Hydrogen Internal Combustion
A new perspective on an old idea

Nick Owen
Technical Director, Dolphin N2
28th November 2023

 | Decarbonising Heavy-Duty Transport & Decentralised Power Generation | dolphin-n2.com

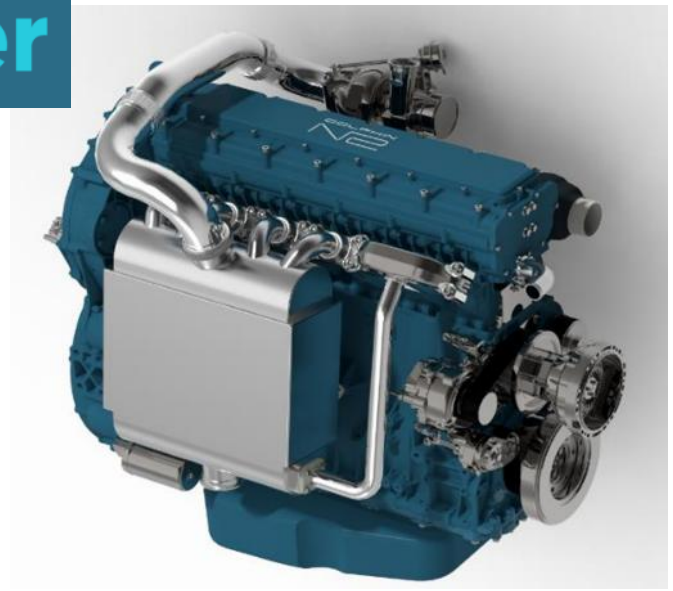
Dolphin N2: Established to commercialise the game-changing Recuperated Split Cycle Engine

Dolphin N2 Limited

- Established in 2017 as part of Ricardo
- Acquired by FPT Industrial, part of the Iveco Group, in 2019
- Based UK, ~40 staff
- Developing the **Recuperated Split Cycle Engine** and now also other forms of Hydrogen ICE for heavy duty power

Thermopower

FPT POWERTRAIN TECHNOLOGIES



Collaborative Projects & Partnerships

Innovate UK

ADVANCED PROPULSION CENTRE UK

Department for Business, Energy & Industrial Strategy

Step CO_2

RE-ARMD

HYDRATE

HIFLUX

University of Brighton

COSTAIN

zircotec

The University Of Sheffield. Advanced Manufacturing Research Centre

BOEING

HyCulture

HydroMAR-E

CNH INDUSTRIAL

Eminox

BMT

FPT POWERTRAIN TECHNOLOGIES

Engas Global

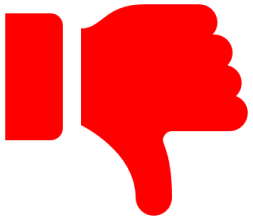
an electrolyser and H_2 compressor company

IVECO • GROUP

Transport & Mobile Machinery: Time to un-learn?

You may have heard some of the following – all untrue

- If it's got wheels, it has to go battery electric
- We must achieve zero emissions from the exhaust pipe to achieve net zero
- The internal combustion engine is inefficient, can never be clean, and has to be banned



Some things that are true

- We need environmental solutions that are effective, useable and quick to adopt
- Some transport and machinery applications work in pretty tough environments
- Net Zero means Net Zero cradle to grave (not just zero from an exhaust pipe)
- Climate change is the biggest challenge once air quality reaches pareto point
- We have a global infrastructure of supply chains, manufacturing and servicing for engines
- Hydrogen is a pretty good, clean fuel for an engine, and multiple markets are interested in it

What can we achieve with Hydrogen internal combustion engines?

The realities of Heavy Duty Power

- Wide range of duty cycles, many at high load factor
- Round the clock working, limiting time to re-charge or re-fuel
- Harsh, dusty or saline environments
- No fixed infrastructure off highway - re-fuelling may be no more than a jerry-can and a funnel
- Users often lease the equipment – market sensitive to CapEx & OpEx
- Traditionally conservative markets, comfortable with the Diesel engine

- ***A sustainable solution is needed here which is cheap, tough and familiar…***

Why internal combustion, why Hydrogen?

Five good reasons for considering the ICE

1. **It exists and is familiar** – market can change fuel without having to change the power unit (or its supply chain) at the same time
2. **It does the job** – tough, durable, and we know how to use it in a wide range of vehicles and machines
3. **It isn't battery-electric** – meaning that the ramp-up of resources and supply chains can be focused on where batteries make sense
4. **It's fuel flexible** – the same investment in manufacture can cover diesel, gasoline, bio-methane and hydrogen variants, all with high impurity tolerance
5. **It's clean and efficient** – despite what some say; including NOx…

Three good reasons for using Hydrogen

1. **Readily made** from a variety of sustainable sources, centrally or locally
2. **Better energy density** (by weight) & charging speed than electric
3. **A common fuel** for ICE & Fuel Cell – and many industrial or domestic chemical & thermal processes

ICE or Fuel Cell? Why not both?

Efficiency

- Fuel cell is not limited by thermodynamics
- But, in reality the PEMFC is most efficient at light loads – not always best for heavy duty
- And ICE is competitive at high loads once cooling fans and drive losses are accounted

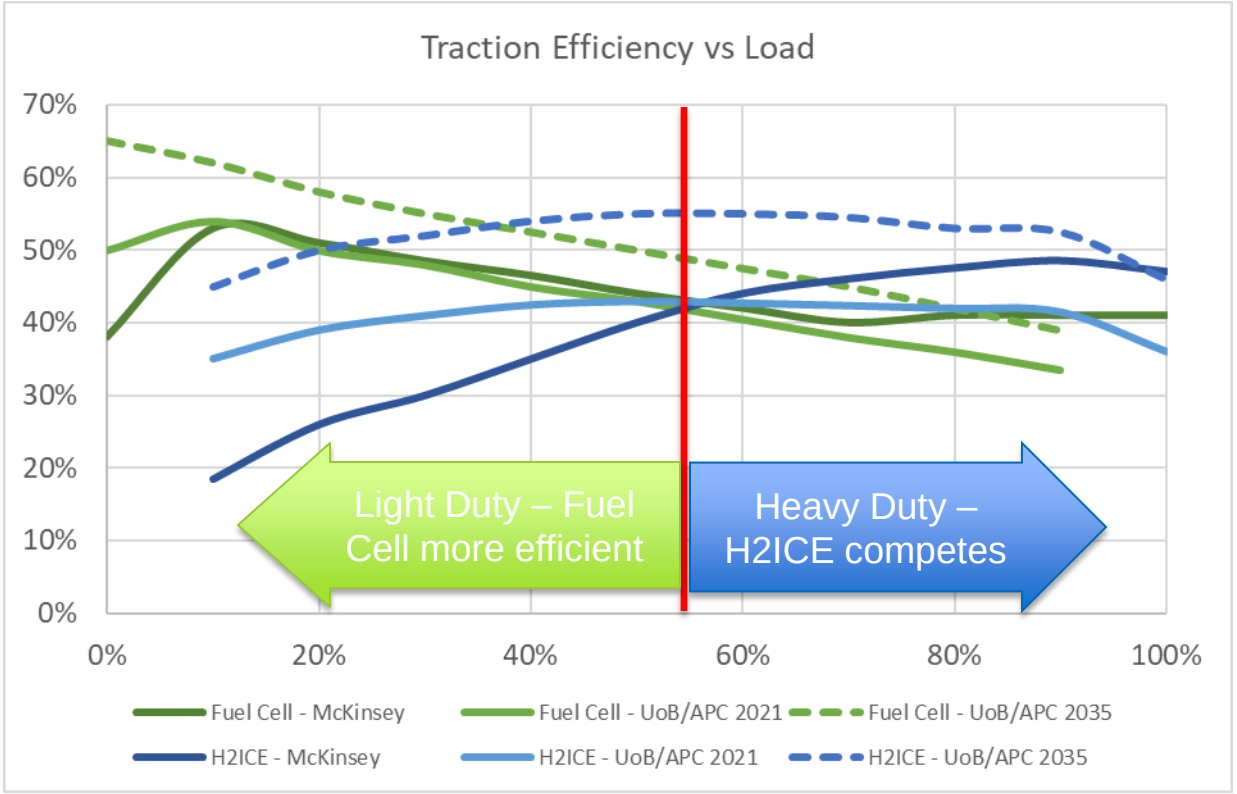
Air Quality & Noise

- Advantage Fuel Cell – especially for Noise
- But a lean-burning and after-treated ICE is very clean indeed – can clean ambient air
- Impact on human health negligible versus other 21st century issues such as road accidents, pandemics, mental health, and climate change

Initial Cost

- ICE likely to remain cheaper for some time

Both will co-exist, and complement each other by creating Hydrogen demand

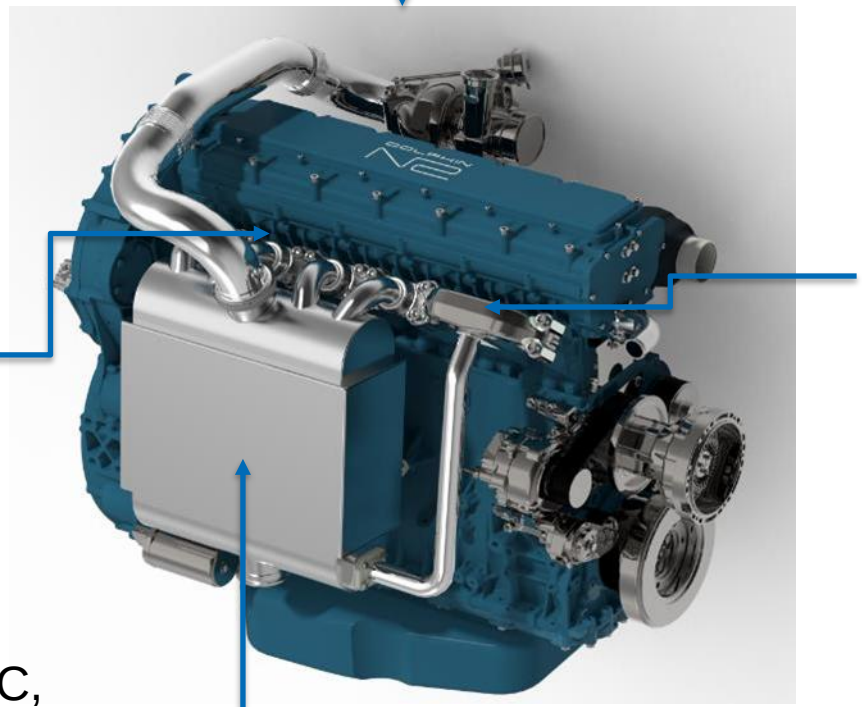


Fuel Cell vs Hydrogen ICE: *Reports from McKinsey (2021) and APC / University of Brighton (2021) highlight how the higher loads of Heavy Duty might favour an efficient Hydrogen ICE*

The Recuperated Split Cycle Engine

Target performance on Hydrogen: 180kW; 55% BTE; 1-2g/kWh pre-SCR NOx

1. Overall package is standard ICE shape. (Here, an in-line six)



2. The front two cylinders induct and compress, delivering air at up to 70 bar.

   Compression is cooled by water injection for greater efficiency.

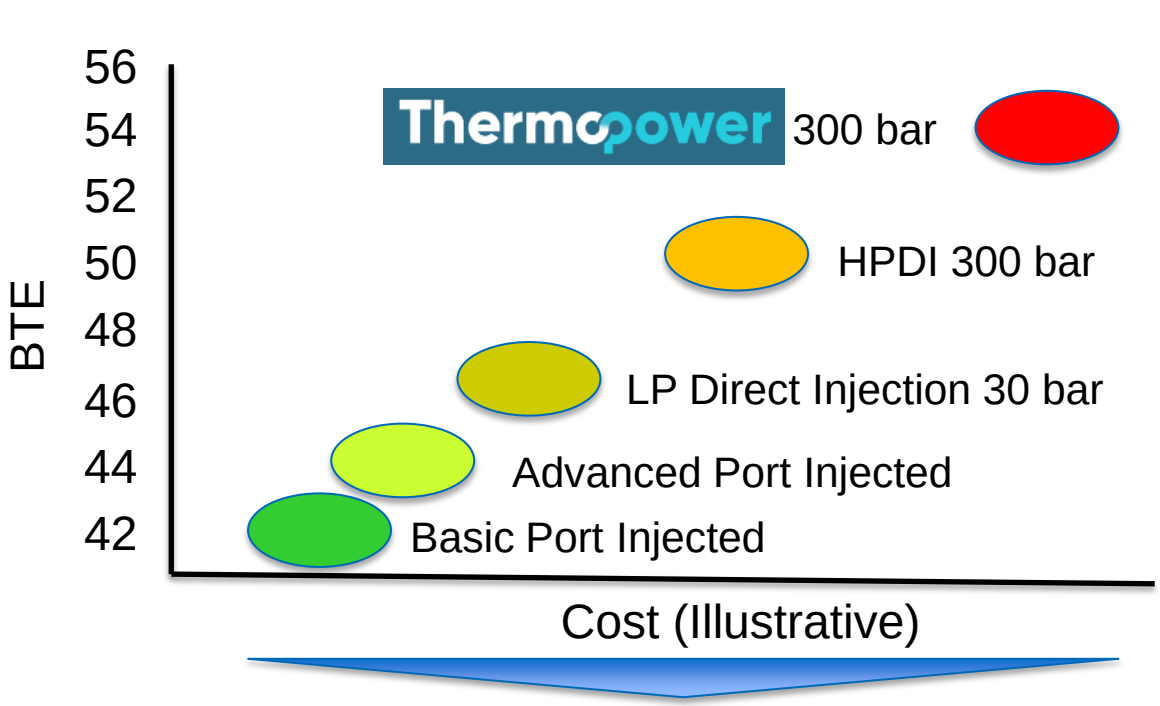
3. The recuperator uses post-turbo exhaust to heat this air up to 700°C. This heat recovery is the main driver of efficiency benefit.

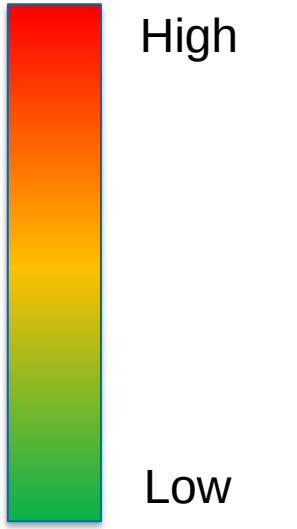
4. The rear four cylinders host Combustion and Expansion.

   Higher displacement than the Compressor (2-3x) is required to extract efficiency.

   Air and Fuel are co-injected at TDC, creating a unique mixing and combustion regime.
   Works especially well with Hydrogen.

Hydrogen ICE Roadmap: Horses for Courses





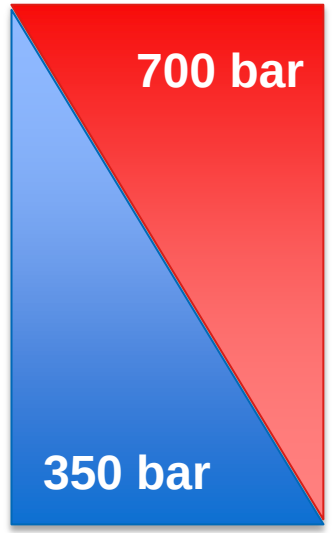
Why Buy?

High Utilisation, Long Haul
Limited tank space
High Hydrogen price

Spectrum of users

Low Utilisation, Short Haul
Low Hydrogen price

What Tank?



Efficiency driver is higher pressure, direct injection of Hydrogen into the engine.
This has implications for cost, robustness, complexity, maturity and onboard storage pressure.

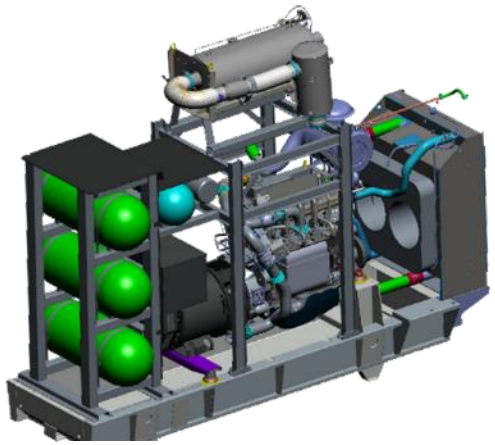
There is no “one size fits all”

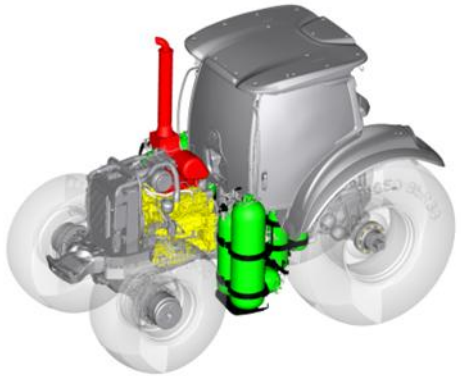
A complex market needs a spectrum of solutions, so it can choose the most cost-effective…

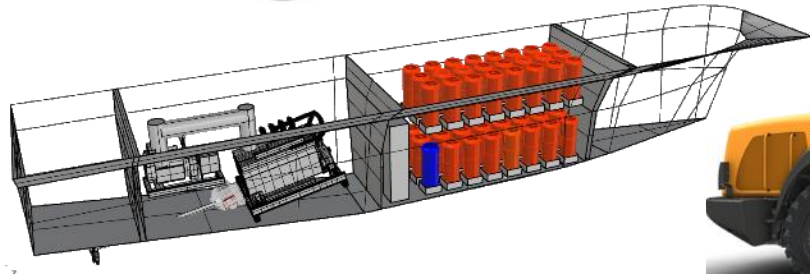
Off-highway is a particularly promising area for a Hydrogen ICE

Why Off Highway?

- Increasingly coming under the spotlight, after many years of on-highway focus
- Greater acceptance of H2-ICE as “acceptably clean” by regulators
- Often find electrification challenging
- Construction sites, farms and ports are self-contained “communities”, with options for local energy (biomethane, wind, solar) including on-site electrolysis
- Trained users, no public access
- Added cost of Hydrogen fuel is noted, but small compared to the high value of the primary output, e.g. city construction projects
- And Hydrogen is not inescapably expensive, especially from wrong-time renewables







Four key factors for an early adopting “Hydrogen Community”

EU project “Roads2HyCom”, 2008

Technology Accessibility

Public Acceptance

Political Will

Potential for Growth

Conclusion: The Hydrogen ICE is coming

- **The Hydrogen ICE must be an important part of any Hydrogen thinking**
  - Easy to adopt, because it's based on what we do now
  - Clean and efficient enough to be attractive, for quite some time, maybe indefinitely
  - Actually helps the Fuel Cell to market – both will co-exist

- **We will see them first Off Highway**
  - Large construction sites, farms, ports all well suited to become early "hydrogen communities"
  - Active engagement by stakeholders is happening now
  - Strong regulatory acceptance and political will

- **And they have not reached the end of the road, in any sense**
  - Accepted in European Commission proposals for zero-carbon truck technology
  - Recuperated Split Cycle engine shows that combustion can stay competitive
  - A spectrum of solutions, that we can – and must - adopt now