3.16kg CO_2, 1.23kg H_2O per kg fuel, soot
- Contrails mostly form above 30,000 ft, higher relative humidity
- Carbon dioxide life cycle however is 200+ years
- SAFSs produce 50-70% fewer, larger ice crystals due to lower aromatics
  - ***Fewer ice particles with SAF, diameter increase-> shorter life***
- *Higher Clouds colder-block more radiation to space*
- **Burning Biodiesel (HEFA) at altitude better than semis**
- *% Blend of LH2 ~ same SAF benefits?*

Dual Hydrogen-Jet Fuel Aircraft

- **Concept:** Retain Jet A wing tanks
  - Add LH_2 tank(s) for all range aircraft

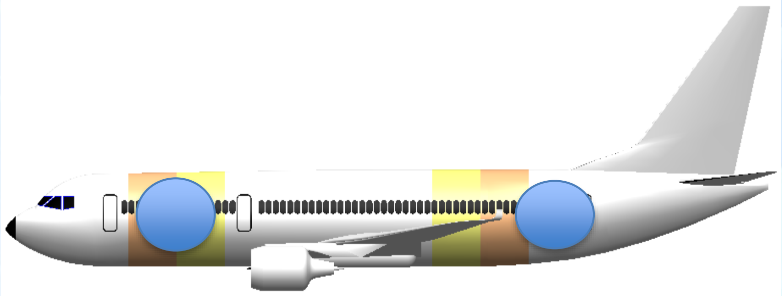


787-8 PAX to -10



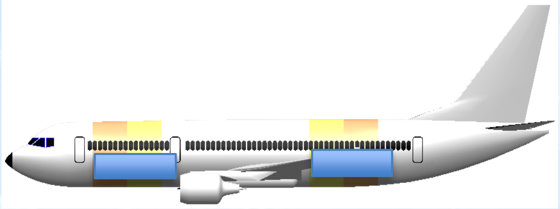
Fly 787-8 PAX in a 787-9, -10

Remove 777 PAX->Tanks



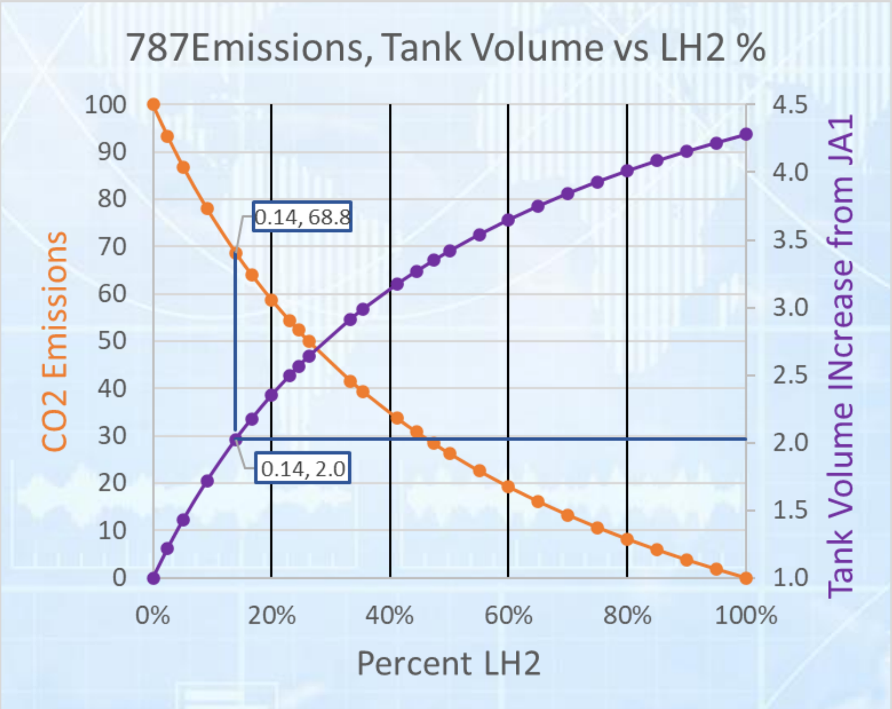
Forward, Aft tanks maintain C.G.

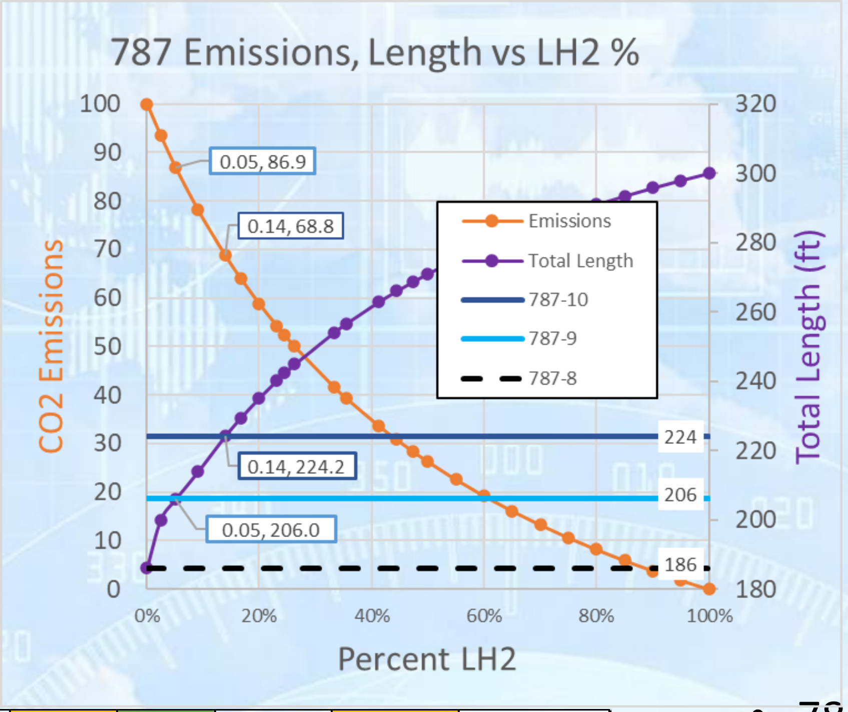
737 Cargo Bay

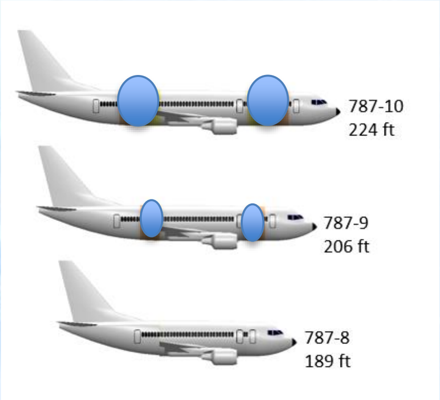


	737	777 / 787	777 / 787
PAX/row	6	8	9
Wt+ Bag	205	205	205
Seat	25	25	25
Lbs/row	1380	1840	2070
Pitch(in)	32	32	32
PAX lbs/in	43.1	57.5	64.7
Cargo (lb/in)	28	28	28
PAX-Cargo lb/in	71	86	93

Shift 787-8 PAX to -10*







~ 30% reduction
*First Order Analysis – No Aircraft Design
787-8 33,528 gals

	L(m)	L(ft)	dL (ft)	PAX	PAX dif	%LH2	PAX %	% Fuel	% Cost	dCO2	Tank Vol	TOW	JA1 Range
787-10	68.3	224	38.1	330	88	**13.9%**	27%	3%	**30%**	31	2.02	**509084**	**6430**
787-9	62.8	206	20.0	290	48	**5.1%**	15%	3%	**17%**	13	1.43	**509038**	7635
787-8	56.7	186	0.0	242	0	**0.0%**				0	1.00	502500	7355

- 787-8 to -9
  - -48PAX, 13% dCO2, 17% Operating costs
- 787-9 to -10
  - -88 Pax, 31% dCO2, 30% Operation Costs

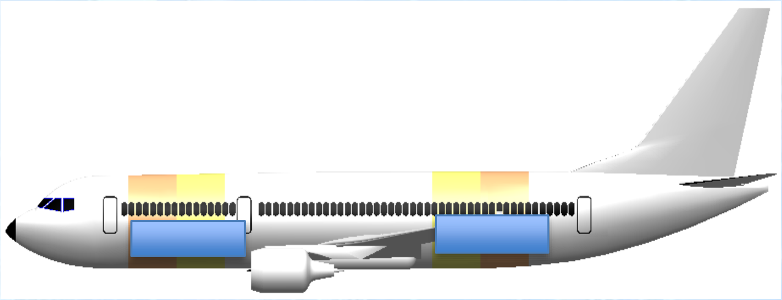
Currently, 787-10 is 57,500 lbs more than -8 MTOW (***560,000*** vs 502,500 lb)
Adding LH2 reduces overall fuel/tank weight, less PAX weight
LH2 volume requires larger Fuselage -> length becomes impractical
Separating Tanks maintains center of gravity

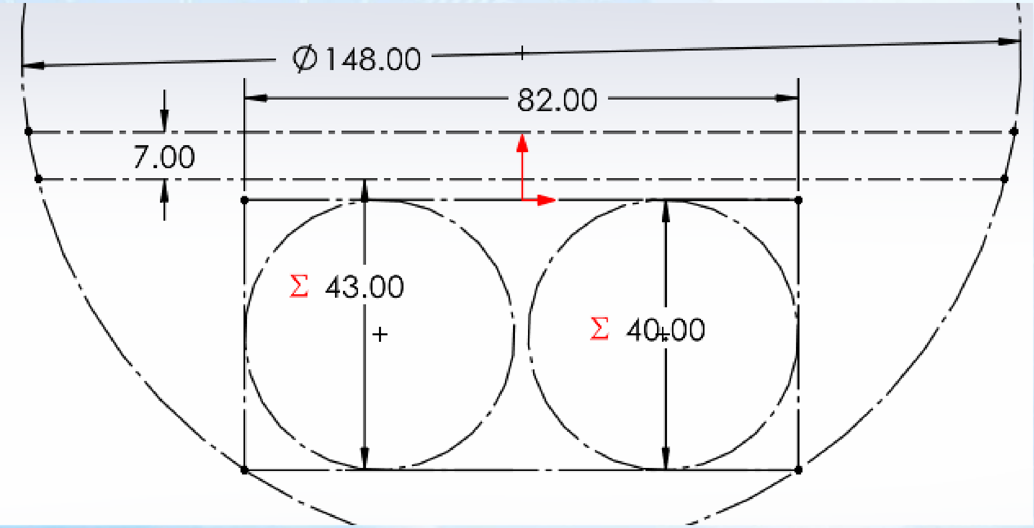
		km
Japan	hawaii	6500
Chicago	Hawaii	6750
NY	London	5570
NY	Hawaii	7981

Fuselage lbs/ft	255
Fuselage LH2 Penalty	3.8
Fuselage LH2 lb/ft	969
Tank/Fuel Mass Ratio	0.4

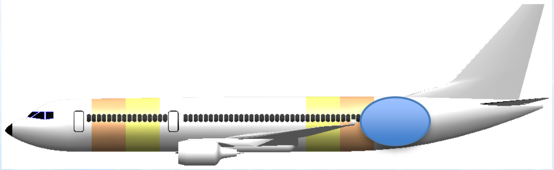
737 Fill - Cargo Bays

- Two 40” (28-38” ID Cylinders) – 20’ length each
- 6875 gals - 737 capacity
- 18% - 6” thickness for tank/support 1300 gal/6875
- 34% - 2” thickness 2300 gal/6875





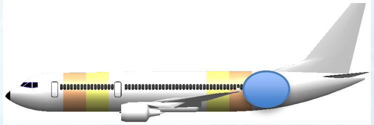
It’s the volume induced PAX costs, grid bottlenecks



- 30% LH2 by energy doubles the fuel volume of Jet A aircraft
- it’s ~ all that can fit – need new configurations, less fuel burn
- LH2-cost competitive with Jet Fuel-significantly less emissions
  - $3/kg IRA subsidy – will fuel be free with H2 production build up?
  - Add Liquefaction likely $2-3/kg, scaling dependent, at airport
  - H2 via pipelines collocated with other Pull applications to optimize cost
  - Costs driven by less PAX, airport infrastructure, and grid bottlenecks
  - Needs test data in real world conditions, technology to include more LH2

- Alternatively – reduce the range.   A Mid Range 6500 nm LH2 aircraft could fly 2000 nm at close to 100% less emissions, $/PAX is the concern

Dual H2-Jet Fuel Aircraft Vision

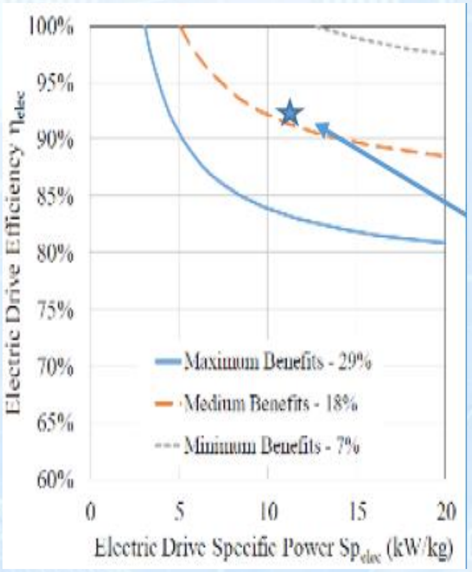


- **2028 Dual Hydrogen Jet Fuel Flight Demonstration**
  – Demonstrate that current aircraft and infrastructure can reduce emissions economically adding liquid hydrogen by 30% by 2028 to identify new or resolve challenges due to the stringent mass, volume, and safety requirements
- **Vision Forward is that emissions will be decreased through**
  - Dual H_2-Jet Fuel Aircraft providing partial pull to build out H2 infrastructure– cargo configs first (?)
    - H2 less cost and wider availability than 50/50 SAF Blend (PV wholesale/off-grid decentralized power + $3/kg subsidy)
  - Adding H_2 Airport liquefaction hubs annually, adapt to tech maturation, lessons learned
    - Introduce efficiency gains with liquefaction: provide low quality heat for buildings vs cooling towers
  - Building H2 plant locations near Pull applications (airports, concrete, steel, transport). Must consider energy transport, decentralized grids, excess capacity to address transmission bottlenecks and $
    - 10 times cheaper to transport H_2 in pipeline vs cable ; Liquefaction must be as close as possible to aircraft (transport costs)
    - LH2 acts as energy storage, buy cheap excess energy (duck curve) to address grid cost and transmission solutions
    - Aid offshore wind connection plan, and develop microgrids and H2 pipelines to address energy transport costs
  - Development of new technology and different aircraft configurations required to meet Net Zero
  - By retaining the wing tanks, it does not preclude SAF Aviation Climate Action Plan Vision

Adding Electrical Power Enables Multiple Configurations to Reduce Fuel Burn

- LH2 offers ‘free’ cooling to improve power conversion efficiency, improve engine life, performance, further reduce fuel burn

<u>Propulsive benefits drive required electrical system efficiency and to lesser degree kW/kg</u>



<u>Aft Fan</u>

<u>Blended Wing Body</u>

Ingest more turbulent, slower moving boundary layer (BLI) and accelerate to produce thrust

Multiple Distributed propulsors – stability without <u>control surfaces </u>(engines only -inefficient), BLI
High Bypass Ratio – decouple shaft speed
“Cut tail off” - less drag (not stable). Best for LH2?

Current Demonstrators

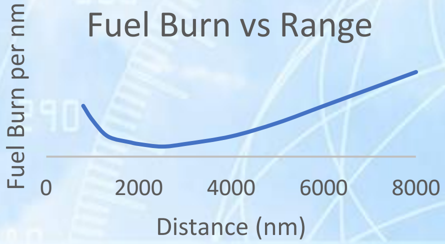
<u>Transonic Truss Braced Wing</u>

Increased wing aspect ratio- less drag
Many challenges to develop
→ Add partial LH2 to demonstrator

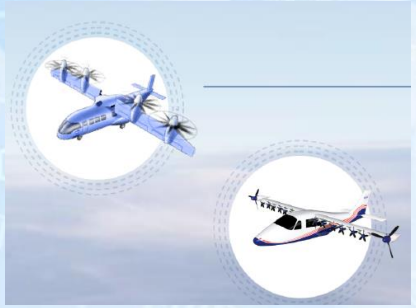
<u>BWB for Air Force Tanker -</u>
<u>Jet Zero</u> Demonstrator

New Business Model Driven by Emissions?

- Revenue PAX km ($ per passenger-km)
- What about fuel efficiency?
  - Long haul average is 31.5 PAX-km/liter
  - 27 to 40 PAX-km/liter is variation of all airlines
- Fuel consumption is 3-4 liters per 100 PAX-km
  - Autos 8 (2000) → 5.4 (2016) liters per 100 PK
  - Aircraft lower if fully packed and a bit faster too
- En-route stops vs non-stop can reduce Fuel per PAX-nm



Larger Volume?



Batteries /Fuel Cells for short trips?

BWB for Air Force Tanker - Jet Zero Demonstrator

Copper vs SC AC Loss

- Efficiency is key metric
- Lower AC loss improves system metrics, reduces machine design complexities

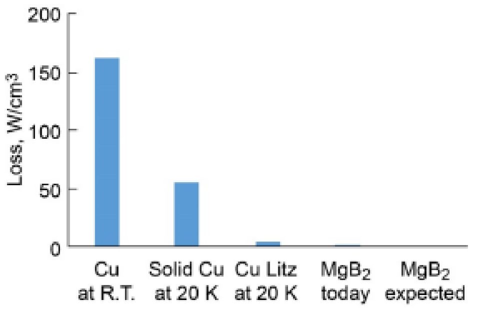


Figure 17.—Losses in various copper and MgB_2 wires. All wires are 0.96 mm in diameter and carry 100 A operating current in an AC magnetic field of 0.5 T at 200 Hz. Solid copper case at 20 K includes 12 percent magnetoresistance plus large eddy current loss. Copper Litz wire has 100-µm filaments. Room temperature (R.T.).

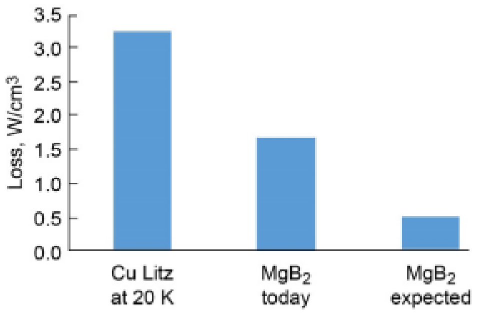
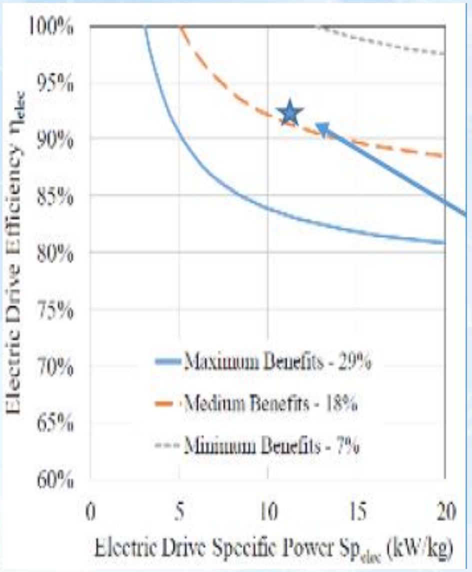


Figure 18.—Losses of cryogenic copper Litz wire and MgB_2 wires.



Propulsive benefits drive required efficiency and to lesser degree kW/kg

https://ntrs.nasa.gov/api/citations/20205005815/downloads/TM-20205005815.pdf
https://www.energy.gov/sites/prod/files/2020/12/f81/hfto-h2-airports-workshop-2020-schneider.pdf

LH2 and SAF both depend on delivery of Lower Cost Energy H2 production may be the key to reduce costs

- US Grid- patchwork of 1000s local utilities who do not account for long-term benefits and lower costs
- Off-Grid Power Will Be Our New Norm-'local' renewable future market is decentralized, GW microgrids

- Large facilities producing hydrogen can be switched on or off as supply of electricity fluctuates could be key to reduce high emission industries and economically consume excess capacity to reduce grid bottlenecks and distribution costs
- Waste Heat Recovery Opportunity: Cement accounts for 8% of emissions; Of many options, produce green H2 on site; integrate with Electrolysis to improve efficiency
- Potential of hydrogen to decarbonize Steel production 4% (up 30% in costs)
- Engineers have modified conventional diesel engine powered by hydrogen and small amount of diesel to cut emissions 85%
- *MIT reversed SOFC degradation and enhanced performance*

Optimizing an Integrated Renewable-Electrolysis System (nrel.gov)

If you buy PV wholesale (afternoons when demand is low, supply is high) **H2 is $3/kg**

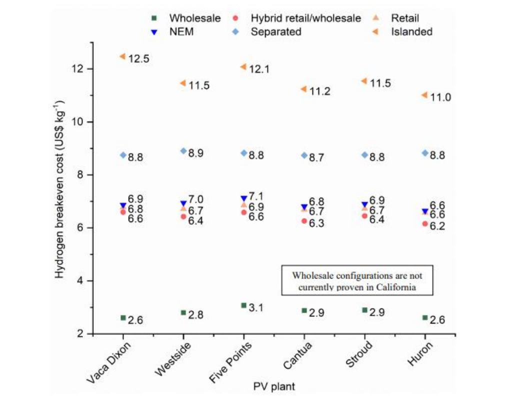
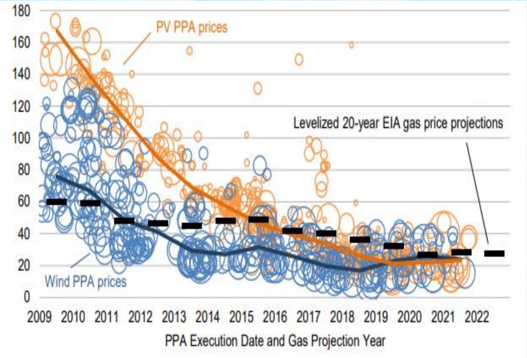


Figure ES-2. Current hydrogen breakeven production cost for PV + Electrolysis systems with six market configurations and six candidate locations

Renewables face Multiple Bottlenecks

- U.S. Cents/kWh: Solar 3.4 (+Storage 11), Natural Gas 8.6, Coal 18, On-Shore 4.2, Fixed off-shore 4.8
- Offshore can produce far more power than onshore wind, but floating costs must fall substantially
- U.S. has 1,250 GW capacity -> 2000 GW looking to be constructed, which exceeds the capacity of the entire US power plant fleet
  Not Enough Transmission Infrastructure. Wind and Solar face HUGE interconnect fees and connection can take years.
- Offshore Wind Does not have a plan of where it needs to go
- Off-Grid Power Will Be Our New Norm-'local' renewable future market is decentralized to reduce costs
- Lack of battery materials limits EV growth
  - *Debt bill reduces federal environmental permitting to 2 yrs*
- Over a decade to install 6 wind turbines on Lake Erie
  - Cats, Buildings, Pesticides, Fossil fuels kill more birds than wind turbines; Minimal on Lake Erie as birds often shun direct migration across the water

Levelized Power Purchase Agreements 2021 ($/MWh) energy.gov



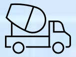
Wind PPA prices—and, more recently, utility-scale solar PPA prices—have, in many cases, been competitive with the projected fuel costs of gas-fired combined cycle generators

Purchase Agreements→ renewable energy production costs are sufficient for H2 Production today

Where to Place H2 Hubs?

Off-Grid/Excess Renewable Power to Reduce Emissions Economically

- Need studies to examine H2 pull locations (airports, steel, concrete) near excess power (land and offshore wind, solar), near interstates and pipelines
- Natural gas pipelines are limited to ~10% hydrogen so dedicated pipelines need consideration as well
- Possible <u>diesel / H_2 can be combined- without significant Nox- </u>opening up Semi Transport, mining vehicles
- [It is about 10 times cheaper to transport energy by a hydrogen pipeline than by an electric cable]
  - Produce H2 near renewable energy source



- Connects SW Solar (duck curve – excess power around noon and low demand)
- Connects land and offshore wind
- Connects pull H_2 applications (aviation, steel, concrete, transport, others)
- Grid – pipes and/or HVDC? Along major interstates?
- Must optimize to reduce transmission costs and bottlenecks

- Map is for illustration purposes only

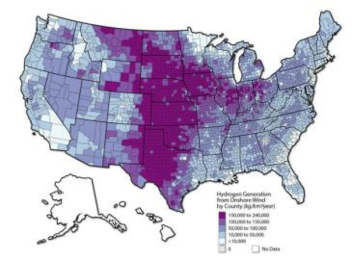
Lowering Costs of H_2 Production

- ***MIT reversed SOFC degradation and enhanced performance***
  – Extending lifetime of solid oxide fuel cells will help deliver low-cost, high-efficiency H2 production
- It is about 10 times cheaper to transport energy by a hydrogen pipeline than by an electric cable
  – Produce H2 near renewable energy source
- Off grid less expensive than on grid power - opportunity for off and off-shore wind to provide power locally, not be idled
- Solid Oxide Electrolysis Efficiency improves with temperature (did not include MIT discovery to improve electrodes)
  – Locate H2 Electrolysis Near Concrete and Steel Plants

04 May 2023 Bloom Energy demonstrates H_2 production with solid oxide electrolyzer at NASA Ames This high-temperature, high-efficiency unit produces 20%−25% more H_2 per megawatt (MW) than commercially demonstrated lower temperature electrolylzers such as proton electrolyte membrane (PEM) or alkaline. The current demonstration expands on Bloom's recent project on a 100-kW system located at the Department of Energy's Idaho National Laboratory (INL) which achieved record-breaking electrolyzer efficiency.

2022 Reactivation of chromia poisoned oxygen exchange kinetics in mixed conducting solid oxide fuel cell electrodes by serial infiltration of lithia

NREL Hydrogen Production Maps
Map – Wind 2016



Offshore by State

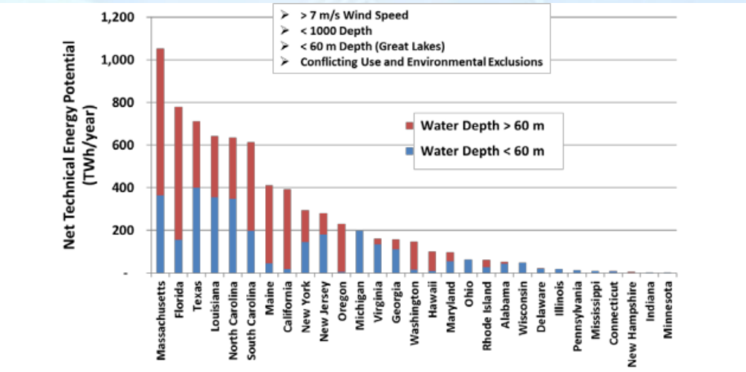


Figure ES-4. Offshore wind net technical energy potential (7,203 TWh/year) by state for depths of more than and less than 60 m

Synthetic Aviation Fuels – Energy required and limited resources drive costs

Sustainable Aviation Fuels: The Key to Decarbonizing Aviation | Rhodium Group (rhg.com)

- ***Feedstock limited SAF (HEFA) ~2X Jet Fuel $/kg; Alcohol to Jet, PtL 3-6X***
- PtL via Direct Air Capture (DAC) + Green H_2 is only synthetic fuel that does not face feedstock limitations for unbounded production
- **E-Kerosene (Ptl) 7-10 times more expensive than Jet A**

Direct Air Capture-- why so expensive?

Natural Gas vs. Electricity for Solvent-Based Direct Air Capture – McQueen
Frontiers.org

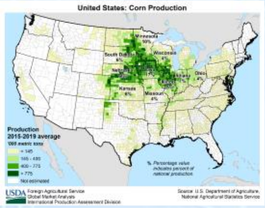
- 240-300 MW captures 1MtCO_2/year (~$240/Mt$CO_2$)
- Upstream natural gas leakage increases costs of DAC dramatically
  - Methane Global Warming Potential Multiplier vs Carbon Dioxide
    - 86 for GWP20 (20-year time horizon)   32 for GWP100 (100-year)
  - Nat. gas less expensive than electricity for same thermal output
- Electric Calciner cannot be cycled; requires storage via wind/solar
- Less concentration, higher costs – coal plants are not capturing CO_2
- Exhibit 21 Euro H2 Study - to 2050: ~ linear decrease from $240/Mt$CO_2$

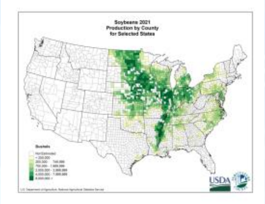
Ethanol: 47% (to 70%) less GHG than gas- Land Use, Fertilizer, Practices Key
U.S. Production: ***18B gal/yr ⇔ U.S. Aviation 18B gal***
US, Brazil dominate Ethanol Production Rainforest destruction soars 2022

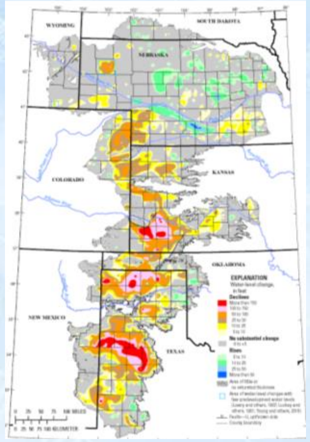
"Ultimately, there are many different ways to analyze DAC technologies and many knobs can be turned that lead to both high and low cost estimates. it is increasingly important to create transparent and robust system boundaries and their corresponding cost estimates. Such estimates are needed to inform policy and help society arrive at realistic expectations."

	Feedstocks – Synthetic Aviation Fuels
HEFA	Hydroprocessed esters fatty acids-Oil crops
Gas-FT	Feedstock Gasification (solid waste, cellulosic)
AtJ	Alcohol-to-jet (corn, sugarcane, cellulosic)
Ptl	Power to liquid (green LH2+carbon capture-DAC)

Texas managed depletion of Ogallala Aquifer is 6.5x its recharge rate. Fracking-16M gal per well







Data to 2015

"US High Plains produces more than 50 million tonnes of grain yearly and depends on the aquifers for as much as 90 percent of its irrigation needs. Taken as a whole, therefore, the model shows that **continued depletion** of the High Plains aquifers at current levels represents **a significant threat to food and water security both in the US and globally**. Grain production in Texas could be reduced by 40%."

Aircraft Design/Infrastructure/Power/Carbon SAF

Aircraft Design

- B-57 switched to LH2 powered flight over Lake Erie in 1956 with existing engines-first dual hydrogen jet fuel aircraft demonstration
  - Requirement for well-insulated, sealed, cryogenic tank and fuel system represents a challenge to the designer now requires flight demonstrations to raise the technology readiness
  - Cryogenically insulated systems do not pose an insurmountable problem for dual fuel aircraft; must minimize heat leaks, and provide flight-weight tanks, withstand 1000s of take-offs and landings, address safety and certification of a radically different transportation system—find the unknown unknowns
  - Support structure must consider thermal expansion and contraction over delta T
  - Fuel weight decreases by factor of 2.8 LH2 versus Jet A
  - LH2 aircraft have lower lift to drag ratios, larger fuselages
  - Engine life and other technologies improves with LH2 cooling
- New aircraft configurations and technology are required to reduce fuel burn, weight to achieve net zero economically
- Liquid Hydrogen offers a 30% reduction in emissions for all range aircraft at substantially less risk than carbon SAF

Infrastructure / Power

- US Grid has 1,200 GW Capacity; Bottlenecks hamper growth
- 2,000 GW waiting installation approval (600 GW Storage)
- Wind, Solar, and Gas have all levelized to $30/MWh (2022)
- Its 10X cheaper to ship energy via pipeline than cables
- US Grid is a patchwork of 1000s of local utilities and does not account for the long-term benefits and lower costs
- Grid transmission based on fossil fuel must shift to decentralized microgrids to accommodate renewables and lower costs, but there is no functional system to figure out how to pay for and regulate the 1000s of utilities
- Wholesale PV combined with current electrolysis can produce hydrogen at $3/kg and likely lower when combined with wind and off grid power

Carbon SAF

- Carbon based Synthetic Aviation fuel faces resource limitations and significant energy usage to reduce emissions economically – 2050 goals are unsustainable

Dual Hydrogen Jet Fuel Aircraft Summary

- *1956 Dual Hydrogen Jet Fuel Flight over Lake Erie*
- *30% LH2 by energy reduces CO_2 emissions 30%, provides 'pull' for H2 economy in fixed, high energy need locations*
- *Liquid hydrogen cooling enables fuel burn reductions, new aircraft configurations*
- *Demonstrations are required today* to address the requirement for well-insulated, sealed, cryogenic tank and fuel system and infrastructure challenges
- *Sustainable Aviation Fuel is driven by grid bottlenecks and costs*
- *Studies and demonstrations are required to develop a cost-effective, energy and H_2 transportation grid that can take advantage of hourly excess renewable energy*
  - *Studies are required to identify airports that can most readily adapt to LH2 aircraft*
  - *H2 production from off-grid power likely near offshore wind and interstates, near steel and concrete for high quality waste heat efficiency gain (15%); locate near other H2 customers; minimize pipeline length; utilize liquefaction low quality waste heat to reduce emissions*

Thank You

Questions?