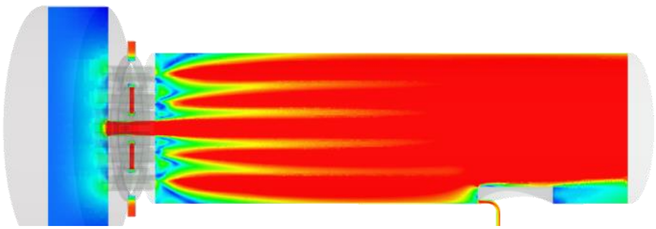
Transitioning to a Carbon-Neutral Future: A Review of Low/Zero Carbon Fuel Combustion Research at Southwest Research Institute

Brian Connolly
Research Engineer
Propulsion and Energy Machinery

Southwest Research Institute

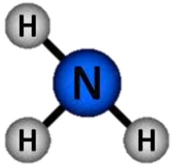
Low/Zero Carbon Fuel Combustion Activities at SwRI

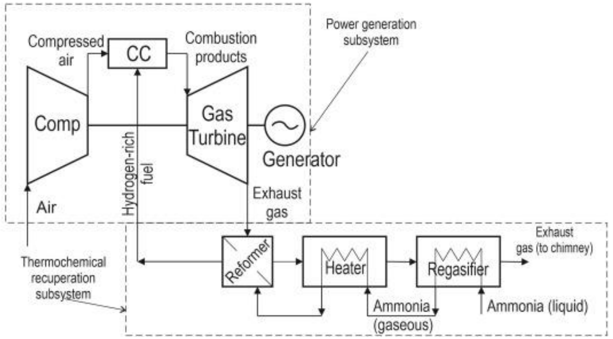
Hydrogen (H_2)

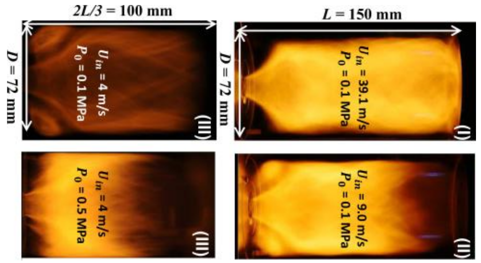


Courtesy: Dr. Tim Allison and Dr. Brian Connolly

Ammonia (NH_3)

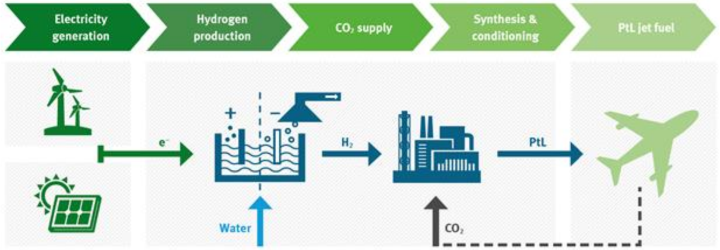


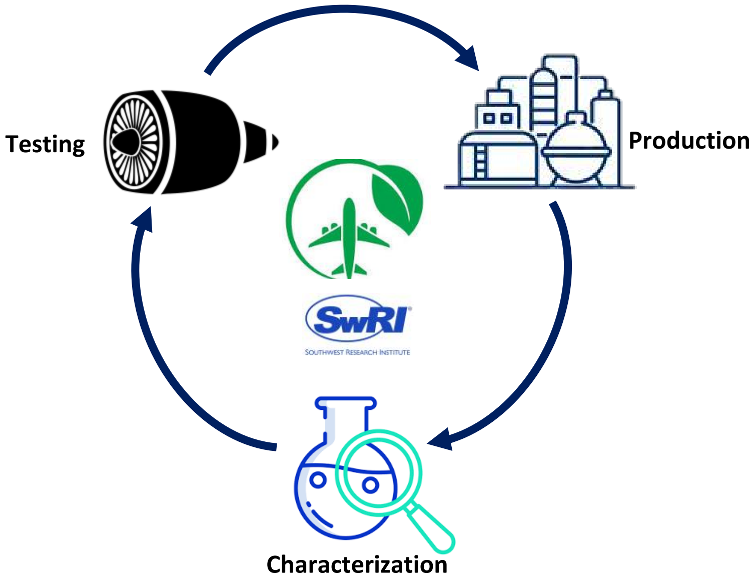




Source: Paschenko et al., 2022 , Kobayashi et al., 2019

Sustainable Aviation Fuels (SAF)

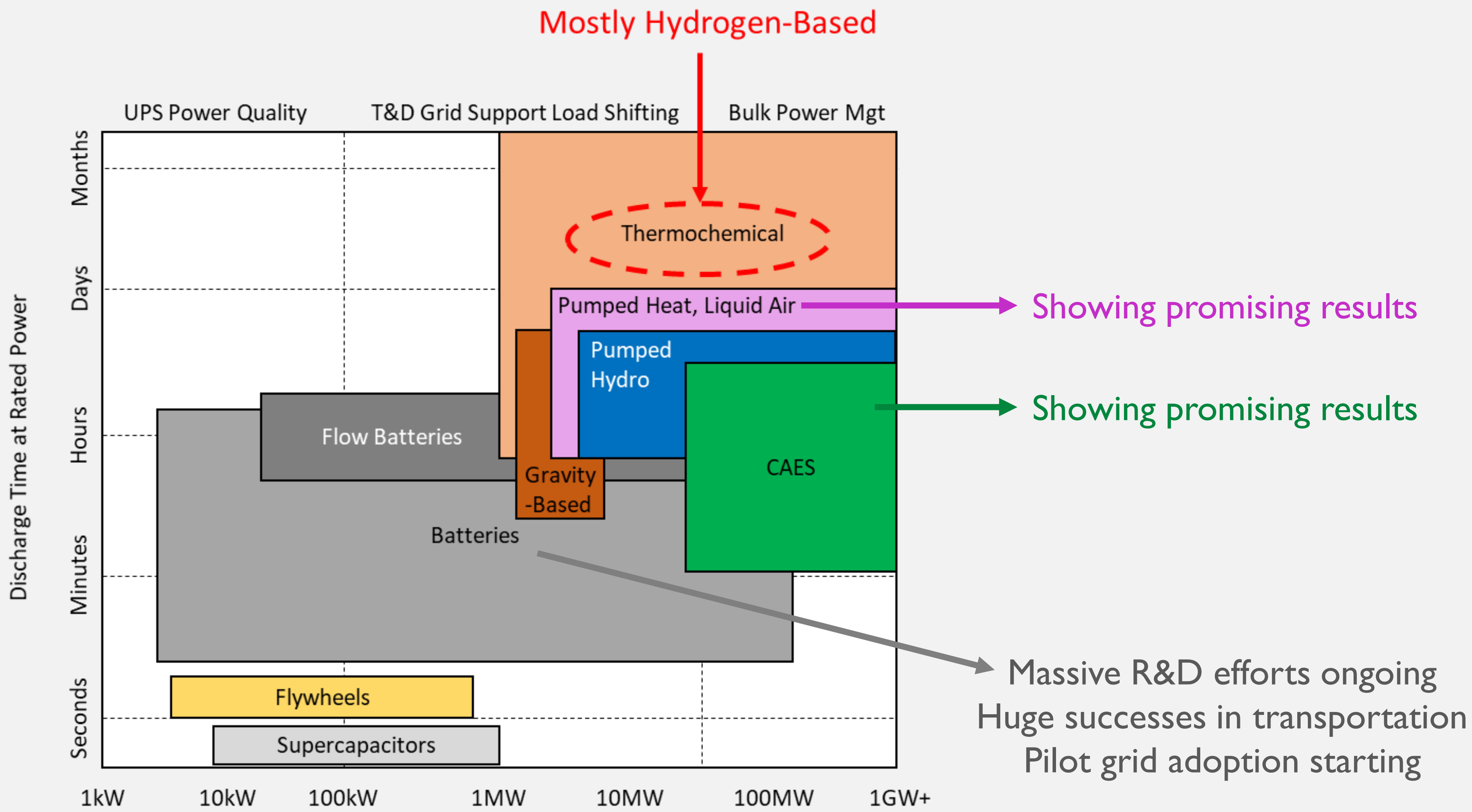




Source: EESI

Energy Storage Landscape

Load balancing requirements for a renewables-dominated grid are typically on the order of hours to days



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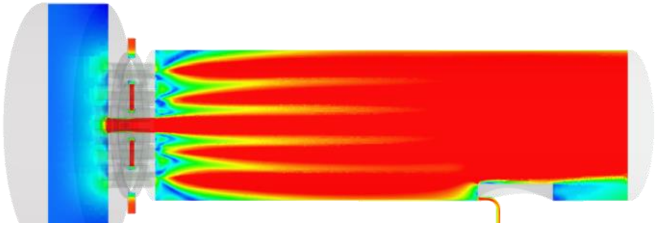

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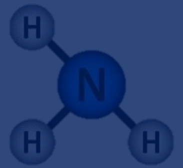

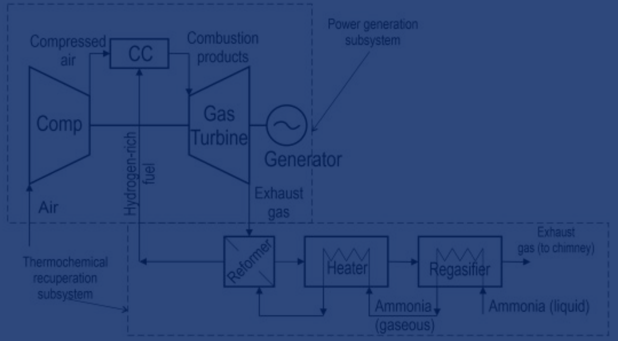

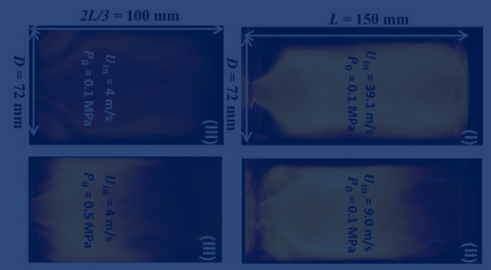

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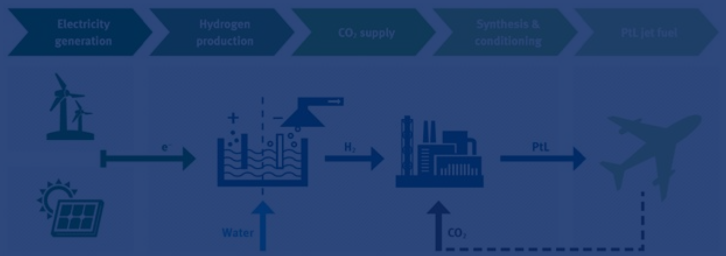
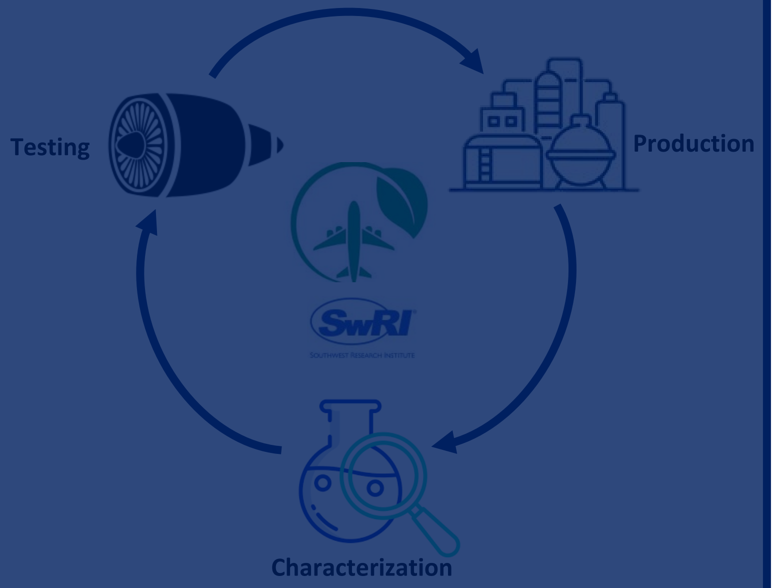
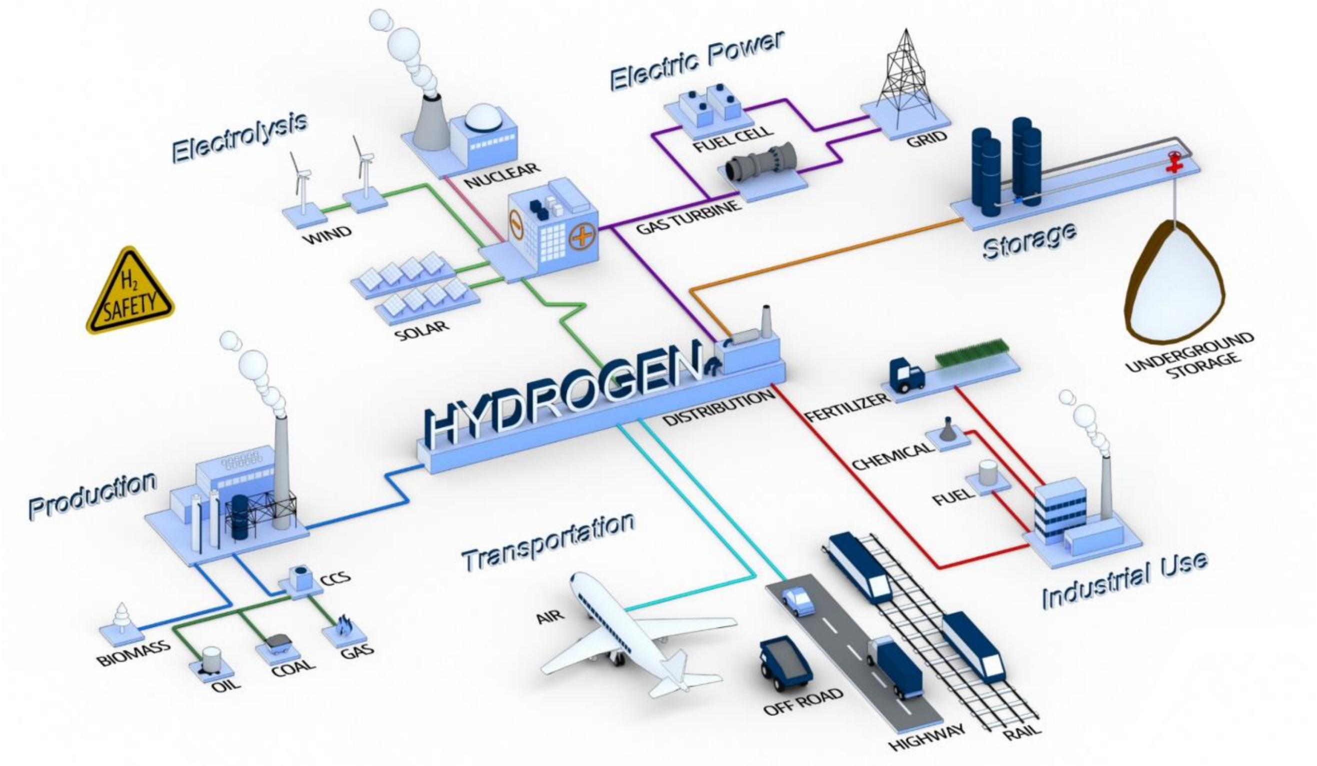




Source: EESI

Why H_2?



Fuel	NH_3	H_2	CH_4	C_3H_8
Maximum burning velocity (cm/s)	7	291	37	43
Lower calorific value (MJ/kg)	18.6	120	50	46.4
Flammability limit (in terms of Φ)	0.63-1.4	0.1-7.1	0.5-1.7	0.51-2.5
Auto-ignition temperature (K)	924	844	813	739
Adiabatic flame temperature (K)	2073	2383	2223	2273

Source: Elbaz et al, 2022

- No carbon emissions
- Easy (but expensive) to produce
- Larger flammability limits
- Highly flammable
- Difficult to reliably burn
- Difficult to transport
- Difficult to store

H_2 stable combustion is difficult to achieve

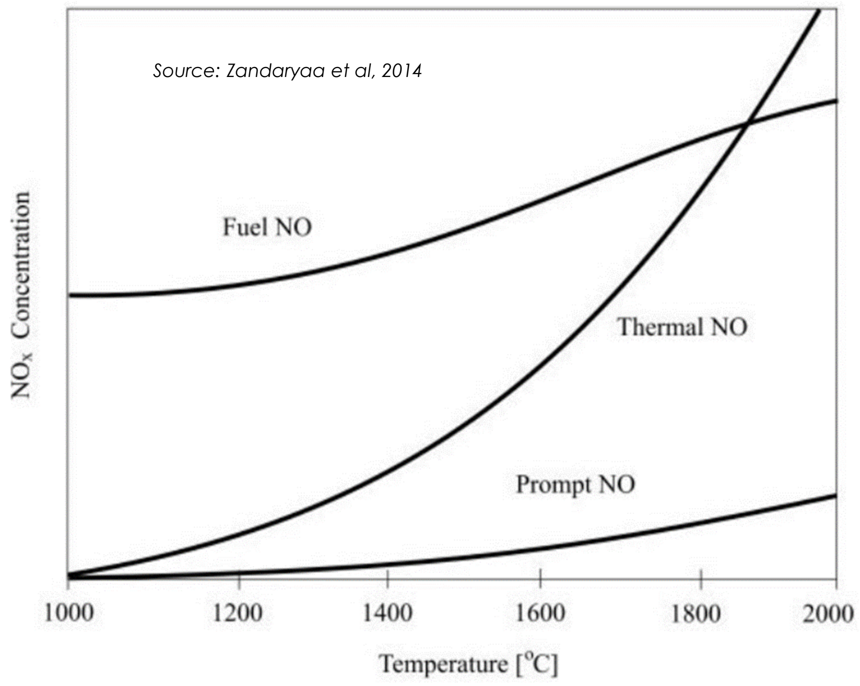
- Flashback – flame can travel upstream and briefly enter the fuel injector or fuel line
- Hot spots – poor mixing can lead to high NO_x and non-uniform combustor heating
- Volume – hydrogen requires more oxygen, so more air or oxy-fuel combustion needed
- Joule-Thomson Effect – at process temperatures, hydrogen heats when expanding

$$H_2 + (O_2 + N_2) \rightarrow H_2O + N_2 + \text{energy}$$

isn't the whole story

N_2 in the air dissociates

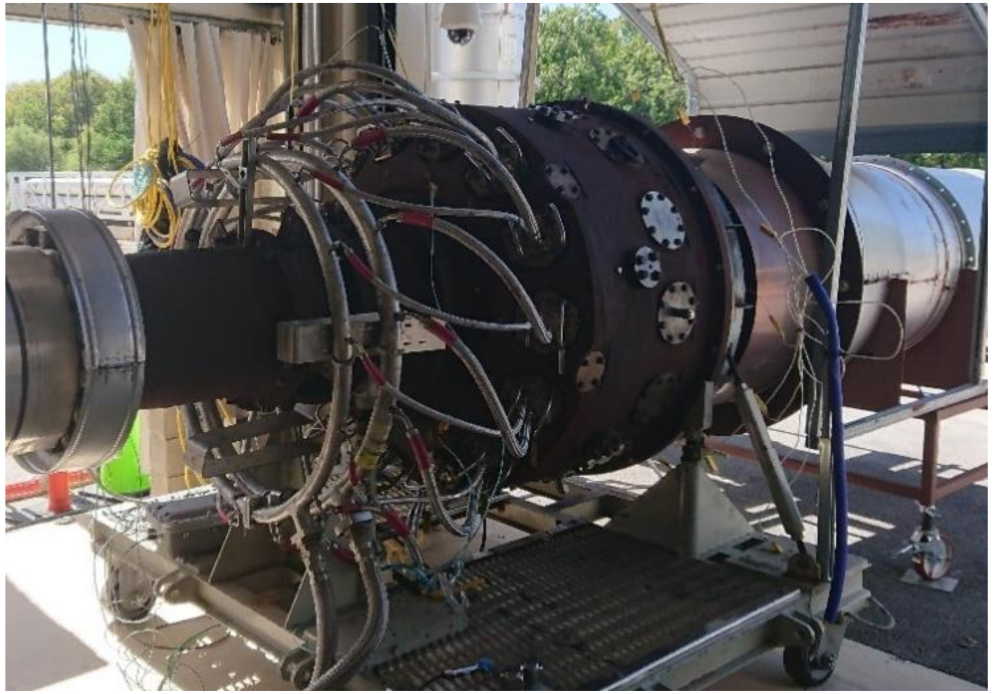
No fuel NO_x for H_2 but
Thermal NO_x: Temperature dependent
Prompt NO_x: Reaction/Temperature dependent



H_2 combustion at SwRI

U.S. DEPARTMENT OF ENERGY

- SwRI operates a gas turbine (GT) combustion test facility to support the development of new combustion system



SwRI tested a Titan 130 SoLoNOx combustion system with CH_4/H_2 blended fuels – DE-EE0008415

The facility is design for:

P_{max} = 28 barg

T_{max} = 800 K

Q_{max} air = 6.4 kg/s

Q_{max} H_2 = 0.055 kg/s

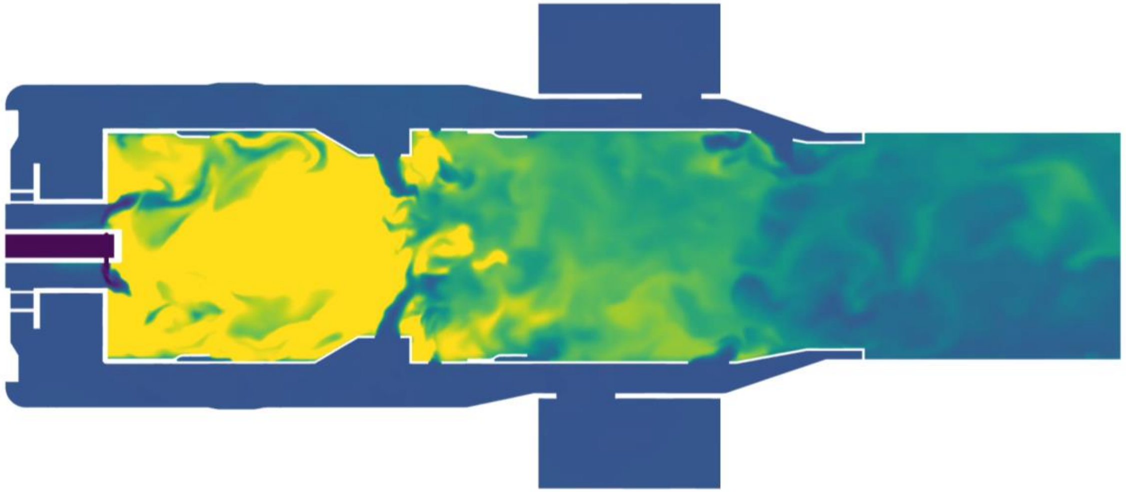
SwRI

Source: Beck et al, 2023

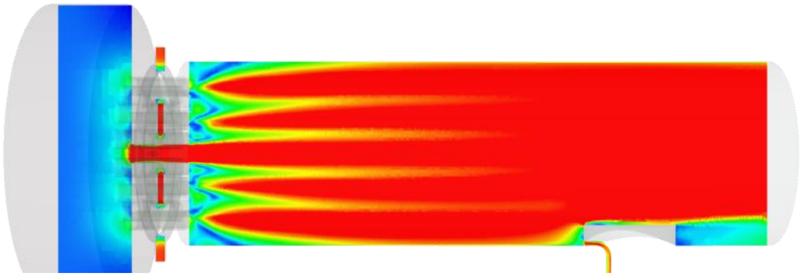
H_2 combustion at SwRI

- Combustion design and simulations

TurboGen CHP Rich Quench Lean (RQL) Combustor

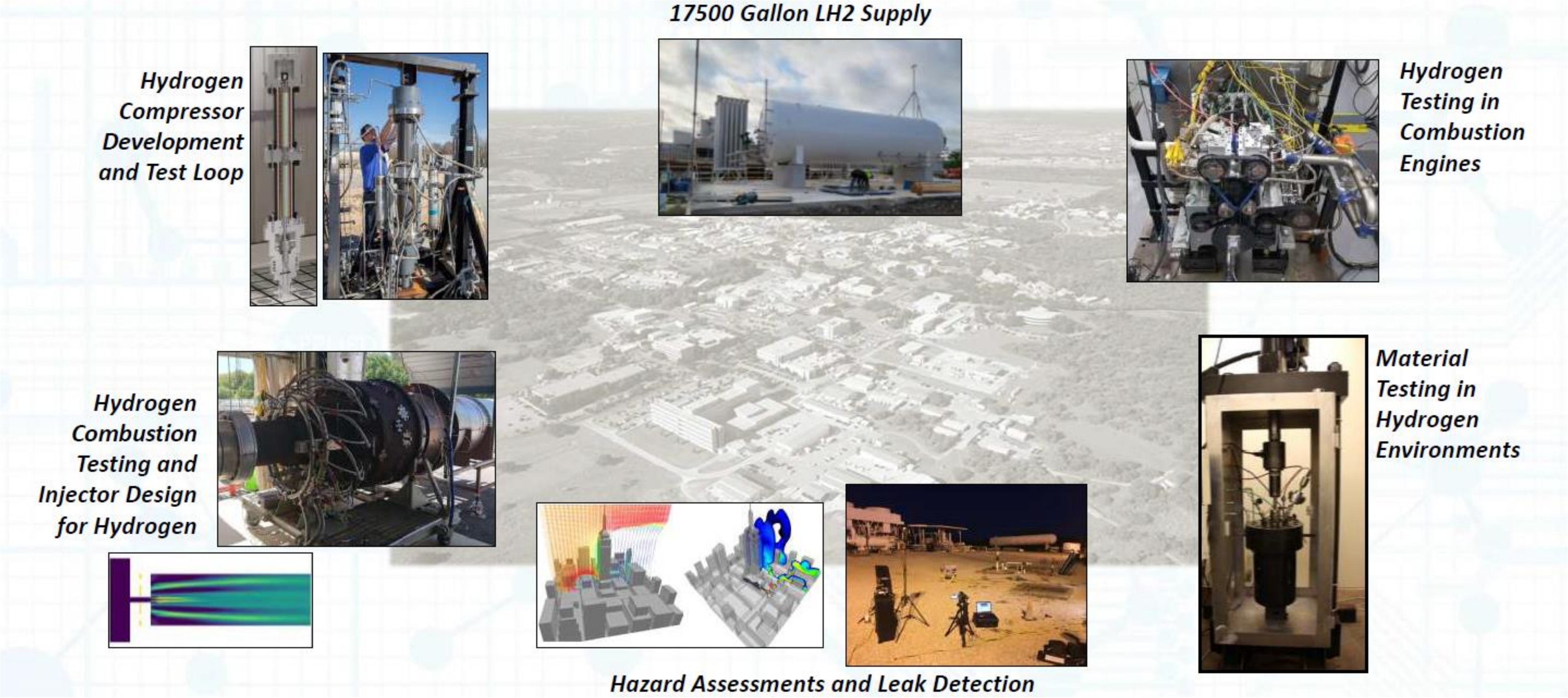


Doosan and Convergent Science validation of NASA partially premixed experiments



Courtesy: Dr. Brian Connolly

Not just H_2 combustion at SwRI



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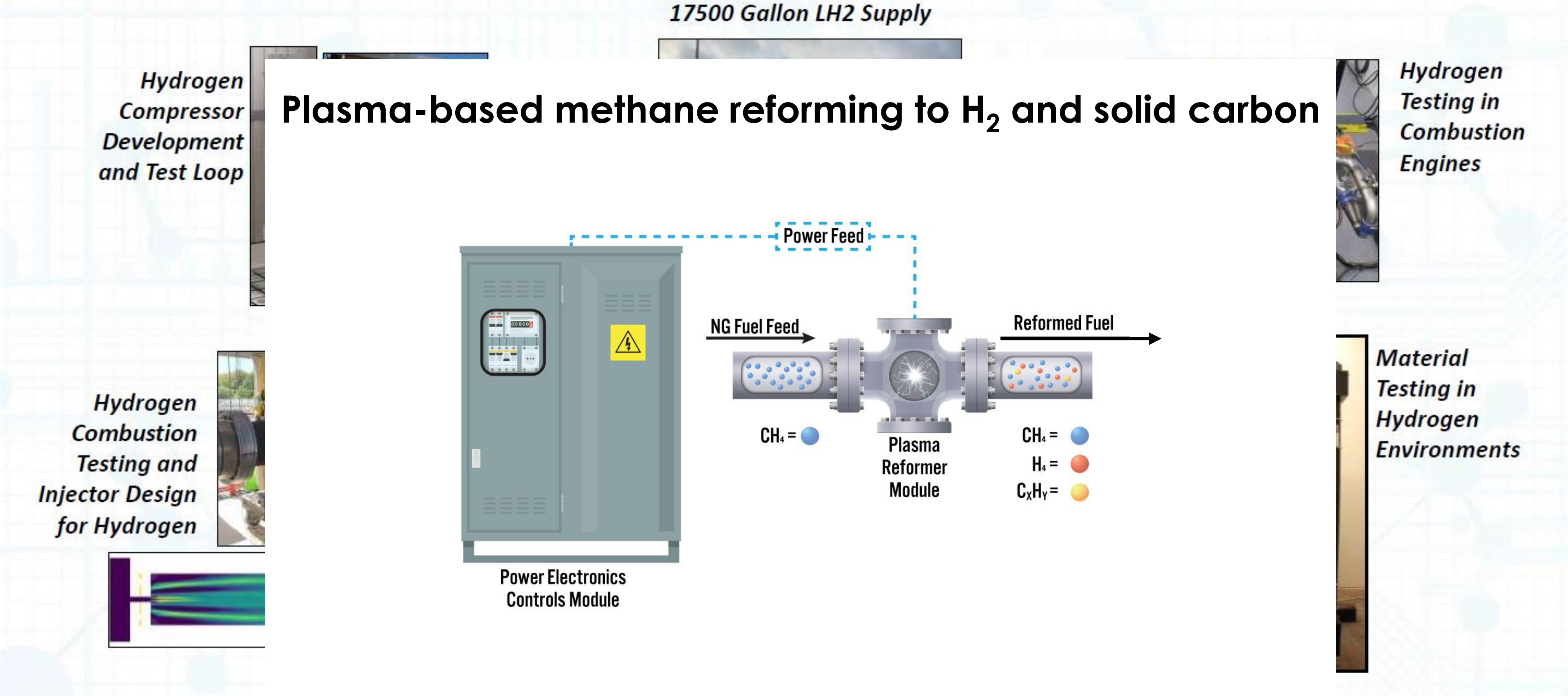

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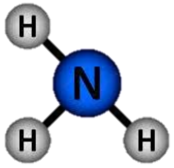
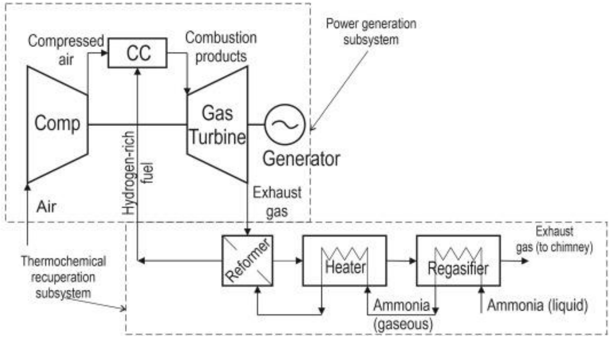
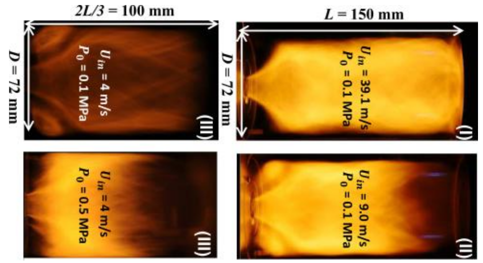
Ammonia (NH_3)

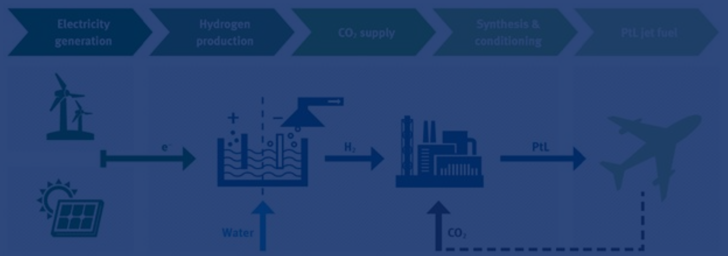


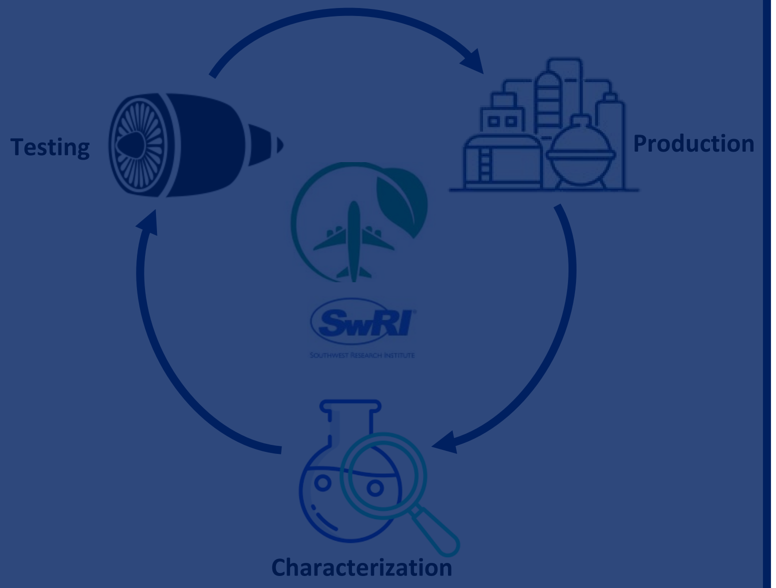




Source: Paschchenko et al., 2022 , Kobayashi et al., 2019

Sustainable Aviation Fuels (SAF)

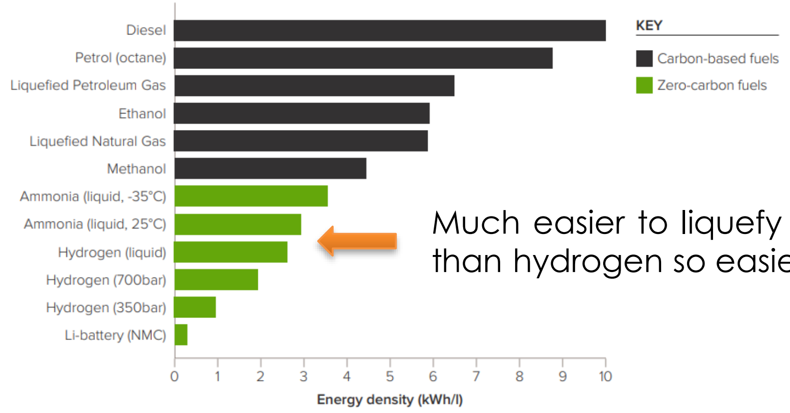




Source: EESI

Why NH_3?

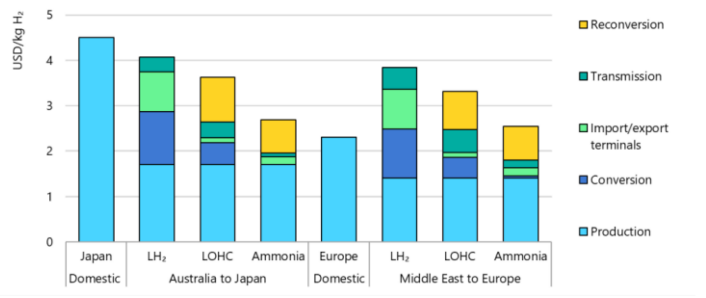
- Higher volumetric energy density than H_2



Much easier to liquefy ammonia than hydrogen so easier to store

Source: The Royal Society

- Infrastructure for production, delivery, and storage are already in place



Ammonia is and will be cheaper due to lower conversion and transmission costs

Source: IAE 2016

Fuel	NH_3	H_2	CH_4	C_3H_8
Maximum burning velocity (cm/s)	7	291	37	43
Lower calorific value (MJ/kg)	18.6	120	50	46.4
Flammability limit (in terms of Φ)	0.63-1.4	0.1-7.1	0.5-1.7	0.51-2.5
Auto-ignition temperature (K)	924	844	813	739
Adiabatic flame temperature (K)	2073	2383	2223	2273

Source: Elbaz et al, 2022

- No carbon emissions
- Easy to produce
- Easy to transport
- Narrow flammability limits
- Not very flammable
- Difficult to reliably burn
- Toxic

Ammonia is hard to burn efficiently and with low NOx emissions

Fuel	NH_3	H_2	CH_4	C_3H_8
Maximum burning velocity (cm/s)	7	291	37	43
Lower calorific value (MJ/kg)	18.6	120	50	46.4
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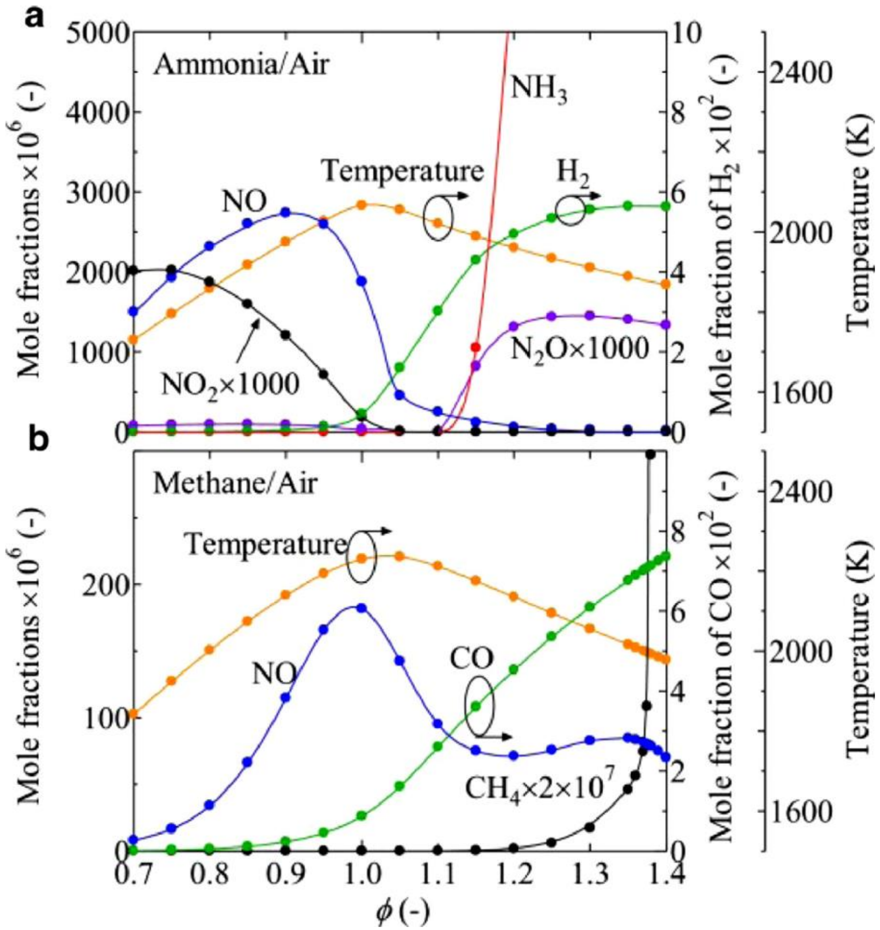
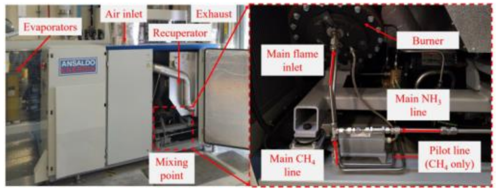


Overall "worse" combustion properties and higher NOx emissions than a conventional CH_4 combustor

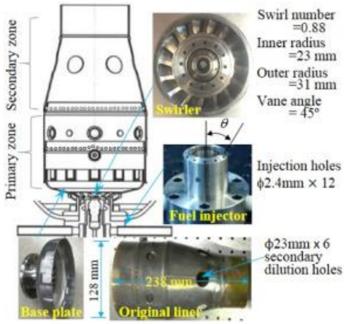
Source: Elbaz et al, 2022

Previous and on-going work on ammonia combustion for gas turbine



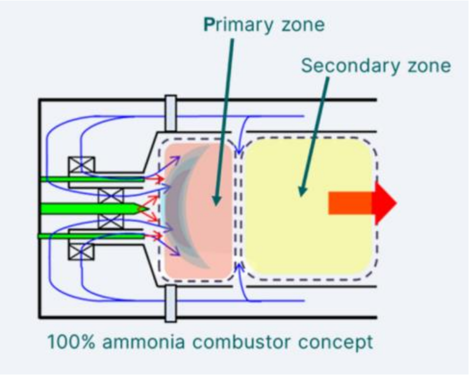
Micro gas turbine powered by ammonia-methane mix (Saudi Arabia)

Source: Avila et al, 2023



Gas turbine combustor powered by ammonia (Japan)

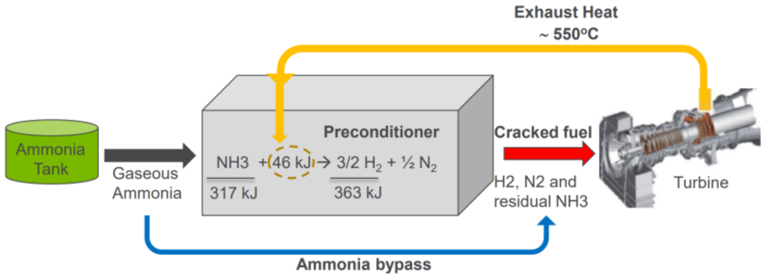
Source: Kobayashi et al, 2019



Source: GE Vernova

GE +IHI two stage combustor for 100% NH_3 combustion (USA + Japan)

Similar approach for CPS, RTX + Uconn, GTI + UCF (USA)



Ammonia craked and mixed with NG ANL + Purdue

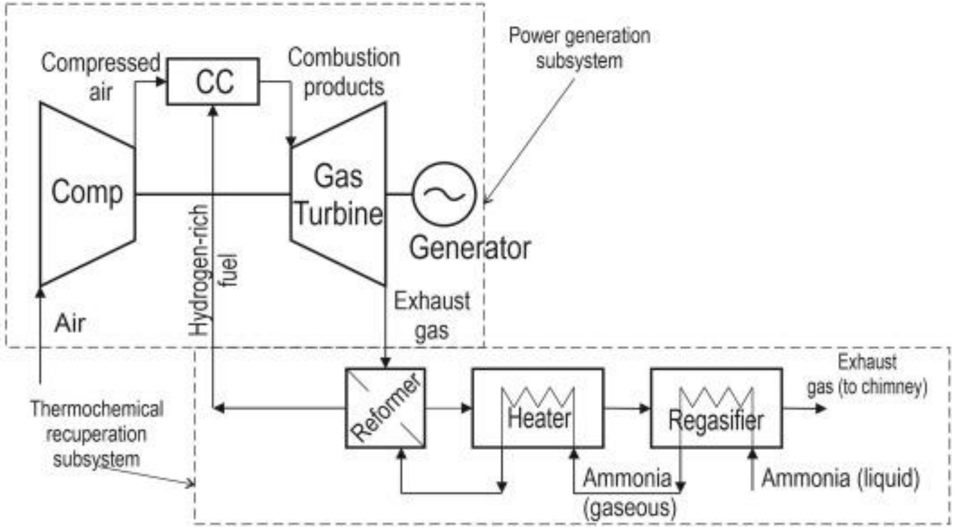
Source: Gupta et al, 2023

Not been demonstrated at relevant conditions

- Dual-fuel configurations (NG + NH_3 or H_2 + NH_3)
- Direct ammonia combustion with two-stage combustors
- Ammonia craking into NH_3 + H_2 + N_2 (not demonstrated at relevant conditions)

Ammonia chemically recuperated gas turbine cycle

A system approach is needed to properly implement ammonia cracking in gas turbine cycles



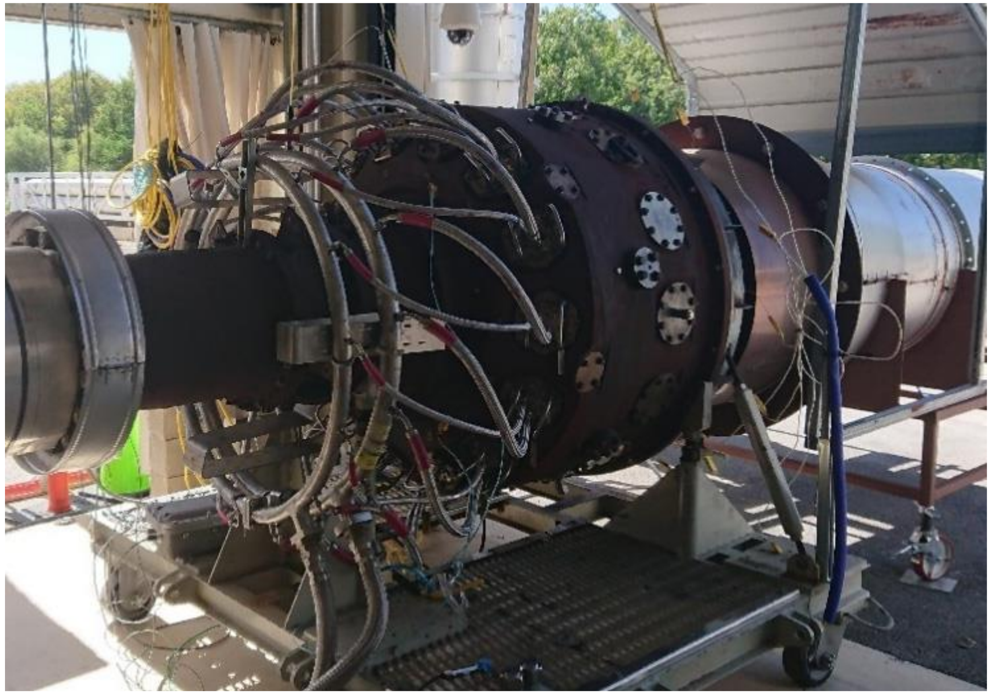
- Demonstrate that NH_3-H_2-N_2-AIR combustion in the context of chemically recuperated gas turbine cycle
- Higher efficiency has been shown but not demonstrated
- Vaporization of NH_3 using exhaust gases can be useful to reduce NH_3 supply infrastructure costs

SOUTHWEST RESEARCH INSTITUTE

Source: Paschenko et al, 2022

NH_3 combustion at SwRI

- SwRI operates a gas turbine (GT) combustion test facility to support the development of new combustion system



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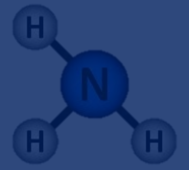

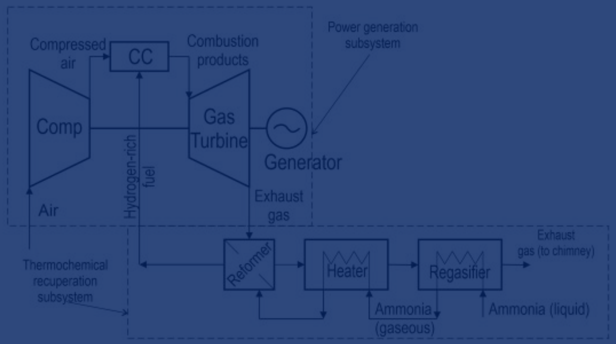

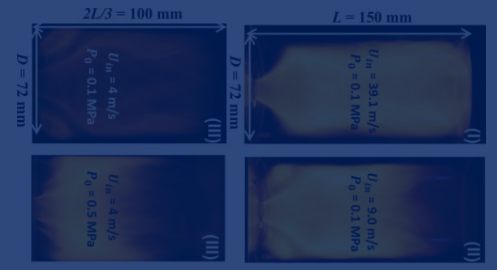

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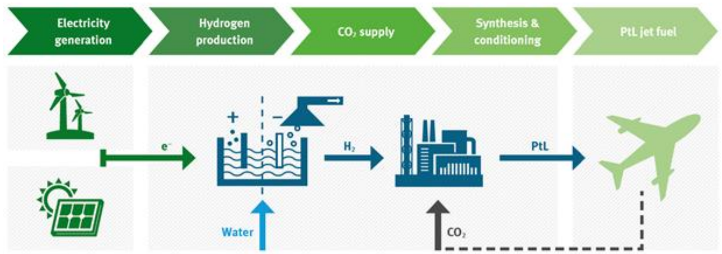
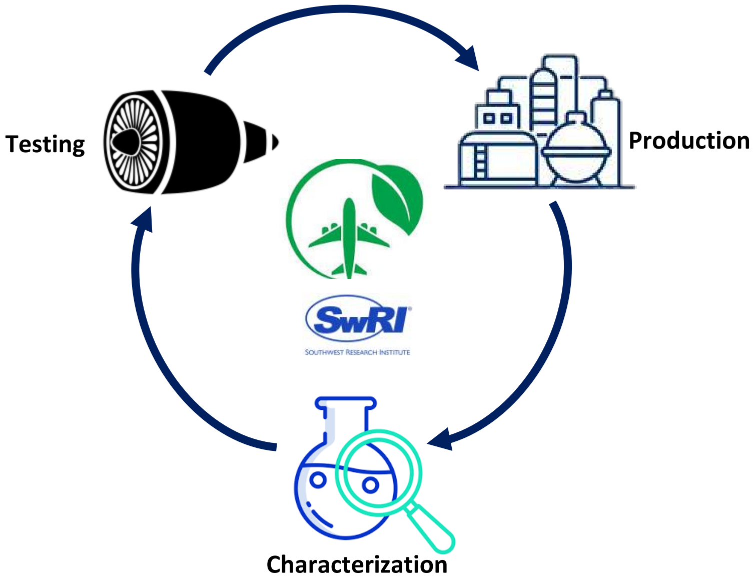
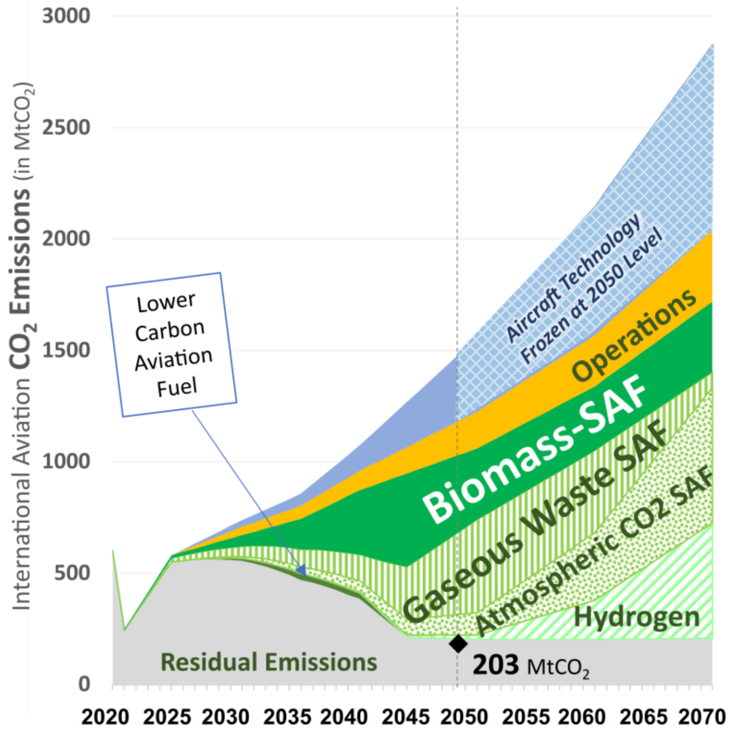


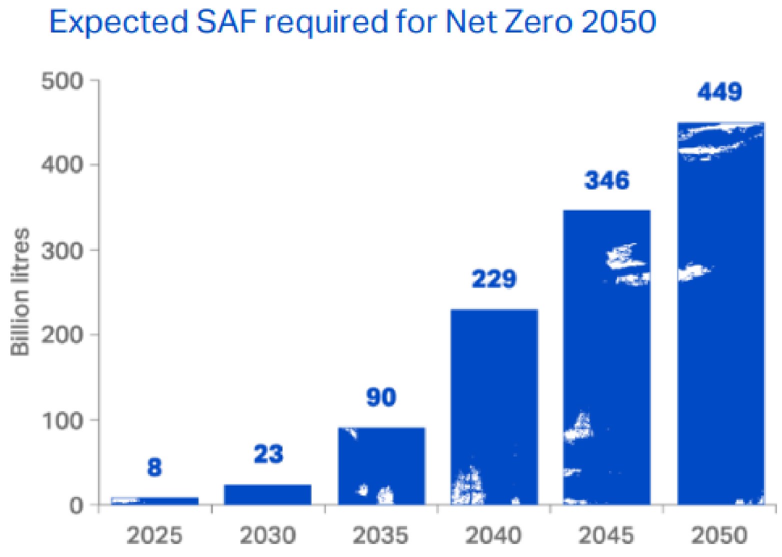


Source: EESI

Why SAF?

A Sustainable Aviation Fuel (SAF) is a fuel for aviation with an alternative feedstock to crude oil which can reduce lifecycle emissions by up to 80% compared to conventional jet fuel.

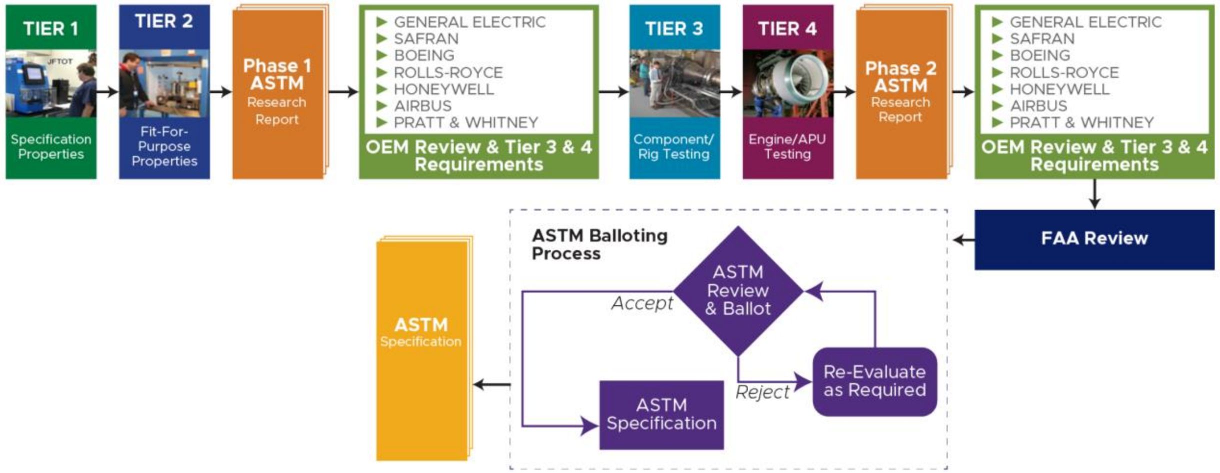




The global SAF market was valued at $1.1 billion in 2023, and it is projected to reach USD $16.8 billion by 2030

Source: ICAO, IATA, Bloomberg, and Markets and Markets

SAF characterization and qualification



Before a fuel can be utilized and further tested, it must meet the ASTM D4054 standard

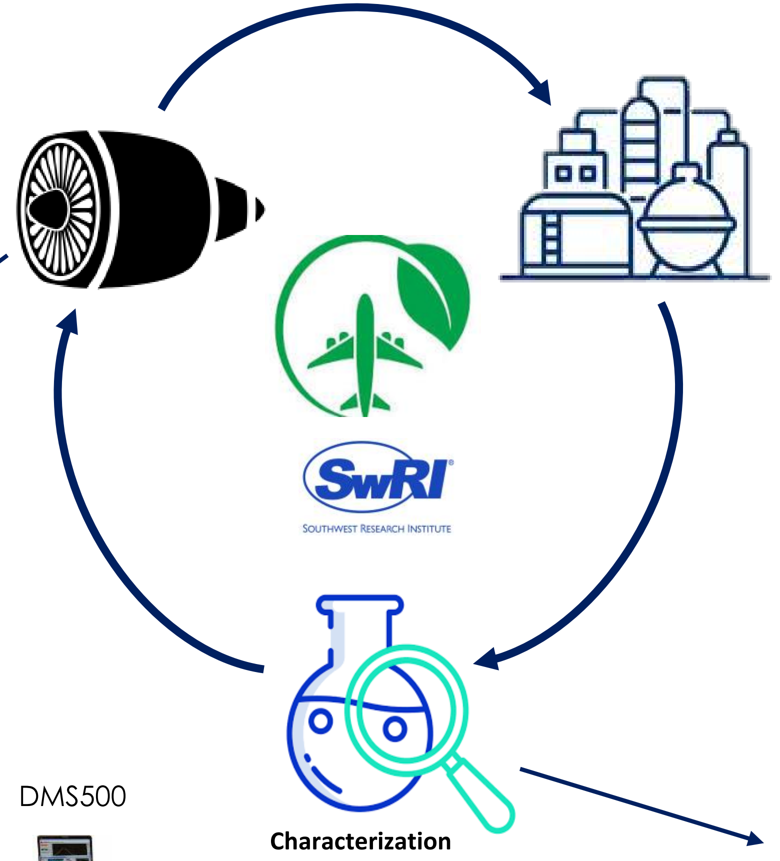
Tier	Approximate Fuel Volume in Gallons (Liters)	Approximate Time in Months	Approximate Cost in U.S. Dollars
Tier 1 – Fuel specification properties	10 (40)	6 months	$50,000 (testing cost)
Tier 2 – Fit-for-purpose properties	10–100 (40–400)		
OEM Review		6–12 months	$350,000 (OEM cost)
Tier 3 – Component and rig testing	250–10,000 (950–40,000)	24–36 months	~$4 million (testing cost)
Tier 4 – Aircraft and engine testing	Up to 225,000 (850,000)		
OEM Review and Approval		6–12 months	~$1 million (OEM cost)

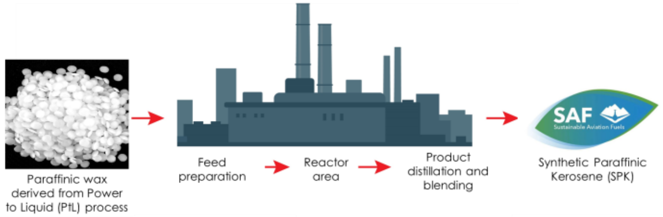
- Extremely expensive in terms of fuel, time, and money
- Still limited to 50% in volume
- Substantial research needed to move to 100%

Source: US DOE

SAF production, characterization, and testing facility at SwRI

Southwest Research Institute



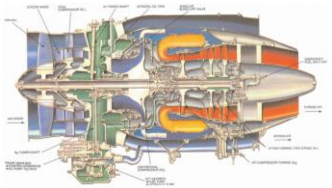


Gas Analyzer

O2, CO, CO_2, NO_x, UHC, H_2S, and SO_2

JT15D

Source: Pratt and Whitney



AVL micro-soot sensor

DMS500

Soot sampling via custom-made probe and electron microscope grids

Test Description	ASTM Method
Composition	
Acid Number	D3242
Aromatics – HPLC	D6379
Sulfur – Mercaptan	D3227
Sulfur – Total	D5453
Volatility	
Distillation	D86
Flash Point by Tag Closed Cup Tester	D56
Density Curve (5°-85°)	D4052_curve
Fluidity	
Freeze Point	D2386
Freeze Point	D7153/5972
Kinematic Viscosity (-20°C)	D445
Kinematic Viscosity (25°C)	D445
Kinematic Viscosity (40°C)	D445
Combustion	
Net Heat of Combustion	D4809
Smoke Point	D1322
Naphthalene Content	D1840
Derived Cetane Number	D6890
Corrosion	
Copper Strip Corrosion	D130
Thermal Stability	
JFTOT	D3241
Contaminants/Handling	
Existent Gum	D381
MSEP w/ Alumicel	D3948
Additives	
Electrical Conductivity	D2624
Lubricity	
Lubricity – BOCLE	D5001
Other - HC Composition	
Carbon/Hydrogen	D5291

D3241 JFTOT

D3241 Ellipsometer

THANK YOU FOR YOUR ATTENTION!