DIESEL PROGRESS SUMMIT

RICARDO

POWERING **SUSTAINABLE** FUTURES

Diesel Fights Back: Innovations in Traditional Engines

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CHALLENGES FOR PROPULSION ON & OFF ROAD

DRIVERS & CHALLENGES

Zero Carbon
Enabling decarbonisation roadmap

Zero Environmental Impact
Full Life Cycle

Zero Pollution
No pollution produced at point of use

Business Case
Address economic viability of technologies

TECHNOLOGY STRATEGY

IMPLICATIONS

Zero carbon solutions must be found

Over total life cycle development-manufacture-usage-end of life the Environmental Impact must be minimised

The propulsion system should produce no harmful emissions during operation

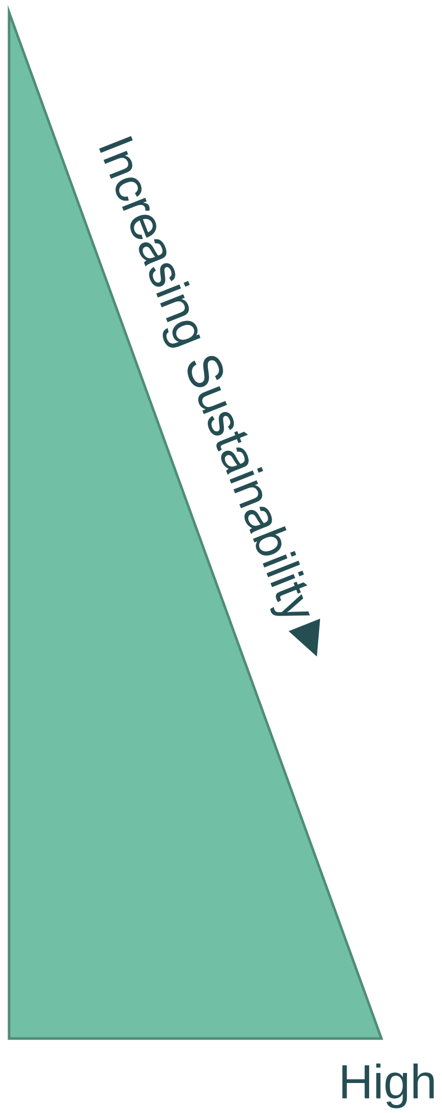
The business case for the total cost of ownership should be viable for manufacturers and operators

POTENTIAL PROPULSION SOLUTIONS

	Zero Carbon	Zero Env. Impact	Zero Pollution at source	Business Case
Battery Electric	Yes, if renewable electricity	Battery lifecycle a challenge	Yes	Battery cost/weight major challenge
Direct Electrical Supply	Yes, if renewable electricity	Low impact	Yes	Infrastructure major challenge
Hydrogen Fuel Cell	Yes, if renewable hydrogen	Rare metals required. Also has battery	Yes	Fuel Cell cost major challenge
Conventional ICE	Challenge if fossil fuel used	Challenge if fossil fuel used	Pollution control under all conditions a challenge	Good, current benchmark
Sustainable ICE	Yes, if renewable fuel used	Good if renewable fuel used		Minor challenges - ICE conversion

TOWARDS A SUSTAINABLE ICE

Incremental improvements	• Friction reduction, reduce thermal losses, waste heat recovery • Efficiency improvement η >> 50% • Emission controls improvement => Euro VII, NRMM Stage VI • On-board monitoring (OBM) of emissions and in-service checks
Drop-in sustainable fuels	• Bio-fuels • E-fuels
Radical improvements	• Opposed piston engines η ≈ 55% • Split cycle engines η ≈ 60%
Fully sustainable fuels	• Hydrogen fuelled ICE plus high efficiency emission controls



INCREMENTAL: 10-15% LESS CO_2 & EUVII / CARB27

40T / Class 8 Long Distance Truck

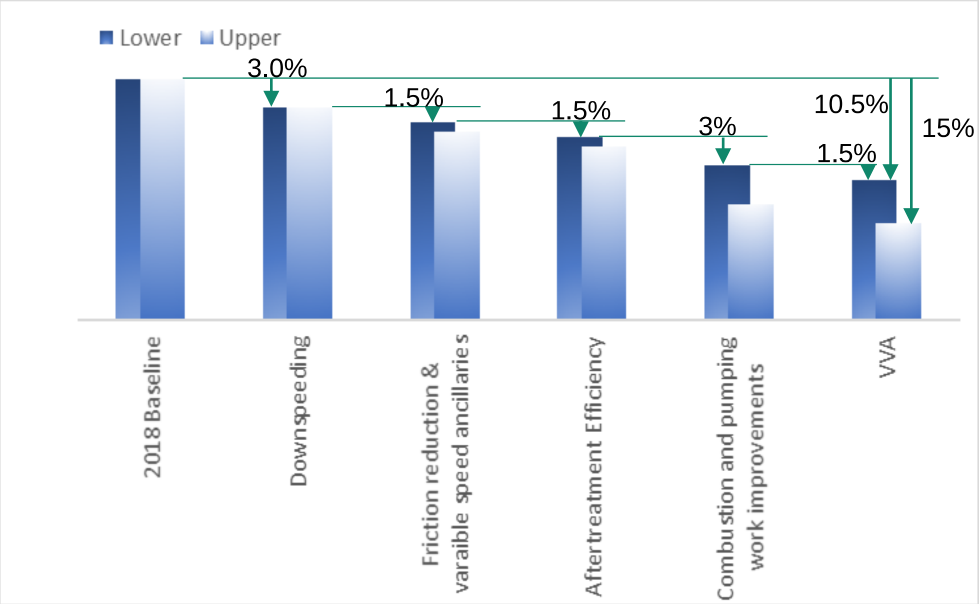
- Engine
  - 350 – 400 kW
  - 11 – 13 L
  - Operation dominated by mid speed and mid load
- NOx emissions at EUVII/CARB27 with SCR

Freightliner Cascadia

Mercedes Benz Actros

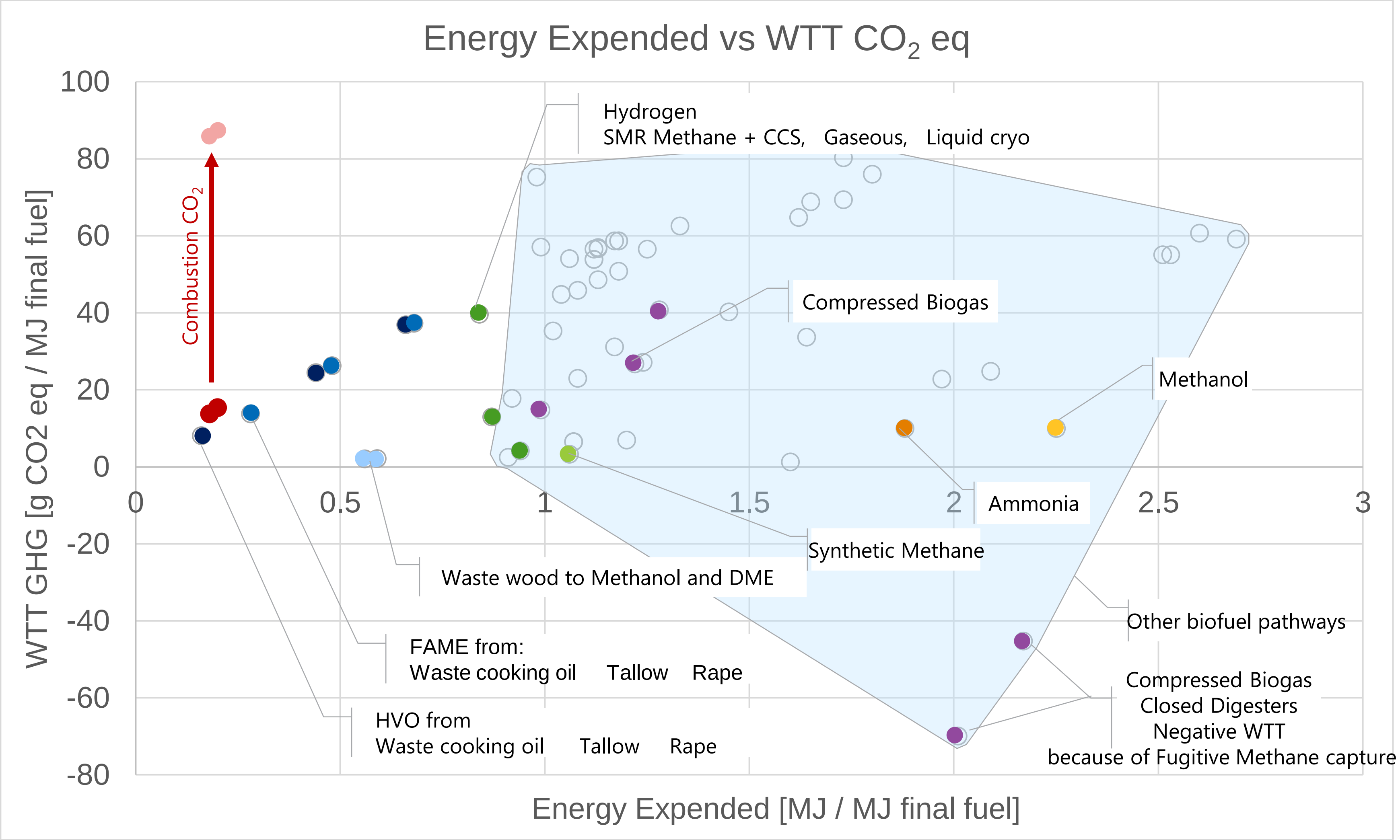
Expected Heavy Duty Diesel Engine Technology for 2030

- Peak cylinder pressure = 280 bar
- EGR rate = ~20%
- Fuel injection pressure = 2800 bar, Injection rate shaping
- Variable valve actuation with lost motion
- Variable oil & water pumps
- Part load cylinder deactivation
- CGI block and head, steel pistons



Estimated CO_2 / GHG Reduction through Engine Technology to 2030

DROP-IN / GASEOUS BIO- & E-FUEL OPTIONS



RADICAL: SPLIT CYCLE ICEs FOR η UP TO 60%

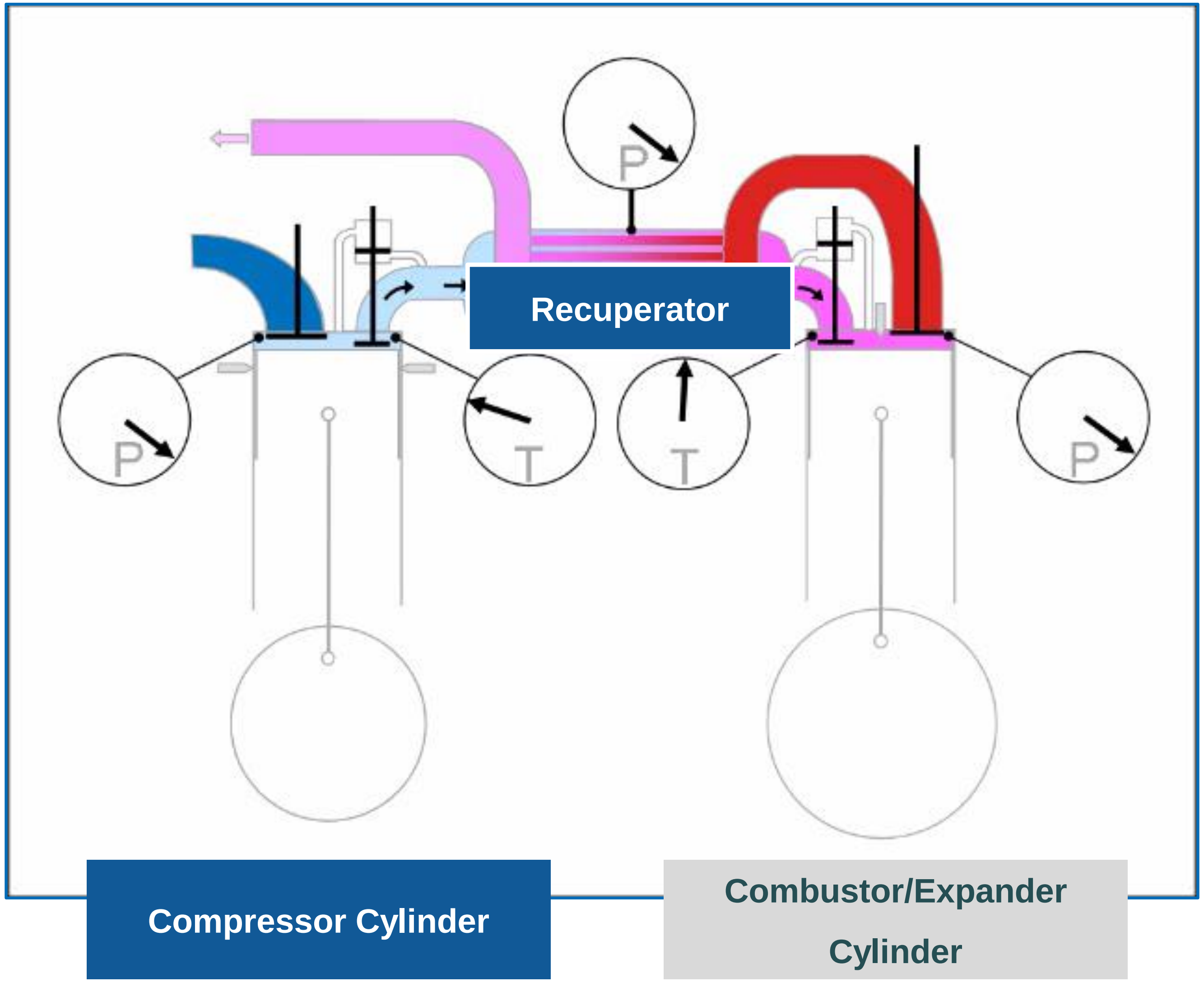
ThermoPower
<SULEV, >50% Efficiency

- **Dedicated Cold & Hot** cylinders of unequal size
- **Insulation** of hot cylinder
- **Recuperation** of exhaust energy
- **Low-NOx Cool Combustion** enabled by dense sonic intake air

CryoPower
Add liquid nitrogen to Cold cylinder
~ZEV, ~60% Efficiency

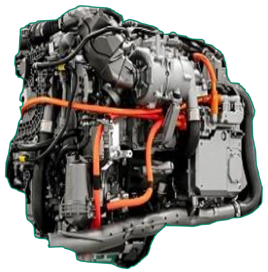
- **Near-isothermal** compression from Liquid N_2 injected

Unprecedented thermal efficiencies **with near zero emissions**



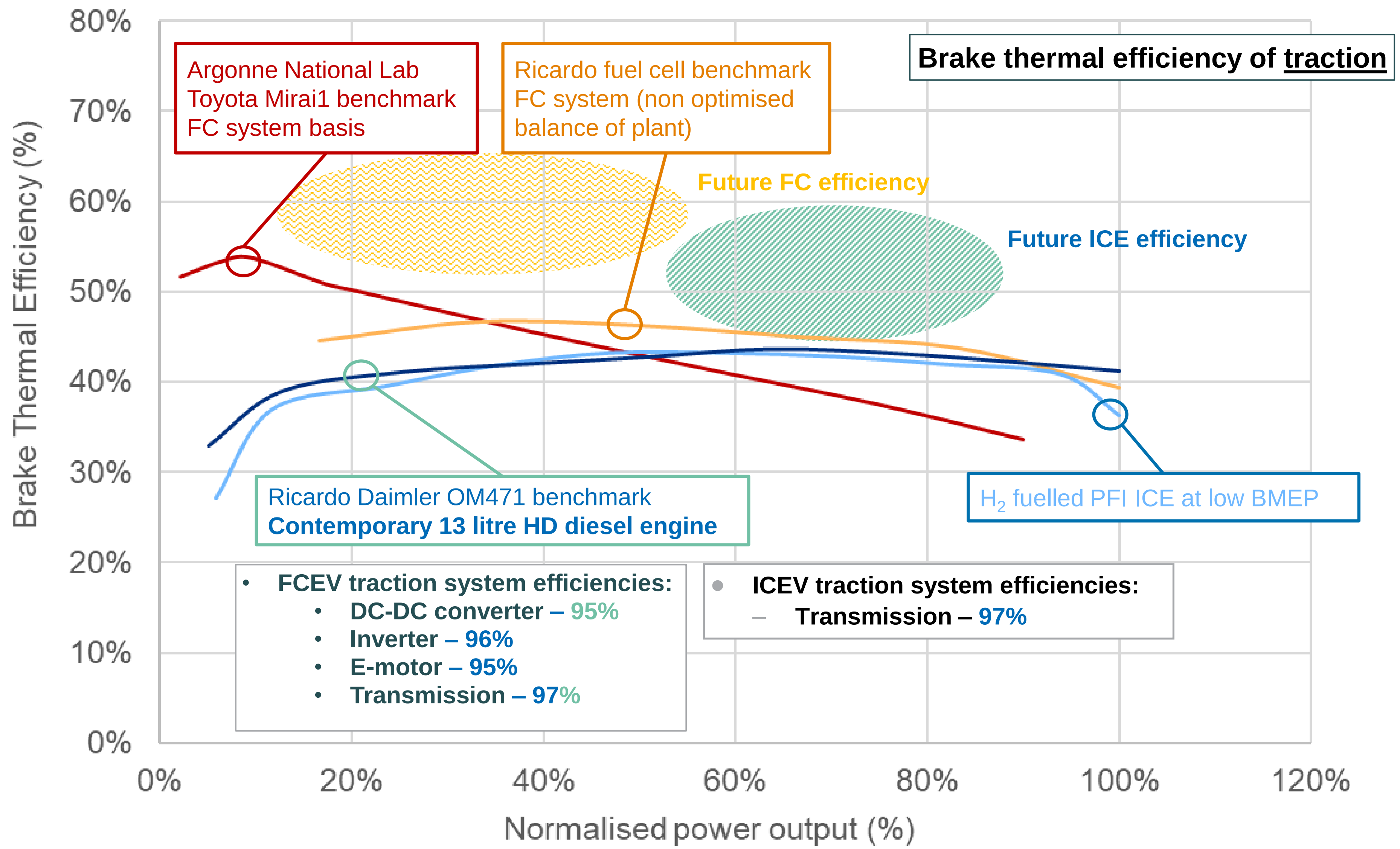
HYDROGEN ICE AND FUEL CELLS COMPARED

H_2 ICE status	Benefit to:	Fuel cell (PEMFC) status
~45%+ expectation for DI H_2 fuelled ICE	→	60%+ electrical efficiency (peak at 25% load)
Low engine-out NOx enabled by lean low temperature combustion Trace oil derived emissions	→	No emissions (if pure H_2 fuel)
Substantial NVH effort	→	Quiet
Lower costs and risks	←	Expensive with technology risks
Tolerant to minor fuel contaminants	←	Fuel purity required
Robust to small particles	←	Sensitive to air contamination
Diesel ICEs durable for >10,000 hours H_2 ICEs expected to be similar	←	Durability & reliability
High grade heat more easily managed	←	Thermal management of low grade heat for PEMFC*



Hydrogen fuelled combustion engines offer a gateway into the Hydrogen Economy and route to Zero Carbon with Fuel Cells being the long term goal

EFFICIENCY POTENTIAL OF H_2ICE AND FC



CONCLUSIONS

- Power Systems for Commercial and Off Highway applications face Major Challenges to move towards the Goals of:
  - Zero Carbon
  - Zero Environmental Life Cycle Impact
  - Zero Emissions at Point of Use
  - Viable business case for the manufacturers and end users
- Full Battery-Electric power, Fuel Cells and Direct Electrical supply may be Long Term solutions but have Major Cost and Infrastructure Disadvantages in the Medium Term
- Internal Combustion Engines offer a Pathway Towards these Goals through
  - Incremental developments of Diesel Engines to Reduce Pollution and Improve Efficiency
  - Bio- and E-fuels to reduce the carbon footprint
  - Radical Developments such as Split Cycle for Major Gains in Thermal Efficiency
  - Zero-carbon and Near Zero Pollution Fuels including Hydrogen