Thermodynamic and Dynamic Performance Characteristics of Retrofit and New H_2 Aircraft Designs

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1

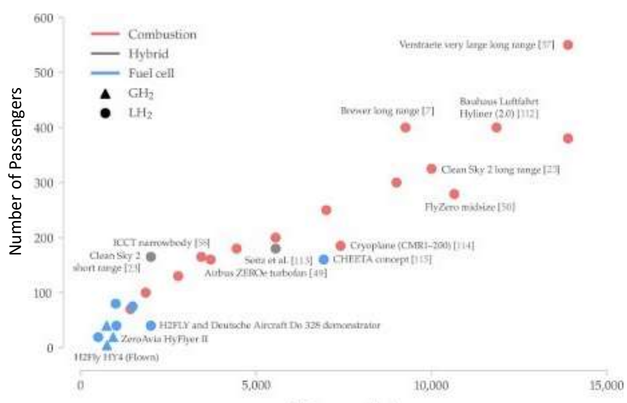
Commercialization of Hydrogen aircraft

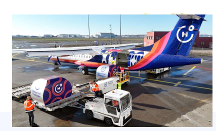
Industry yet to consider SOFC or cryo-compressed storage.

Table: Large hydrogen-powered aircraft that have flown.

Aircraft	First flight	Storage	Propulsion	Notes	Source
NACA-modified B-57	1957	LH_2	Turbojet	One hydrogen-powered engine	Sloop
Tupolev Tu-155	1988	LH_2	Turbofan	One hydrogen-powered engine	Sosounov and Orlov
Boeing Fuel Cell Demonstrator Airplane	2008	GH_2	PEMFC	Fuel cell provided all power in cruise	Boeing
Antares DLR-H2	2009	GH_2, 350 bar	33 kW fuel cell		German Aerospace Center
AeroVironment Global Observer	2011	LH_2			AeroVironment
Boeing Phantom Eye	2012	LH_2	Modified Ford 2.3L ICE		Boeing
H2FLY HY4	2016	GH_2	45 kW PEMFC		German Aerospace Center
ZeroAvia Piper Malibu demonstrator	2020	GH_2, 350 bar	PEMFC	Only partially fuel-cell powered	Harris Warwick
ZeroAvia Dornier 228 demonstrator	2023	GH_2	Fuel cell	Batteries and fuel cell each powered half of left propeller with stock right engine	Crownhart
Universal Hydrogen Dash-8 demonstrator	2023	GH_2	Megawatt-class PEMFC	Fuel cell powered right engine with stock left engine	Norris

Source: Adler, Eytan J., and Joaquim RRA Martins. "Hydrogen-powered aircraft: fundamental concepts, key technologies, and environmental impacts." *Progress in Aerospace Sciences* 141 (2023): 100922.





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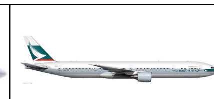
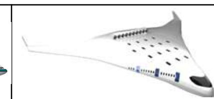
Example Integration analysis

					
	Cessna Citation XLS +	Cessna Citation S550 II	ATR 42-600S	777-300ER	BWB 365
Integration successful	SOFC GT H_2 Combustion	SOFC/GT	PEMFC SOFC/GT	SOFC/GT	SOFC/GT
Max power demand	2.3 MW	1.3 MW	3.5 MW	77.9 MW	59.9 MW
Interior Volume	15.79 m^3	11.3 m^3	75.5 m^3	604 m^3	~1000 m^3
Design Range	2,417 miles	2,299 miles	1,001 miles	6,574 miles +	6,574 miles

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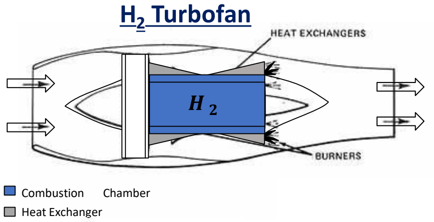
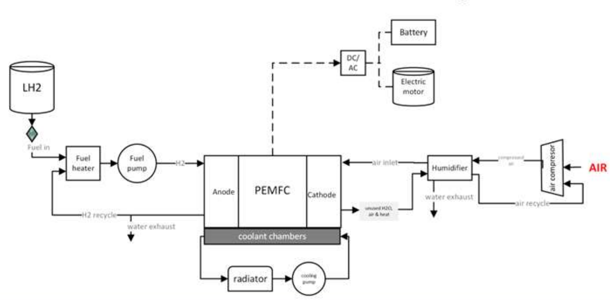
Conceptualize H_2 powertrain models

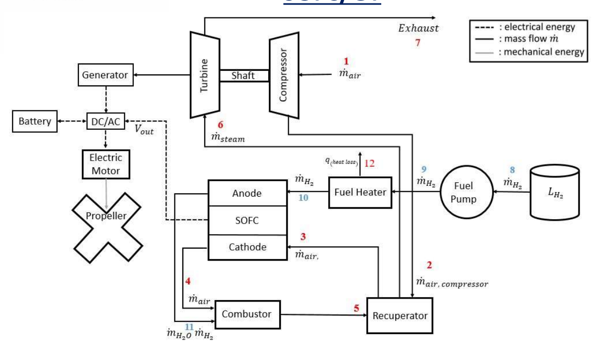
H_2 Turbofan



PEMFC



SOFC/GT



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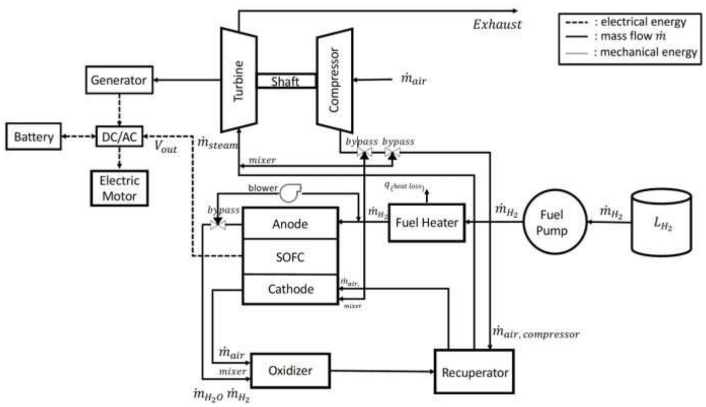
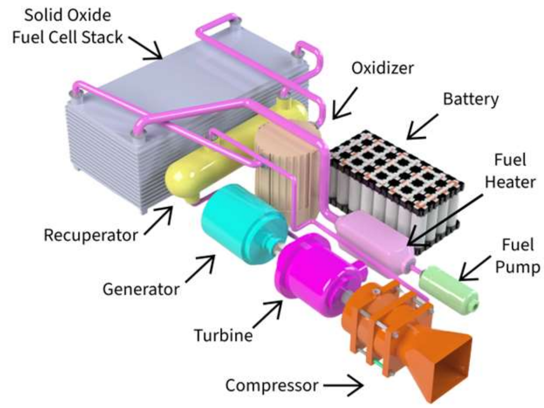
SOFC/GT System





The SOFC/GT hybrid power system shows energy flows through components like the fuel heater, recuperator, and fuel pump, with hydrogen and air pathways.

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Retrofit 1: Citation XLS+

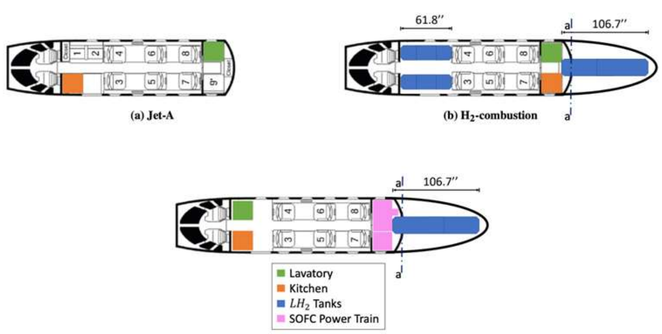

Fig. 8 Interior layouts for retrofit analysis

Table 3 Cessna Citation 560 XLS+ performance specifications

Parameter	Value
Cruise range	3,889.2 km
Maximum number of passengers	9
Maximum speed limit	0.75 Mach
Maximum operating altitude	13,716 m
Thrust specific fuel consumption	0.045 kg/(N · h)

Table 5 Power and SOFC energy requirements

Parameter	Value
Thrust per engine, N	18,322
Maximum Takeoff velocity, km/h	230
Engine maximum power, kW	2,344.96
Energy required by H_2 combustion (MJ)	32,546.51
Energy, kW · h	9,040.70
Fuel cell power (75%), kW	1,758.72
Battery power (25%), kW	586.24
Battery size, kW · h	146.56
Cryocooler maximum power, kW	23.45

Alsamri, Khaled, et al. "Methodology to Assess Emissions and Performance Trade-Offs for a Retrofitted Solid Oxide Fuel Cell Hybrid and Hydrogen Powered Aircraft." *AIAA SCITECH 2023 Forum.* 2023.c

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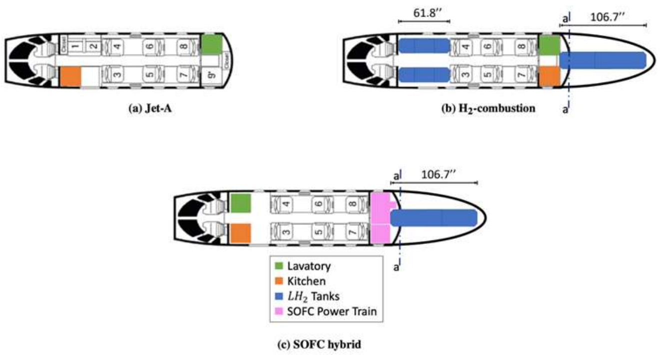

Fig. 8 Interior layouts for retrofit analysis

Table 4 Fuel weights for cruise

Cruise weight	Jet-A, kg	H_2 combustion, kg	SOFC, kg
W_{start}	9,223.35	8,685.22	9,187.86
W_{end}	8,146.54	8,282.74	8,912.17
W_{fuel}	1,077.81	401.68	271.31

SOFC aircraft will consume less fuel due to higher efficiency.

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Retrofit 1: performance & techno-economics framework

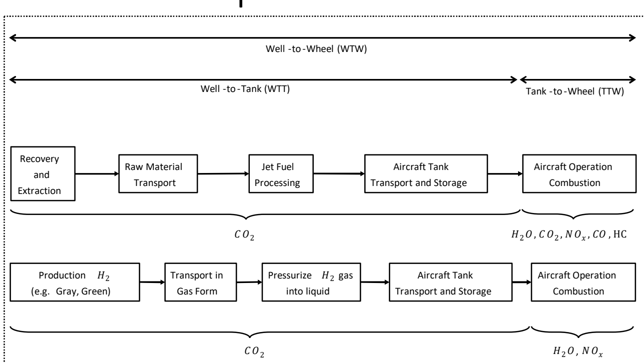

Figure 7: Lifecycle Assessment (LCA) boundary of Jet-A Fuel (Top) and LH2 fuel (Bottom)

Table 7: NOx and H2O total emissions per flight

Emissions	Jet-A (kg)	H_2 (kg)	SOFC Hybrid (kg)
NO_x	9.84	9.19	4.95
H_2O	2161.63	5953.80	3197.67

Table 8: CO2 emissions for full lifecycle analysis of all configurations

Path	Case	Jet-A (kg)	Gray H2 (kg)	Green H2 (kg)	Gray SOFC (kg)	Green SOFC (kg)
Well-to-Tank kg CO2	(i)	864.65	5997.16	3276.06	3223.78	1760.59
	(ii)		12002.18	6552.23	6447.54	3521.28
Tank-to-Wheel kg CO2	(i)	5681.69	0	0	0	0
	(ii)		0	0	0	0
Well-to-Wheel kg CO2	(i)	6546.34	5997.16	3276.06	3223.78	1760.59
	(ii)		12002.18	6552.23	6447.54	3521.28

Emissions Analysis

- Gray and green hydrogen combustion results in 8.38% and 49.96% reduction in WTW CO_2 emissions.
- Gray and green hydrogen powered SOFC hybrid have 50.78% and 73.12% reduction in WTW CO_2.

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Retrofit 1: performance & techno-economics framework

Table 9: Total fuel cost per segment

Segments	Case	Jet-A ($)	Gray H2 ($)	Green H2 ($)	SOFC H2 Gray ($)	SOFC H2 Green ($)
Takeoff	(i)	44.11	64.06	89.54	20.81	29.1
Climb	(i)	1,339.06	1,944.63	2,718.30	631.63	882.92
Cruise	(i)	2,472.67	3,735.78	5,222.06	2,522.35	3,525.87
Descent	(i)	110.28	159.96	223.60	52.02	72.71
Approach	(i)	75.62	109.81	153.50	35.67	49.86
Taxi/Idle	(i)	101.45	147.31	205.92	47.86	66.89
Total Fuel Cost	(i)	4,143.18	6,161.55	8,612.92	3,310.33	4,627.34
Total Fuel Cost	(ii)		12,323.10	17,225.84	6,620.66	9,254.68

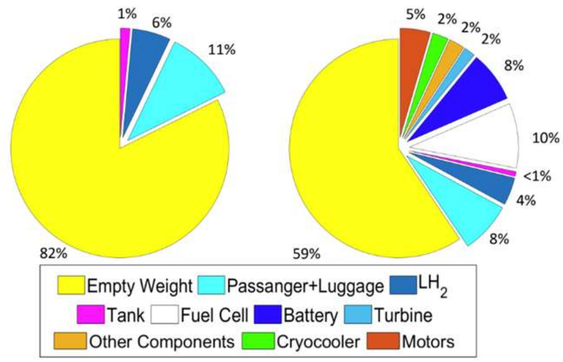

Figure 10: Fractional weights from implementing a retrofit on a H2-combustion (Left) and a SOFC hybrid (Right) powered Cessna Citation 560XLS+

Mass analysis:

- *5% decrease* and *17.87% increase* in takeoff weight for the *H2-combustion* and *SOFC hybrid* aircraft respectively.

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Cost Analysis

- Fuel cost *reduced by 29.3%* when replacing kerosene combustion w/ *SOFC hybrid powered by gray H2*.

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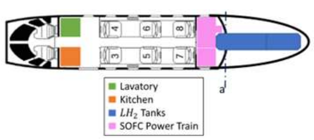
Retrofit 2: Citation S550 S/II



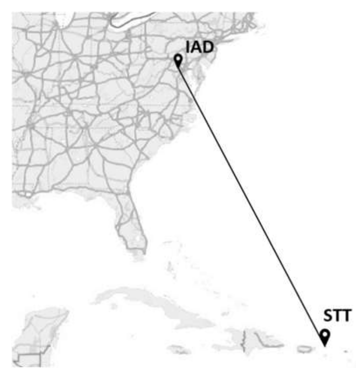


Table 2: Cessna S550 Citation S/II interior dimensions

interior Dimensions	Measurement
Cabin Length	16 feet (4.88 meters)
Cabin Width	4.10 feet (1.49 meters)
Cabin Height	4.9 feet (1.46 meters)
Cabin Volume (excluding baggage)	422 ft³

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Alsamri, Khaled, et al. "Methodology to Assess Emissions and Performance Trade-Offs for a Retrofitted Solid Oxide Fuel Cell Hybrid and Hydrogen Powered Aircraft." *Journal of Aircraft*. 2024.

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Retrofit 2: Citation S550 S/II

Component	Mass (kg)
MTOW	6849 kg
SOFC System	360
Gas Turbine	15.4
Electric Motors	182
Cryocoolers	39.896.8
JT15D-4 Turbofan Engine	253 each
Battery	268
Fuel	394
Tanks	78
Total takeoff mass	5900 <MTOW

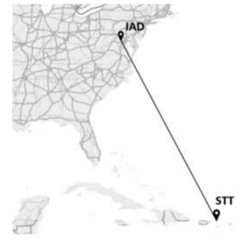

Table 5: Flight conditions for example flight

Parameters	*Values*
Maximum take off weight (lbs)	15,100
Range (nmi)	1551
Takeoff Field Length (ft)	10,501
Cruise Mach Number	0.67
Cruise Altitude (ft)	42,950
Pressure at Cruise Altitude (atm)	0.16
Temperature at Cruise Altitude (°R)	389.97

- Retrofit mass analysis 13% below MTOW.
- SOFC occupies 56.6 ft^3, Battery 4.25 ft^3

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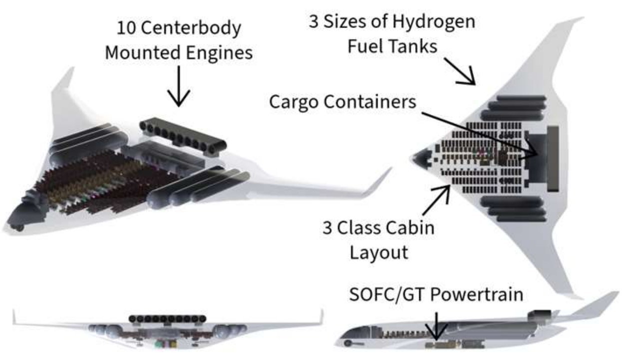
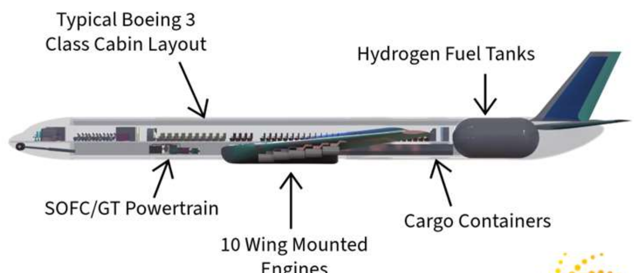
Retrofit 3,4: Hydrogen Class 365

Hydrogen BWB-365



Hydrogen T&W-365



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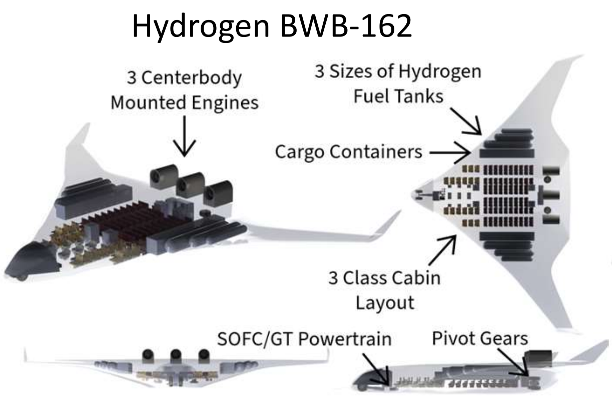
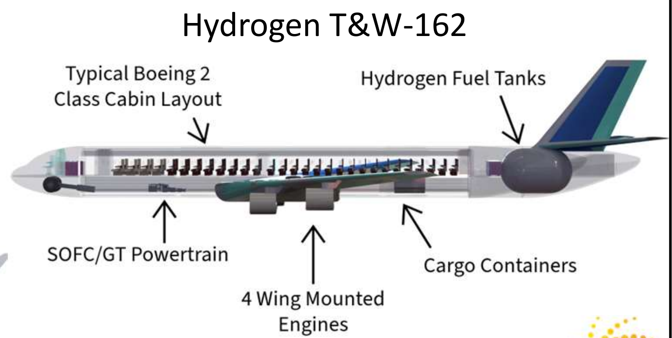
Retrofit 5,6 Hydrogen Class 162





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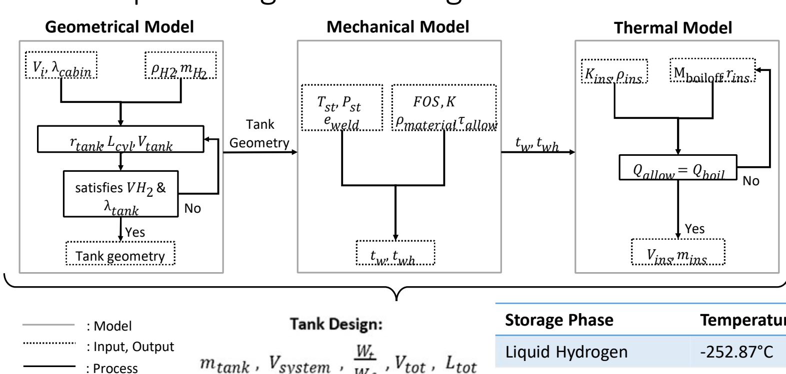
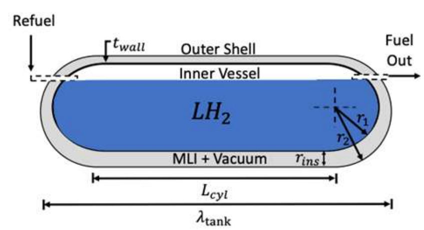
Conceptualizing: Tank configuration module





Tank Design:

$$m_{tank}\,,\ V_{system}\,,\ \frac{W_t}{W_f}\,,\ V_{tot}\,,\ L_{tot}$$

Storage Phase	Temperature Range	Pressure Range	Density
Liquid Hydrogen	-252.87°C	Approx. 1 bara	70.85 kg/m³
Cryocompressed	-196°C to -252.87°C	250 to 700 bara	81 kg/m³ to 87 kg/m³

$$Q = \dot{m} \times h_{fg}$$

$$Q_{tot} = Q_{cond} + Q_{conv} + Q_{rad}$$

$$Q_{\text{total}} = \frac{2\pi L k (T_o - T_i)}{\ln\left(\frac{r_2}{r_1}\right)} + \frac{4\pi r_1^2 K (T_1 - T_2)}{r_2 - r_1} + h\left(2\pi r_2 L + 4\pi r_2^2\right)\left(T_{\text{surface}} - T_{\text{fluid}}\right) + \epsilon\sigma\left(2\pi r_2 L + 4\pi r_2^2\right)\left(T_{\text{hot}}^4 - T_{\text{cold}}^4\right)$$

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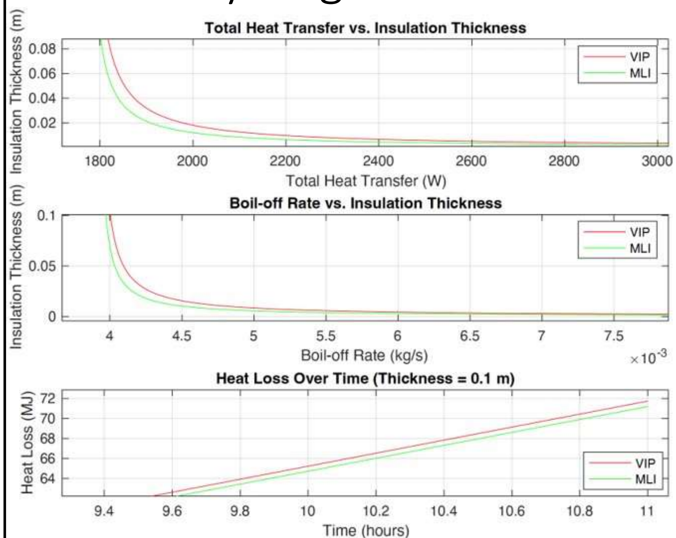
14

BWB- Hydrogen Tanks



$$R = \frac{t}{k \cdot A}$$

$$Q_{\text{conduction}} = \frac{T_{\text{surface}} - T_{\text{air}}}{R}$$

$$Q_{\text{radiation}} = \alpha \cdot \sigma \cdot A \cdot \left(T_{\text{surface}}^4 - T_{\text{air}}^4\right)$$

$$Q_{\text{convection}} = h \cdot A \cdot \left(T_{\text{surface}} - T_{\text{air}}\right)$$

- Insulation thickness increase (0.02 m to 0.1 m) reduces heat transfer (2250 W to 1750 W); Multi-Layer Insulation (MLI) outperforms Vacuum Insulation Panels (VIP).
- Boil-off rates drop (5 g/s to 3.8 g/s) with increased insulation; MLI shows lower rates than VIP.
- Over 11 hours, MLI results in ~70 MJ cumulative heat gain, slightly better than VIP.

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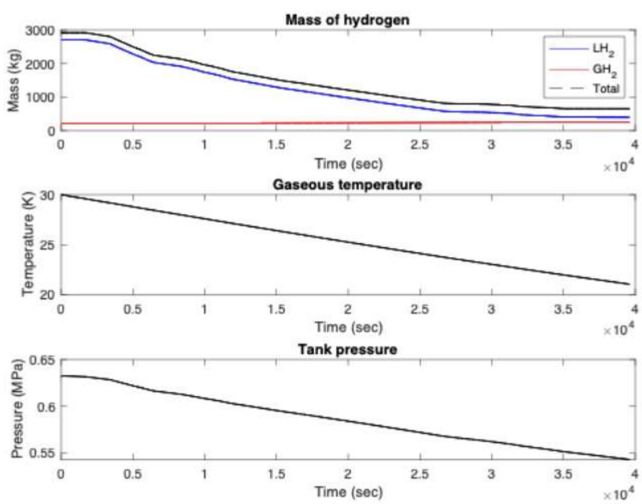
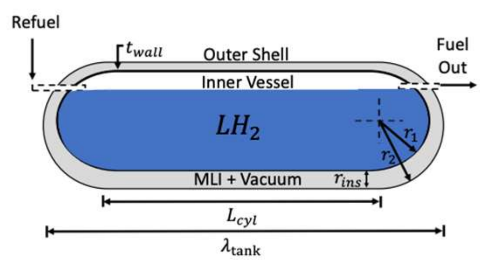
BWB- Hydrogen tank dynamic model





- Hydrogen decreases steadily with a constant cruise consumption rate; initial load is 2916 kg with 7.2% gaseous hydrogen.
- Gaseous temperature decreases from 30K to 24K.
- Tank pressure drops from 0.65MPa to 0.55 MPa

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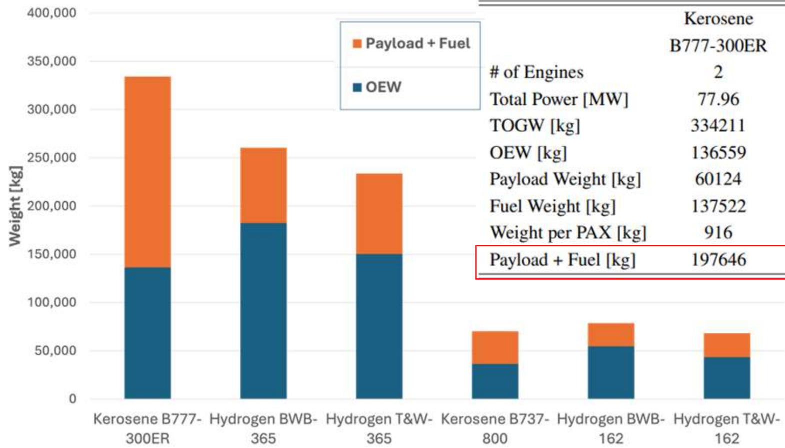
BWB-Weight Comparison



	Kerosene B777-300ER	Hydrogen BWB-365	Hydrogen T&W-365	Kerosene B737-800	Hydrogen BWB-162	Hydrogen T&W-162
# of Engines	2	10	10	2	3	4
Total Power [MW]	77.96	59.9	53.1	10.74	11.91	10.2
TOGW [kg]	334211	260403	233698	70307	78687	68328
OEW [kg]	136559	182334	150346	36334	54555	43382
Payload Weight [kg]	60124	60124	60124	22108	22108	22108
Fuel Weight [kg]	137522	17946	23229	11859	2024	2838
Weight per PAX [kg]	916	713	640	434	486	422
Payload + Fuel [kg]	197646	78069	83352	33968	24132	24946

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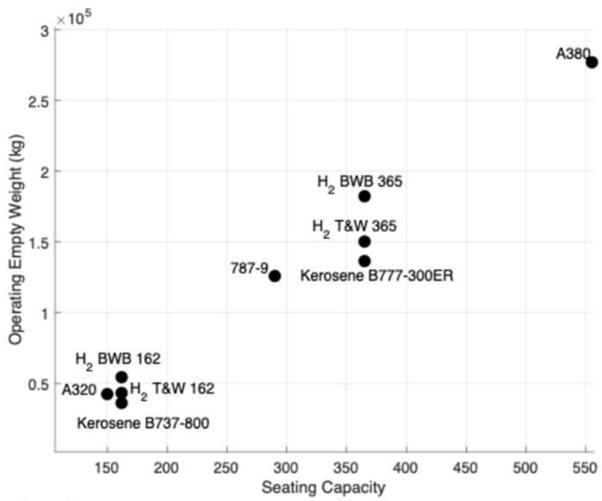
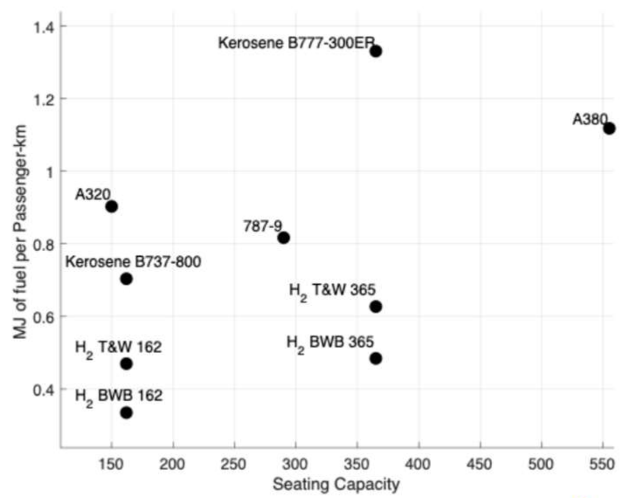
Weight vs. Seating Capacity





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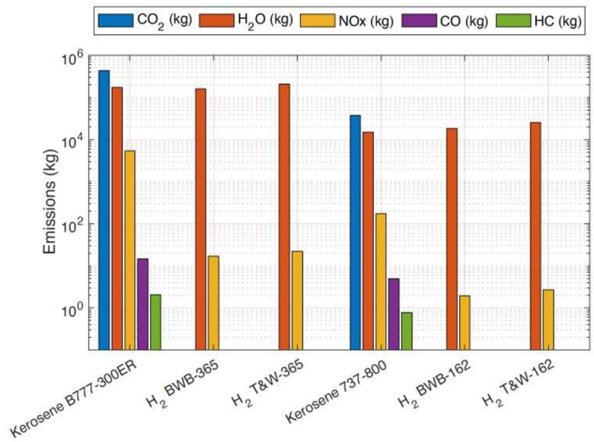
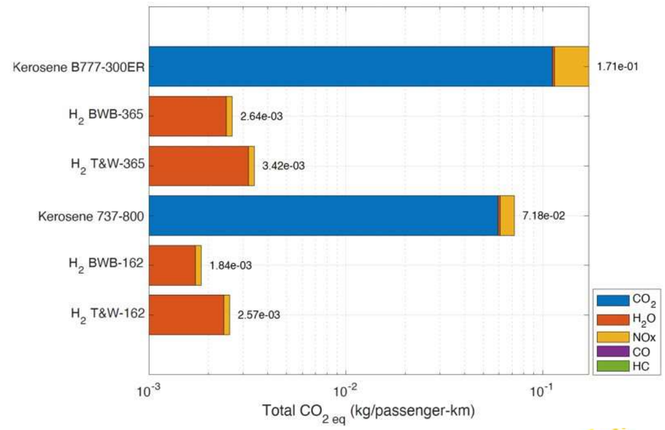
BWB vs. conventional Emissions





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BWB Conclusions

Parameter	Hydrogen BWB-365	Hydrogen BWB-162
OEW Trend	↗ (Increasing due to increased wing surface area and cabin planform area)	
Fuel Weight	↓ 22.7% compared to hydrogen T&W-365	↓ 28.7% compared to hydrogen T&W-162
Fuel Consumption (MJ/passenger-km)	↓ 61% compared to B777-300ER	↓ 52% compared to B737-800
Total Takeoff Weight per Passenger	↓ 22% compared to B777-300ER	↑ 11% compared to B737-800
NOx Emissions	↓ 99.6% compared to B777-300ER	↓ 98.9% compared to B737-800
Total CO2 eq (kg/passenger-km)	↓ 98% compared to B777-300ER	↓ 97% compared to B737-800

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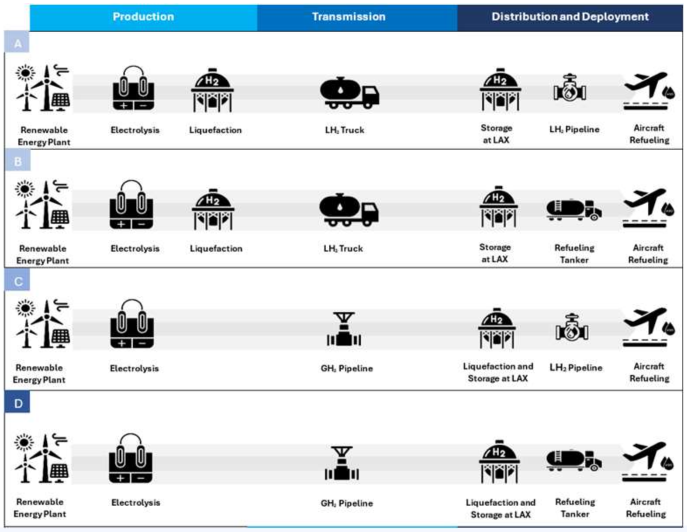
20

Hydrogen On-Site production at LAX via different Scenario



Hydrogen demand for 2030 (5% transition to hydrogen): **3.3 M lit/day**

Hydrogen demand for 2050 (20% transition to hydrogen): **16.78 M lit/day**

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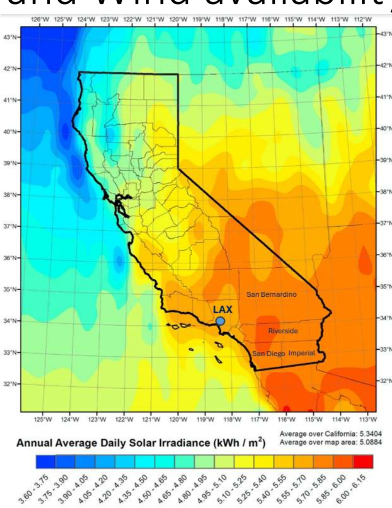
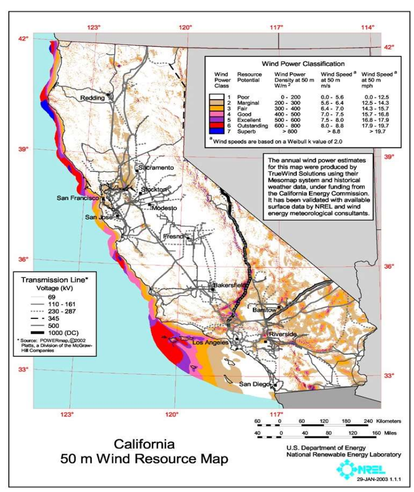
Solar and Wind availability near LAX



Solar radiation available for photovoltaics in California using the GATOR-GCMOM model



Annual estimates of onshore and offshore wind power in California, obtained at a height of 50 m above ground level, based on wind speed frequency distributions and air density

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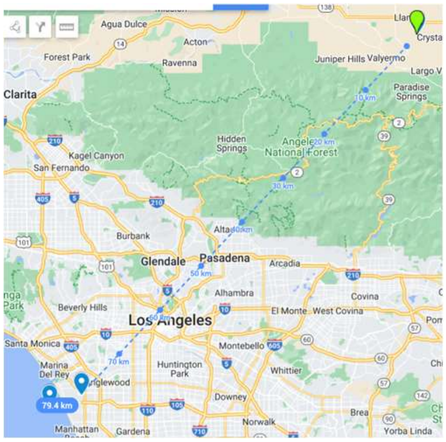
Infrastructure Included in LAX Technoeconomic Analysis



Solar field distance to LAX: 75 km

Off-shore field distance to LAX: 5 km

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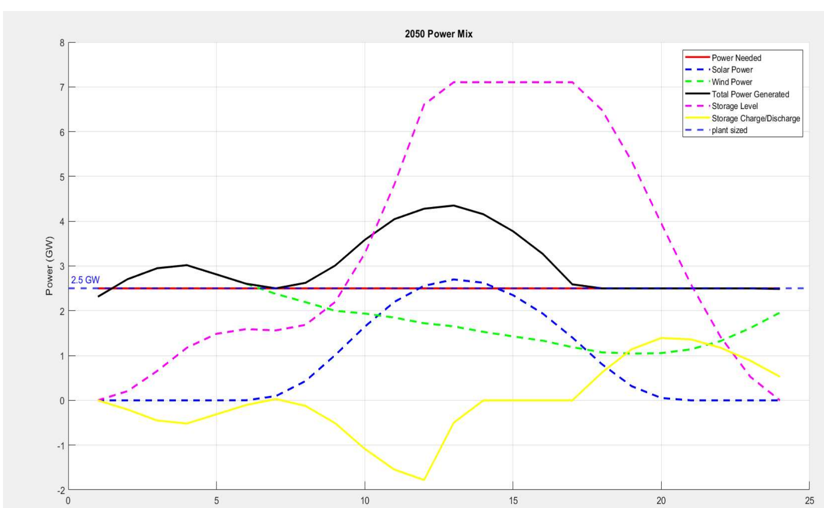
Power Mix for 2050 – Solar, Wind & Battery Capacity (2.5 GW demand)



Maximum Solar Power: 2.70 GW

Maximum Wind Power Generated: 3.02 GW

Storage Capacity GWh : 7.25 GWh

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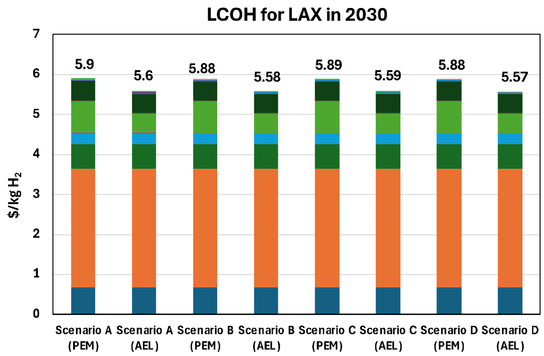
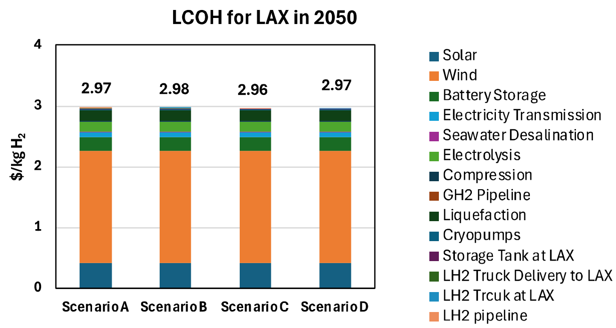
24

Levelized Cost of Hydrogen (LCOH)





$$\text{LCOH} = \frac{\text{Total Annual Cost}}{\text{Annual Hydrogen Production}} = \frac{\sum_i(\text{CAPEX}_i \times \text{CRF}_i + \text{OPEX}_i)}{m_{H_2}}$$

$$\text{CRF} = \frac{d(1+d)^N}{(1+d)^N - 1}$$

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25

Some CEI Publications covering both modeling and experimental aspects of H_2 Aviation:

1. Alsamri, K., De la Cruz, J., Emmanouilidi, M., Huynh, J., & Brouwer, J. (2024). **"Methodology for assessing retrofitted hydrogen combustion and fuel cell aircraft environmental impacts"**. *Journal of Propulsion and Power*, 1-16.
2. Alsamri, K., Rezaei, S., Chung, V., Huynh, J., & Brouwer, J. (2024). **"Dynamic modeling of Hydrogen SOFC/GT powered Aircraft with integration analysis"**. *AIAA SCITECH 2024 Forum* (p. 1532).
3. Chung, Oi Ching Vanessa, et al. "**Design Methodology of Hydrogen Solid Oxide Fuel Cells Propulsion System in Blended Wing Body Aircraft**." *AIAA AVIATION FORUM AND ASCEND 2024*. 2024.
4. Hovakimyan, Gevorg. ***Numeric Design and Performance Analysis of Solid Oxide Fuel Cell–Gas Turbine Hybrids on Aircraft***. University of California, Irvine, 2014.
5. Pratt, Joseph, Brendan Shaffer, Jacob Brouwer, and Scott Samuelsen (2009). **"Sub-atmospheric pressure solid oxide fuel cell experimental setup and initial results"**. *7th International Energy Conversion Engineering Conference*, p. 4525.
6. Tarroja, B., Mueller, F., Pratt, J., & Brouwer, J. (2009). "**Thermodynamic design analysis of a solid oxide fuel cell gas turbine hybrid system for high-altitude applications"**. *7th International Energy Conversion Engineering Conference* (p. 4526).
7. Pratt, Joseph W., Jacob Brouwer, and G. Scott Samuelsen. (2007). **"Performance of proton exchange membrane fuel cell at high-altitude conditions"**. Journal of propulsion and power 23.2 : 437-444.
8. Pratt, Joseph, Jacob Brouwer, and G. Samuelsen.(2005). "**Experimental performance of an air-breathing PEM fuel cell at high altitude conditions"**. *43rd AIAA Aerospace Sciences Meeting and Exhibit*.
9. Freeh, Joshua E., Joseph W. Pratt, and Jacob Brouwer. (2004). **"Development of a solid-oxide fuel cell/gas turbine hybrid system model for aerospace applications"**. *Turbo Expo: Power for Land, Sea, and Air*. Vol. 41723. 2004.

Collaboration with:

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26

Thermodynamic and Dynamic Performance Characteristics of Retrofit and New H_2 Aircraft Designs

Khaled Alsamri, Sajjad Razaei, Jack Brouwer
Clean Energy Institute
University of California Irvine

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27