MariNH$_3$

Clean, green ammonia engines for maritime

The Feasibility of an Ammonia Split Cycle Engine - Answering the Right Questions

MariNH$_3$ conference - 26 June 2024

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Part 1 Shipping Headlines	Part 2 NH3 Fuel (SWOT, Properties, LCA)	Part 3 Right Questions (Beyond 2030, Disruptive)	Part 4 Combustion Approach (Conventional?, Split cycle, Dependent → Independent)
Part 5 Answering Right Questions (Learning from tests, Achieving homogeneous cool combustion)	Part 6 Method & Chemistry (Compared CH4 & H20%, Chemkin-Pro NH3, Flammability limit)	Part 7 Headline Findings (BSEC MJ/kWh, Parametric IVC, Initial °C, Bar)	Part 8 Take home message (What did we answer)

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Established record in energy & transport with industrial impact

Our story, T minus 20 years to now in 2024

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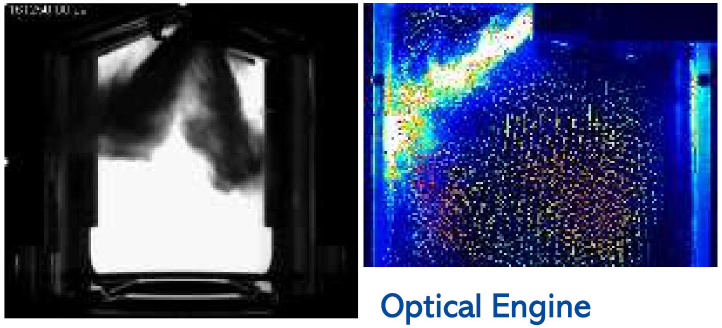
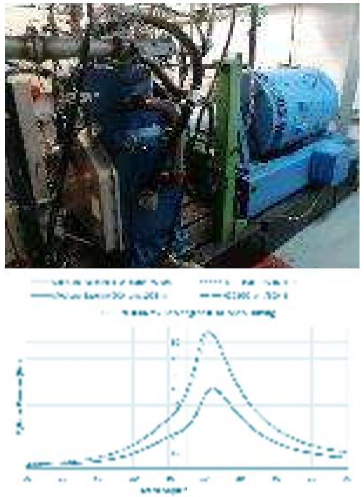
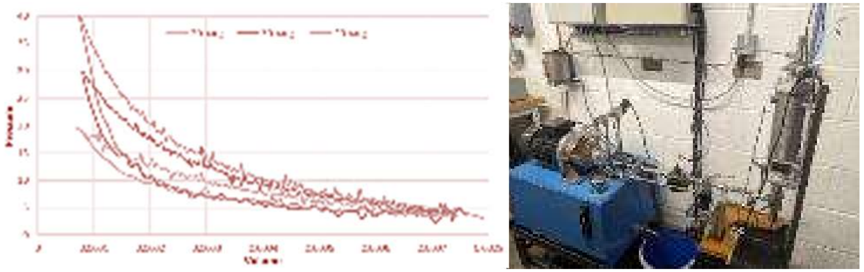


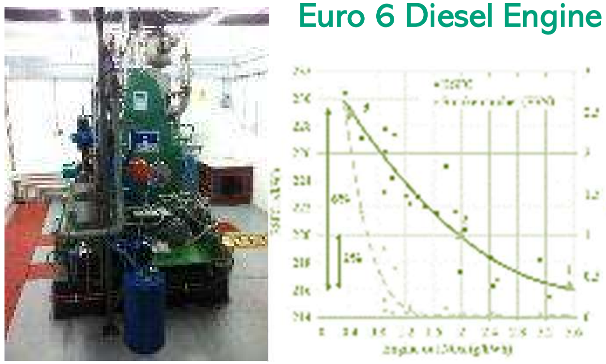
Optical Engine



CH4 - H2 Engine



Liquid air energy storage sub-system



Euro 6 Diesel Engine

Waste Heat Recovery, Incl. NH3 - H2O

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Part 1 Shipping Headlines

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Shipping Headlines When electric can't provide solution for heavy loads!

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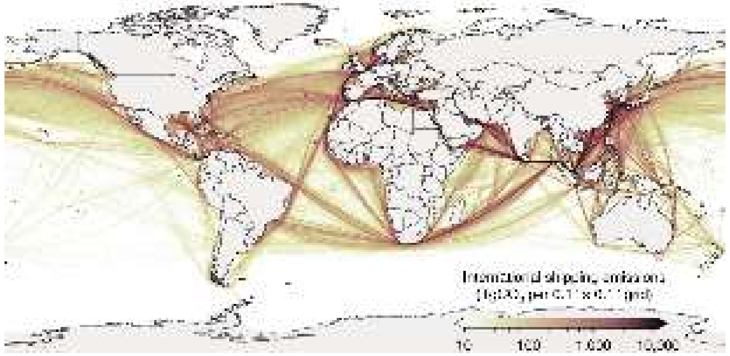
Global shipping 5 mbpd of carbon fuel (45 bathtubs/sec), Carbon free NH3 at 35-60% estimated market share by 2050



CH4 28x GWP, Methane slip 1.5% assumed vs.7% reality

CH_3OH also needs CCS

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Shipping Headlines When electric can't provide solution for heavy loads!

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Champaign of energy, liq. H2 (<-250°C) pilot project, Heat↓, Very energy intensive, Without carbon

NH3 4-Cyl. 5MW R&D 2023, Sail 2026

NH3 or H2 = Cargo space reduction, 3x storage Vol. to CH4

NH3 with Diesel pilot, Lower calorific value, Large fuel injectors

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Part 1 Shipping Headlines

Part 2 NH3 Fuel (SWOT, Properties, LCA)

Fuel Definition SWOT Summary

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S — Strengths

- NH3 carbon free at use, 2nd most used chemical, $73B market, ≈200 Mt/year commodity, stored at moderate pressures with long term stability
- Increasing experience as dual fuel, possibility as pilot with gas (need energy for ignition), or higher cetane fuel (self-ignition), e.g. SIP JST (Japan), 100% NH3 co-firing with CH4 50kW in 2015

W — Weaknesses

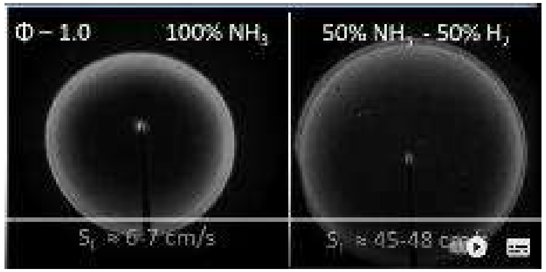
- Lower combustion intensity? (Higher ignition temp., Slow burning speed, Narrow flammability range). But, laminar burn velocities ↑↑ NH3 with H2 or CH2, near linear increase for 20%, exponential afterwards - **This is where we come in!**
- Handle by trained professionals, Dangerous to health > 300 ppm, Hydrophilic, Ammonium Hydroxide, Dissolves flesh, Corrosive to common materials

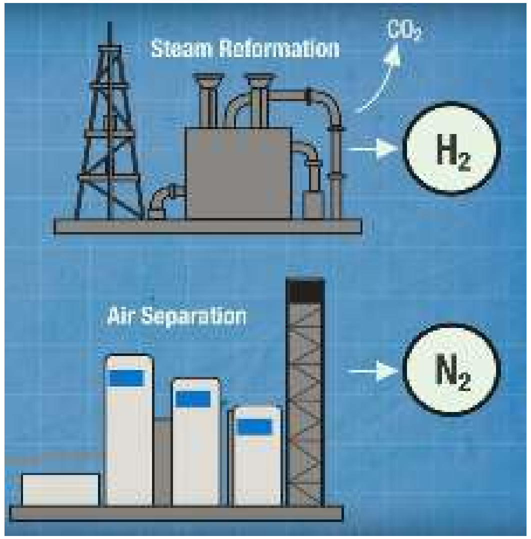
O — Opportunities

- NH3 can decarbonise shipping, H2 density (17.8% wt.). Liq. NH_3 stores H_2 at higher densities than liq. H_2 (121 vs. 70.8 kg-H_2/m^3). So, is NH3 a better H2 carrier, than H2 itself for same volume?

T — Threats

- New can of worms, SMR 3% of world energy, H2 ready! EU only <1% is green H2 electrolysis
- Currently 3x cost, but still cheaper than CH_3OH
- Nitrogen content may exacerbate NOx, NH3 slip - **This is where we come in!**





Fuel Definition Chemical & Physical Properties Summary

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	Properties	Gasoline	Diesel	LPG	CNG	Gaseous hydrogen	Liquid hydrogen	Ammonia
1	Storage method	Liquid	Liquid	Comp. Liquid	Comp. Gas	Comp. Gas	Comp. Liquid	Comp. Liquid
2	Storage temperature (°K)	298	298	298	298	298	20	298
3	Storage pressure (kPa)	101.3	101.3	850	24,821	24,821	102	1030
4	Costa (US$/l)	0.58	0.65	0.72	0.57	0.14	0.18	0.24
5	Formula	C8H18	C12H23	C3H8	CH4	H2	H2	NH3
6	Ratio Carbon:Hydrogen	0.44	0.52	0.38	0.25			
7	Lower heating value (MJ/kg)	44.5	43.5	45.7	38.1	120.1	120.1	18.8
8	Flammability limits min., gas in air (vol. %)	1.4	0.6	1.81	5	4	4	16
9	Flammability limits max., gas in air (vol. %)	7.6	5.5	8.86	15	75	75	25
10	Flame speed (m/s)	0.58	0.87	0.83	8.45	3.51	3.51	0.15
11	Autoignition temperature (°C)	300	230	470	450	571	571	651
12	Minimum ignition energy (MJ)	0.14				0.018		8
13	Flash point (°K)	230.3	346.8	185.3	88.6			239.6
14	Octane	94		112	107	130	130	110
15	Fuel density (kg/m3)	698.3	838.8	1898	187.2	17.5	71.1	602.8
16	Energy density (MJ/m3)	31,074	36,403	86,487	7132	2101	8539	11,333
17	Latent heat of vaporization (kJ/kg)	71.78	47.86	44.4	104.8			1369

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Fuel Definition NH3 Life Cycle Summary

Learning from Road Transport Study (Production, Storage, GWP, Cost)

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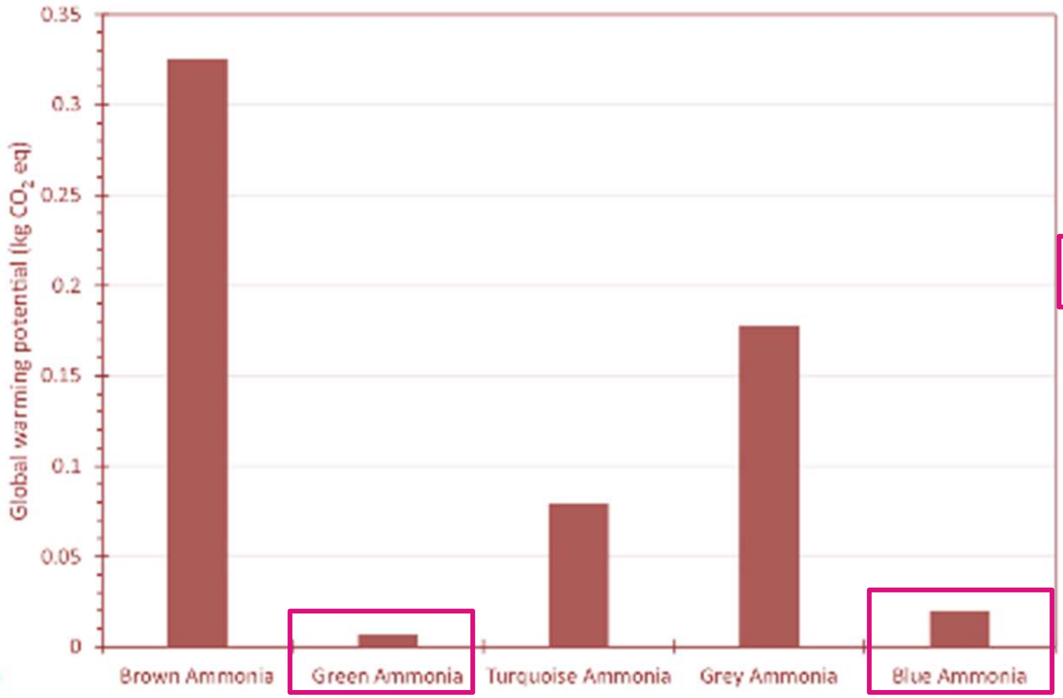
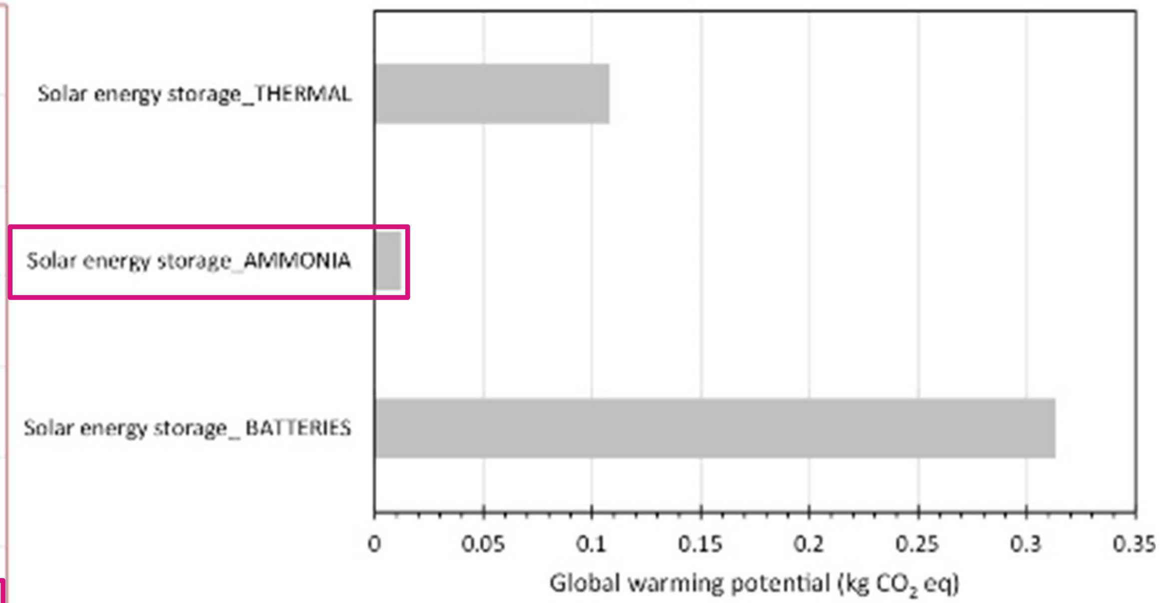
GWP for NH3 production methods using spectrum of hydrogen colour



GWP potential in renewable energy storage



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Fuel Definition NH3 Life Cycle Summary

Learning from Road Transport Study (Production, Storage, GWP, Cost)

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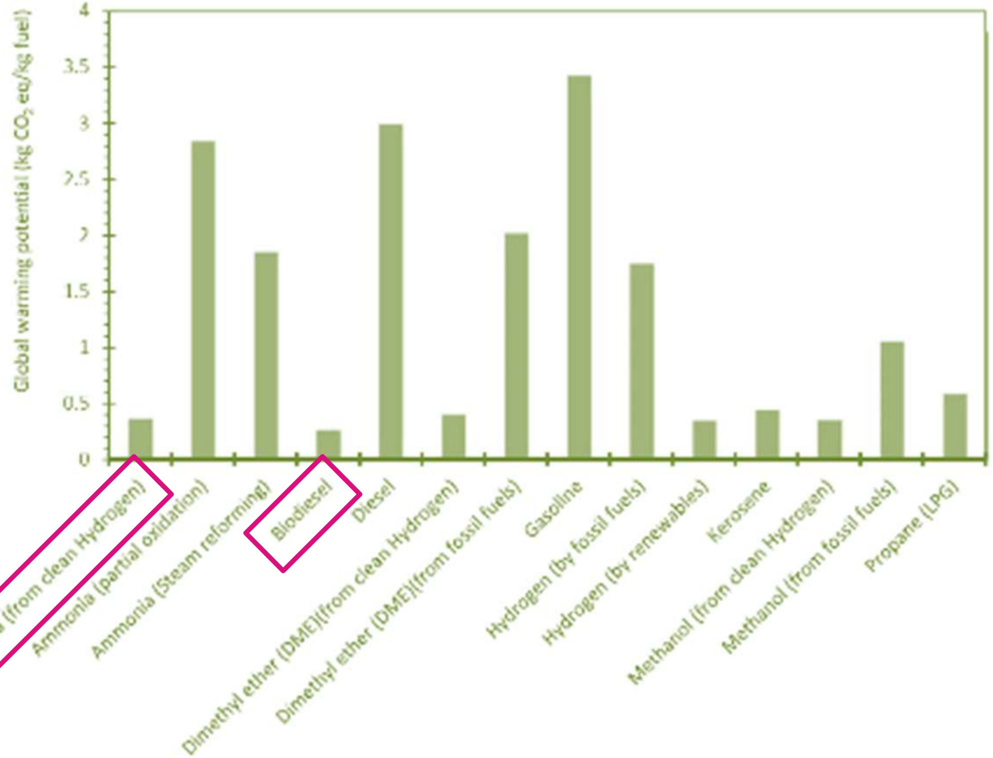
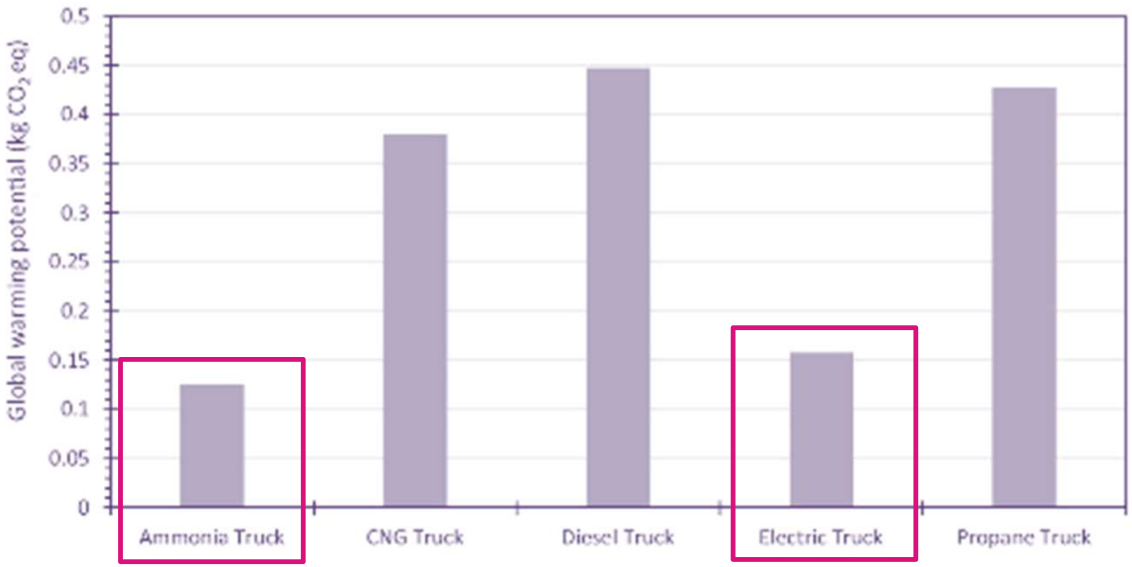
GWP of various fuels



Impact assessment for GWP in road freight-transportation



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Fuel Definition NH3 Life Cycle Summary

Learning from Road Transport Study (Production, Storage, GWP, Cost)

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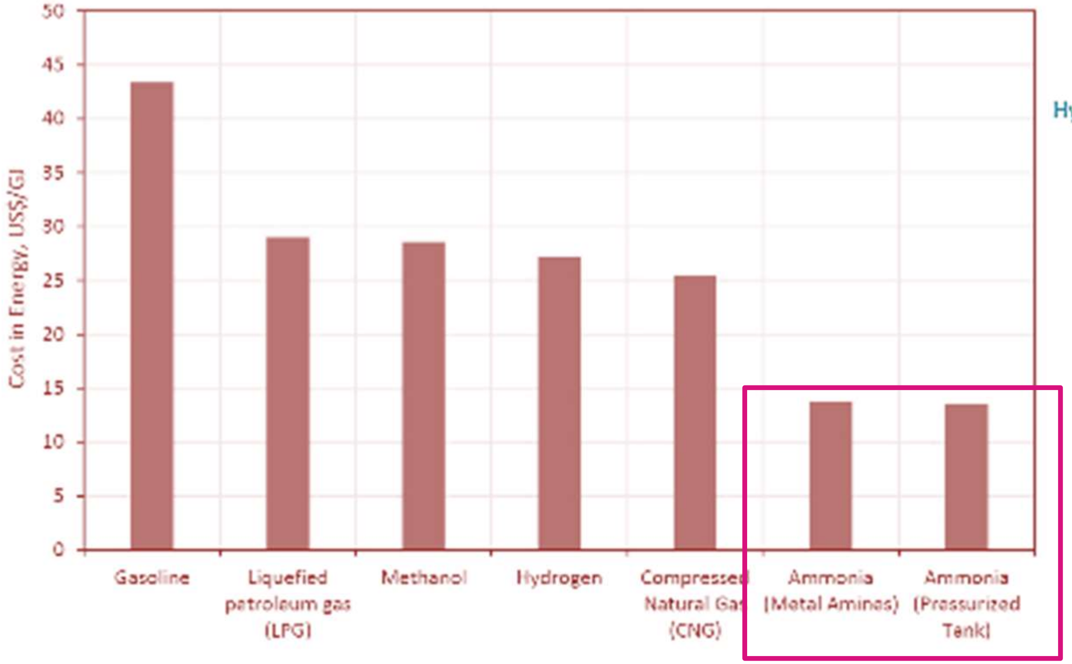
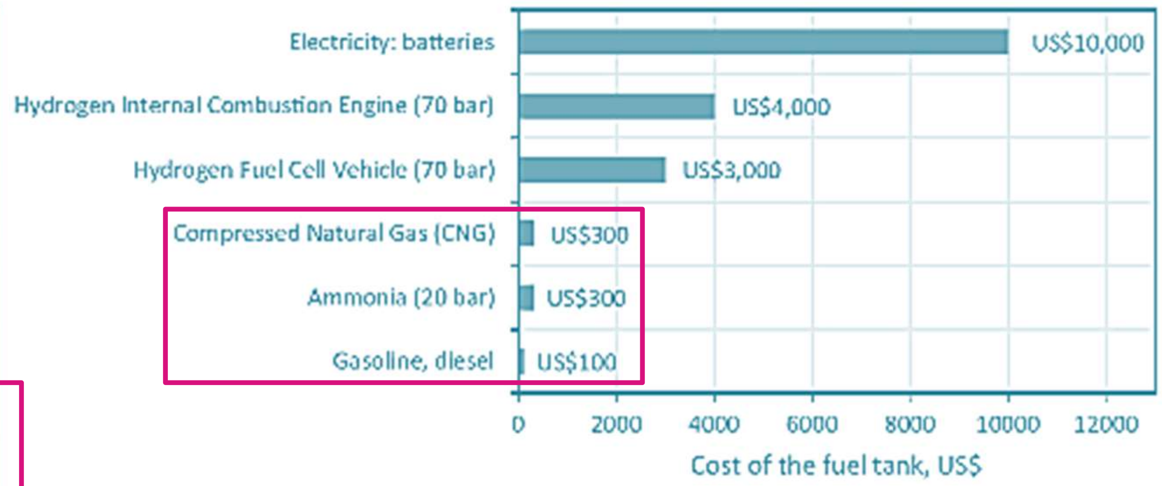
Comparison of the cost per gigajoule of energy for different vehicle fuels



Costs of on-board storage tanks for different types of fuelled vehicles



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Part 2 NH3 Fuel (SWOT, Properties, LCA)

Part 3 Right Questions (Beyond 2030, Disruptive)

Asking the Right Questions for Efficient Carbon Free Fuelled Engines Beyond 2030

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- What is the specific problem we have?
- Why do we need the chosen tool or instrumentation?
- Why do we want to do this specific task?
- What precise question are we trying to answer?
- How is the answer going to be used by us?
- What existing knowledge we have relating to this ?
- What physical principles are involved in our question?
- What unanticipated questions are we raising by the data?

Solution Focused Approach ∆

- 30 questions to answer
- With 3 varied perspectives
- Incremental, Disruptive, Racial

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Asking the Right Questions for Efficient Carbon Free Fuelled Engines Beyond 2030

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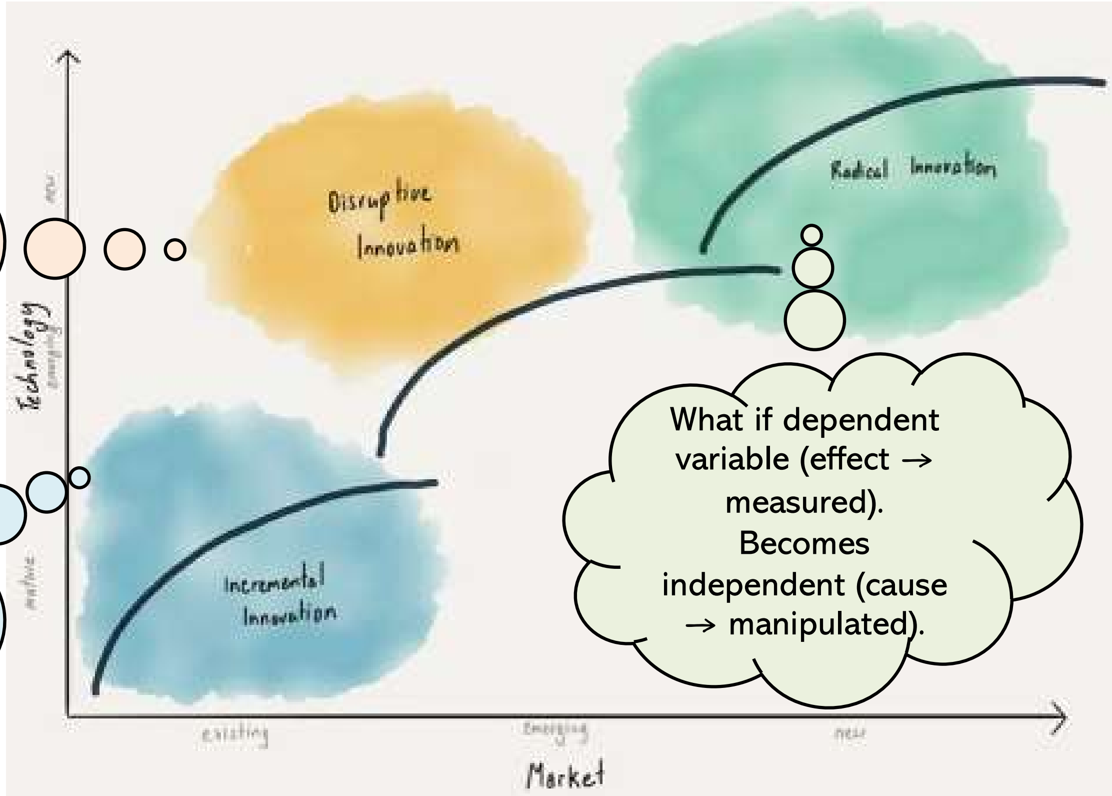
If I agree with you. We would both be wrong.

You can't expect the right answers. If you don't ask the right questions.



What if dependent variable (effect → measured). Becomes independent (cause → manipulated).

Solution Focused Approach ∆

- 30 questions to answer
- With 3 varied perspectives
- Incremental, Disruptive, Radical

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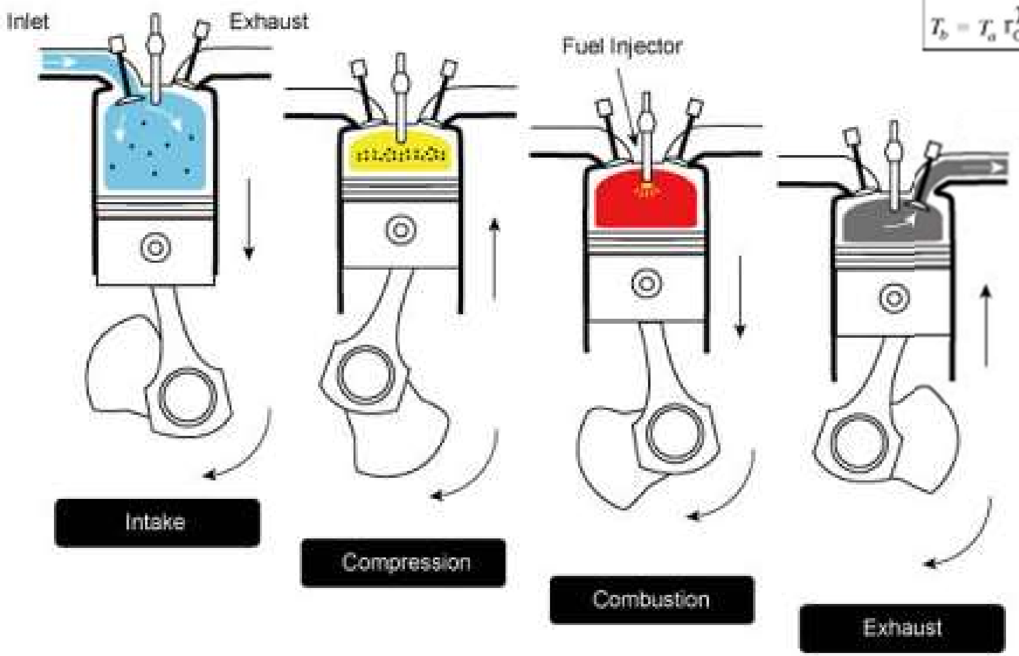
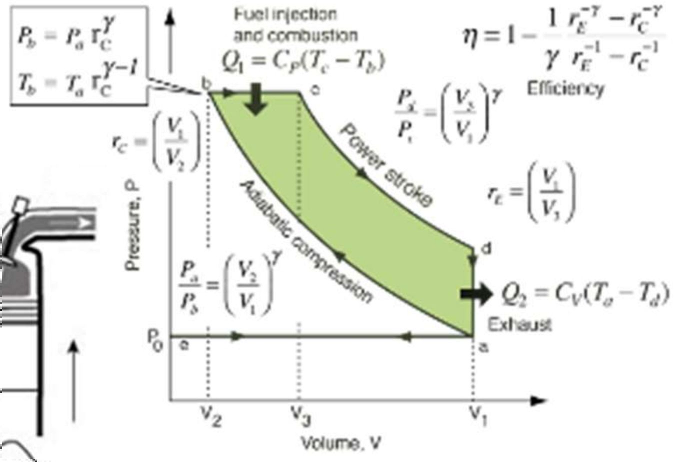
Part 3 Right Questions (Beyond 2030, Disruptive)

Part 4 Combustion Approach (Conventional?, Split cycle, Dependent → Independent)

Combustion Focused Approach Δ

Is this engine cycle really optimal for NH3?





![MariNH3 logo]

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- Intake manifold NH3 gas injection, may sound tempting for homogeneity, but this will be impractical, likely a non-starter
- Its crucial to maintain high pressure liquid deliver, but still somehow, enable homogeneous ignition, with added control of peak temperature

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Combustion Focused Approach Δ

How can recuperated split cycle engine offer new possibilities?

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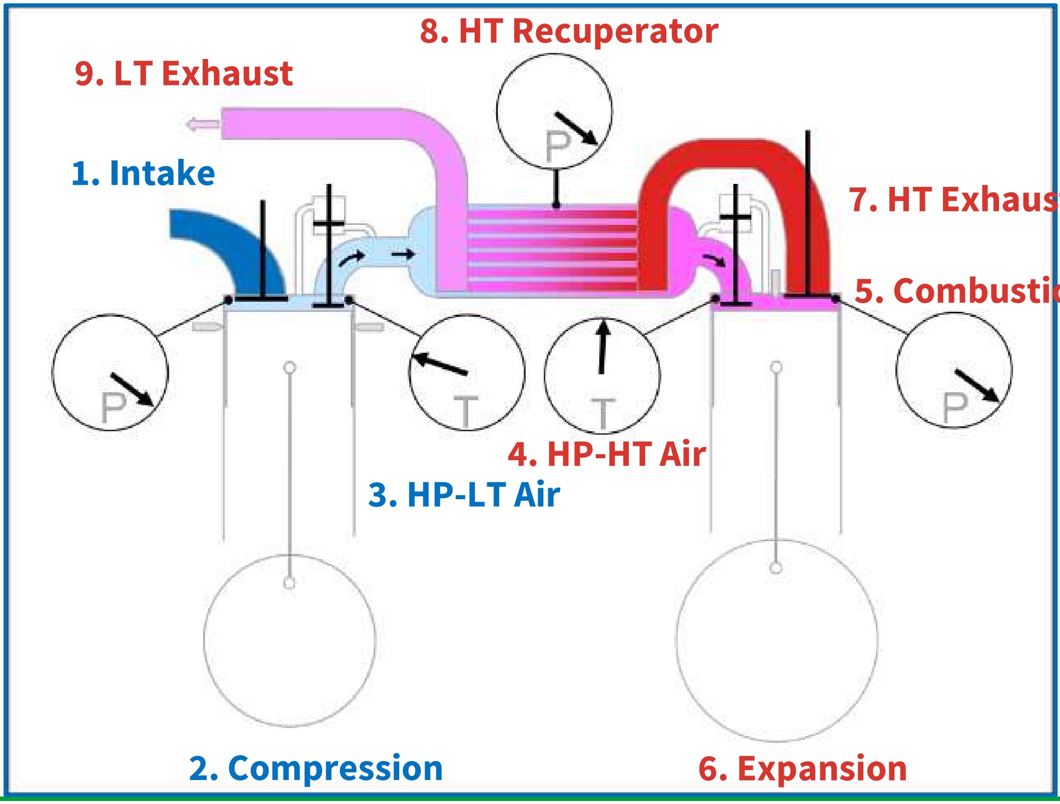

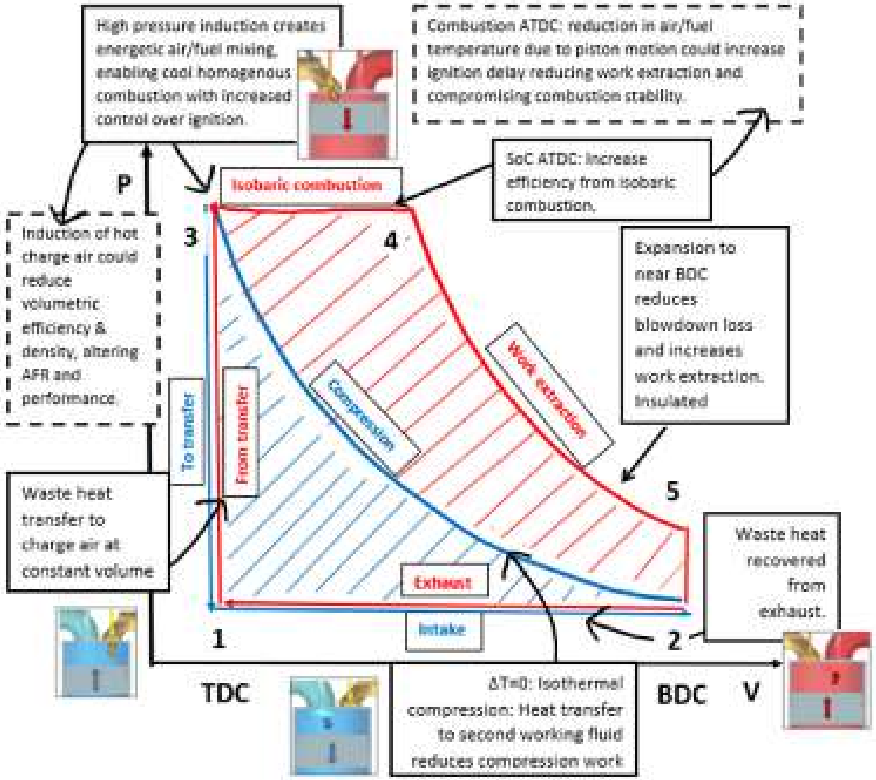

Combustion Focused Approach Δ

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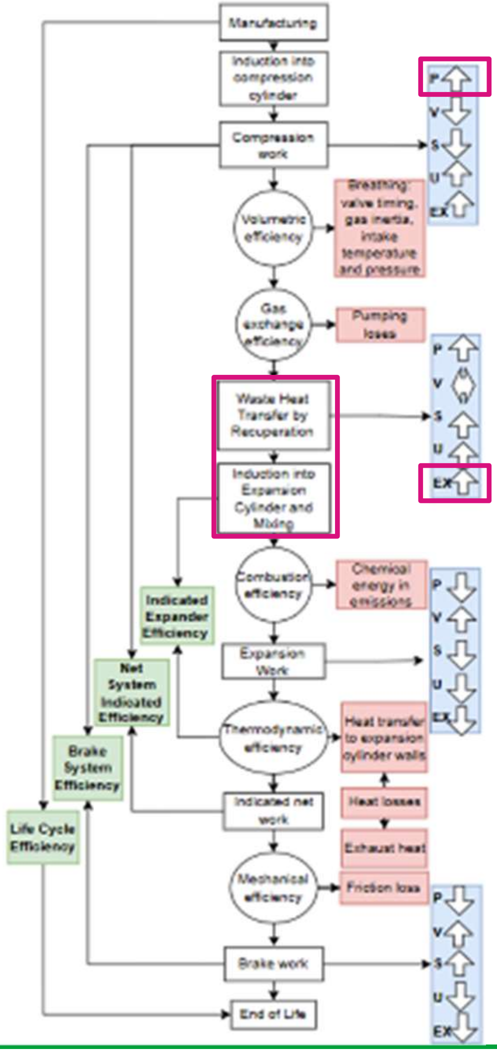

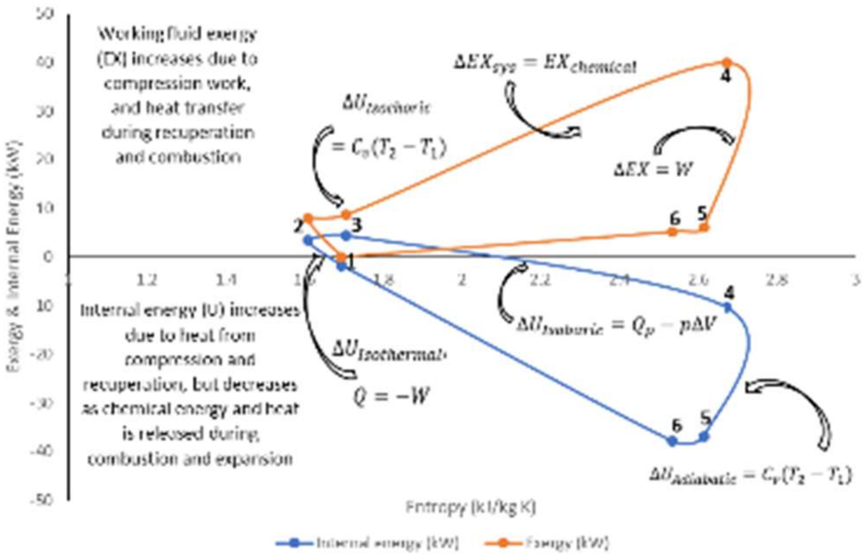

- Split cycle, new propulsion technology, allows questioning, what if, dependent variable (effect → measured) turn into independent (cause → manipulated)
- Near isothermal compression controls start of combustion temperature
- EVC to SoI, offers 40°CA, to demonstrate feasibility of enhanced NH3 combustion

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