H2 internal combustion for Destination Zero

Richard Payne

29 February 2024

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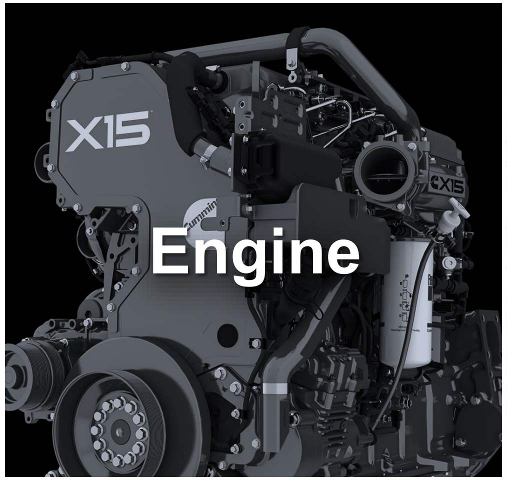
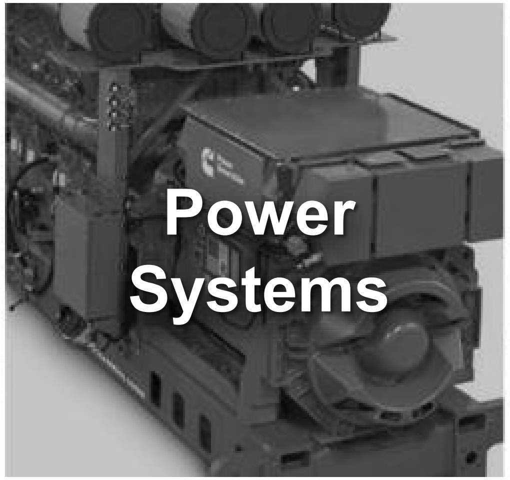
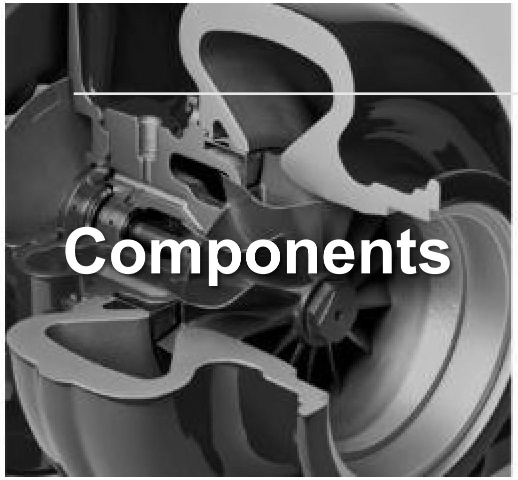
190	Countries and territories*
70,000	Global employees
104	Years of industry leadership
10,600	Cummins certified dealer locations



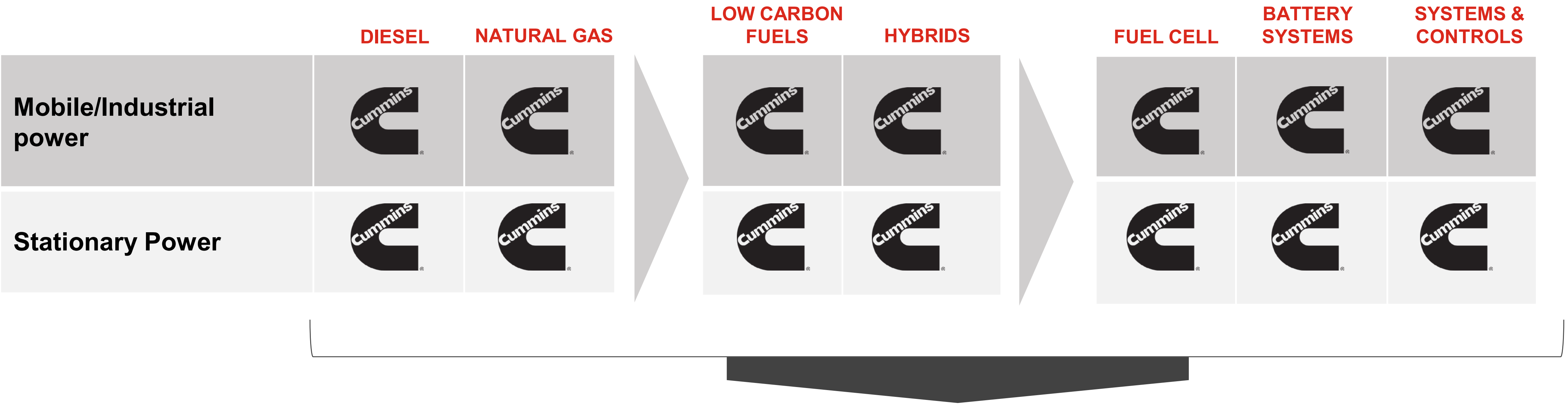




Multiple Awards for **Environmental and Sustainability Leadership**

OUR PRODUCTS

POWER SYSTEMS TECHNOLOGY PORTFOLIO IS ENABLING CUSTOMER TRANSITIONS TO NET ZERO



All supported by our deep experience as a solution provider and a global, dependable support network

Chart represents technology solutions available now through 2024

Project Brunel

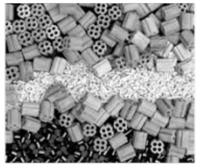
- Project Brunel is a collection of workstreams supported through the Advanced Propulsion Centre (APC) focused on the development of a novel zero-CO_2 hydrogen internal combustion engine based on an optimised spark ignited platform.

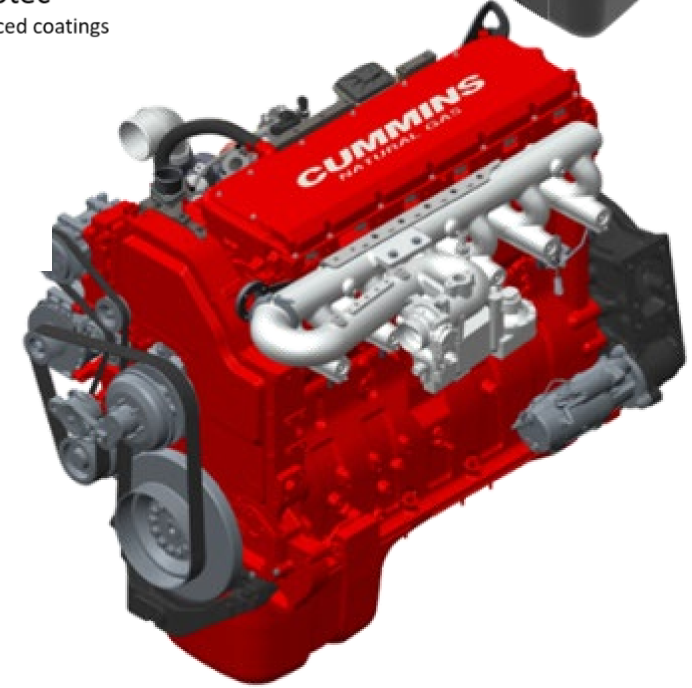
BorgWarner
WP4: Fuel Injection System

Zircotec
WP7: Advanced coatings

Cummins UK (Cummins)
Project Lead, Base Engine Development, Scale-Up, Supply Chain, Integration and Demonstration

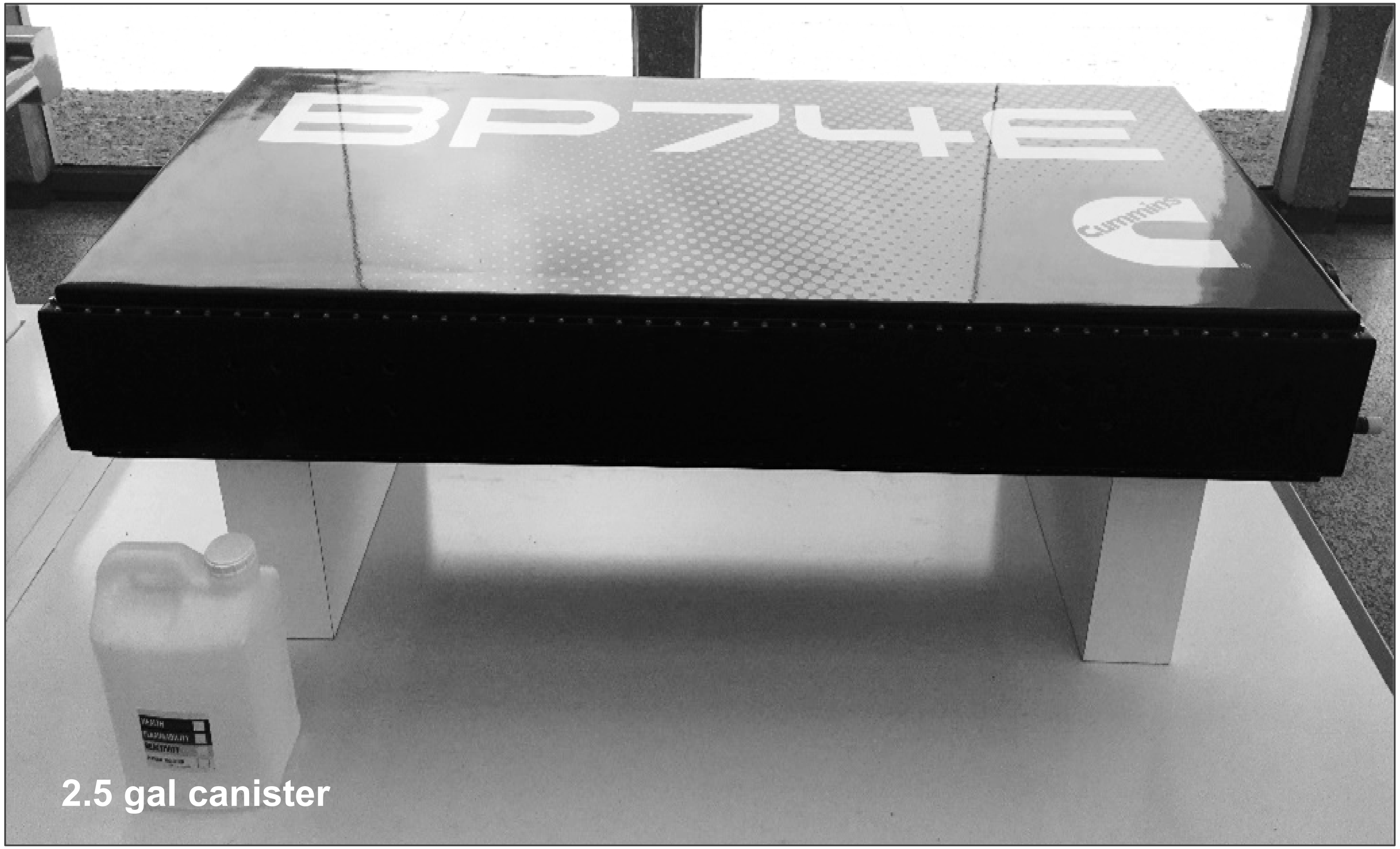
Johnson Matthey (JM)
WP6: Aftertreatment and air-handling system

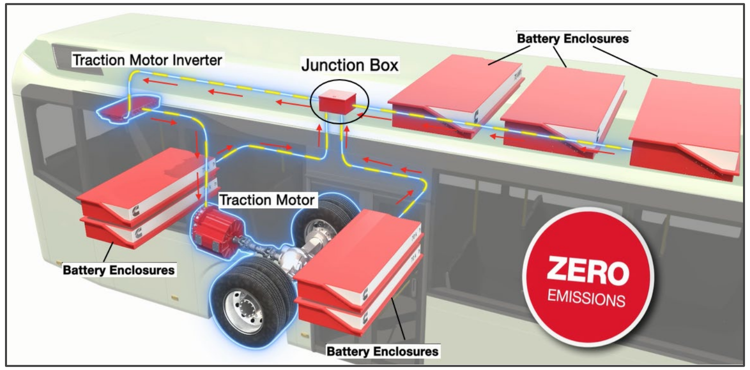




Battery Electric Vehicles Work!

Why not 100% BEV now? *→ Energy Density*

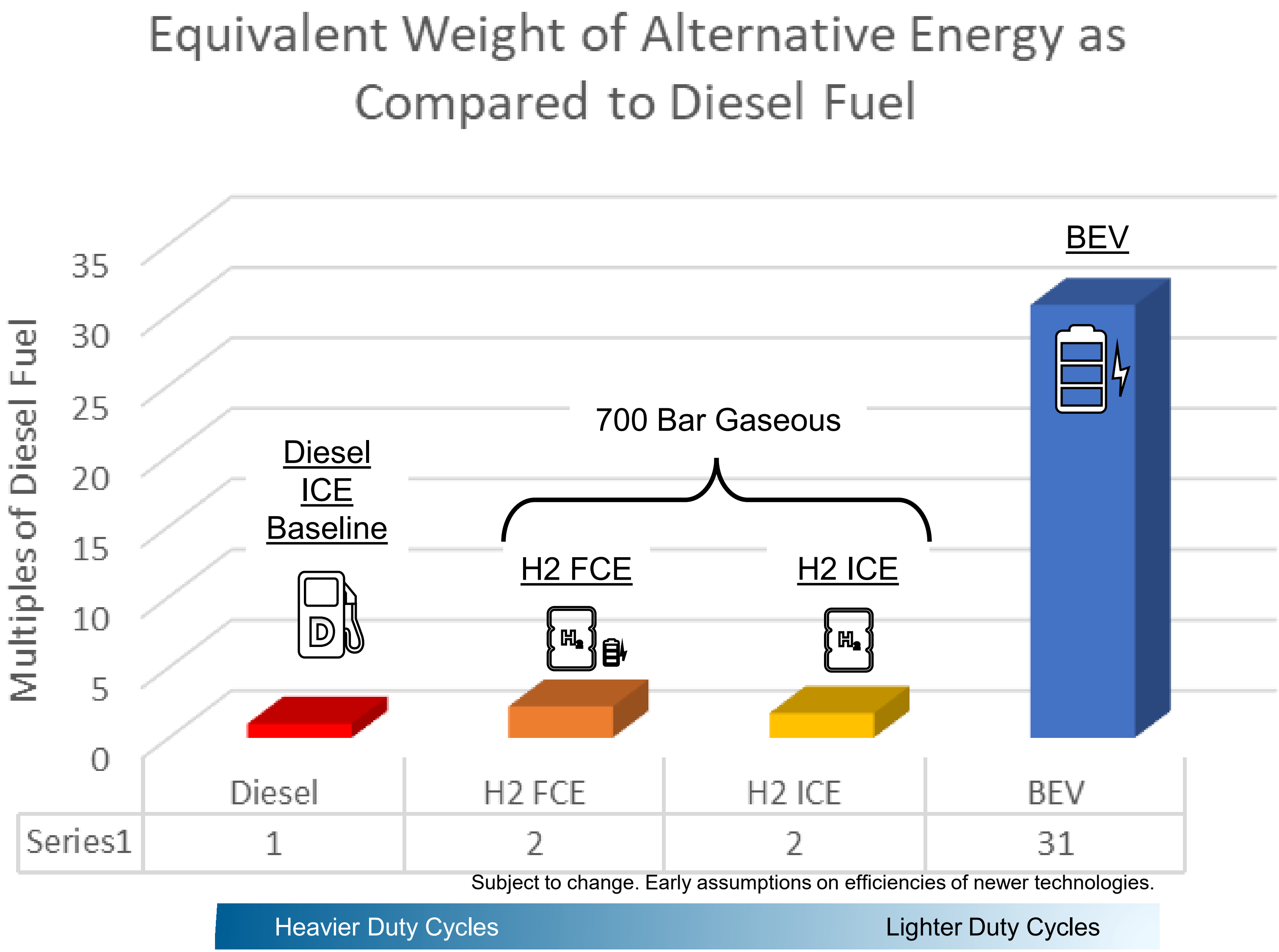




- 74kWh equals to energy content of < 2 gal (10 L) of diesel fuel

Payload penalties, energy density and **charging time** decrease the cost-effectiveness of BEV in HDV.

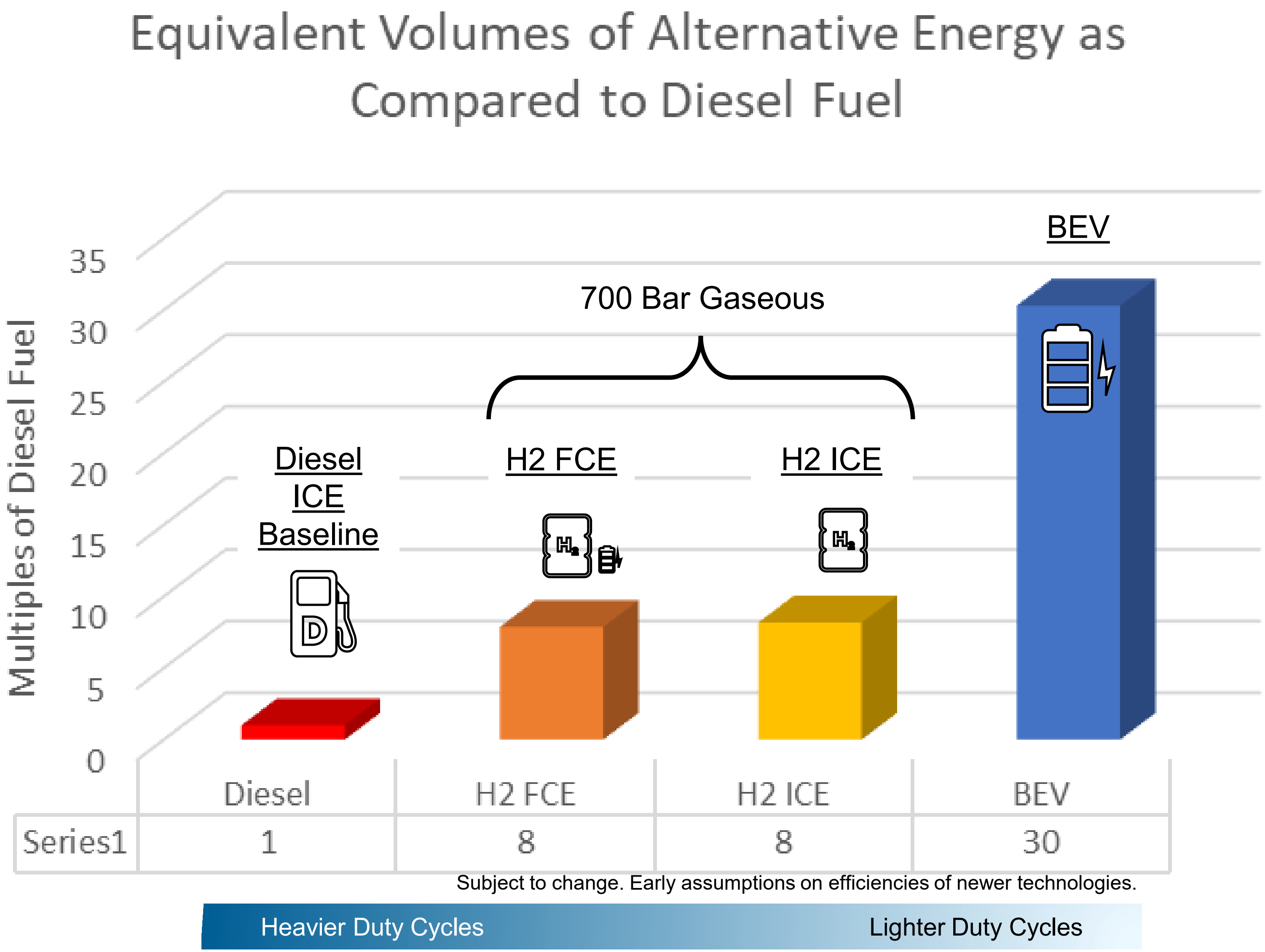
Destination Zero: Energy Gravimetric Density and Duty Cycles



Included:

- Diesel = Fuel + Fuel Tank + DEF + DEF Tank
- H2 FCE = Fuel + Type IV Fuel Tank + Battery
- H2 ICE = Fuel + Type IV Fuel Tank + DEF + DEF Tank
- BEV = Battery Pack @ 135 Wh/Kg

Destination Zero: Energy Volumetric Density and Duty Cycles

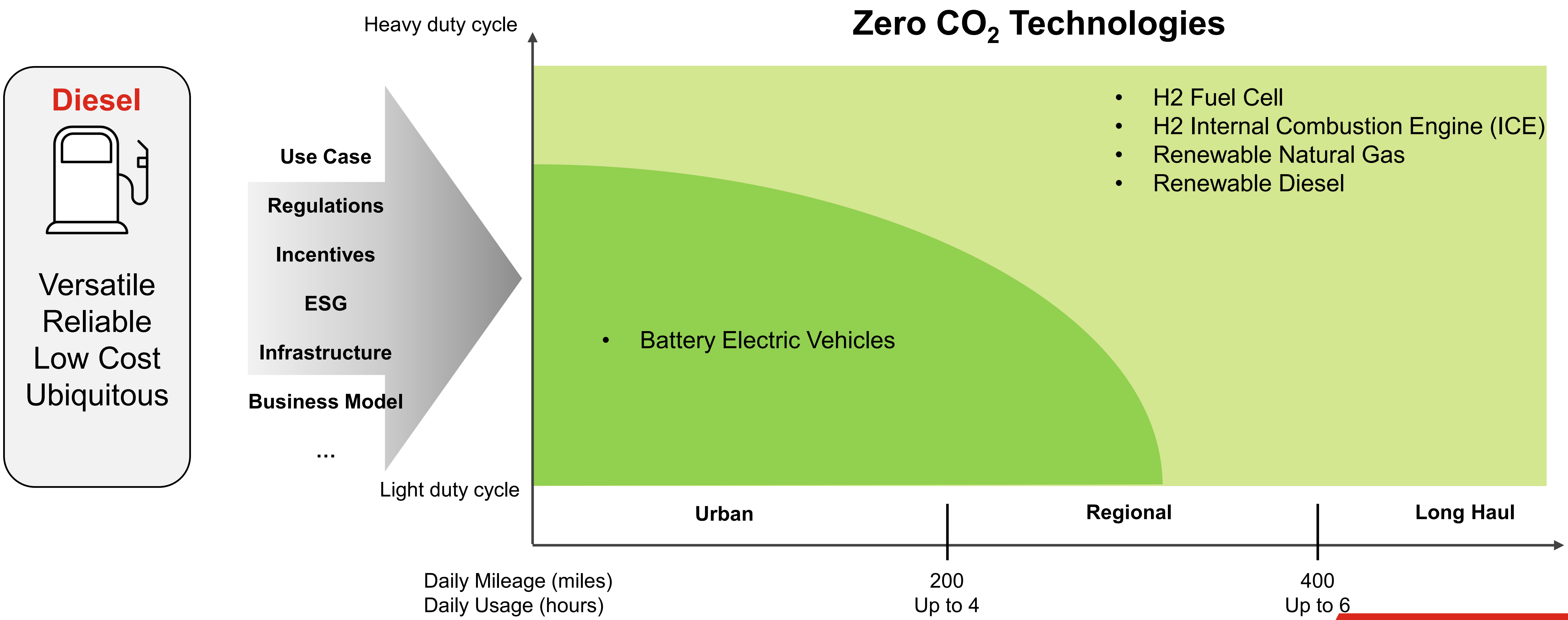


Included:

- Diesel = Fuel + DEF
- H2 FCE = Fuel + Battery
- H2 ICE = Fuel + DEF
- BEV = Battery Pack @ 173 Wh/L

Note: H2 Corrected for Packing Density of Round Tanks

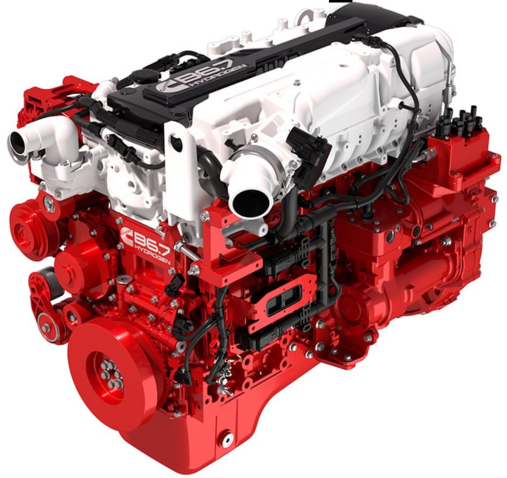
Different Use Cases: Complementary Technologies



How best to use H_2?

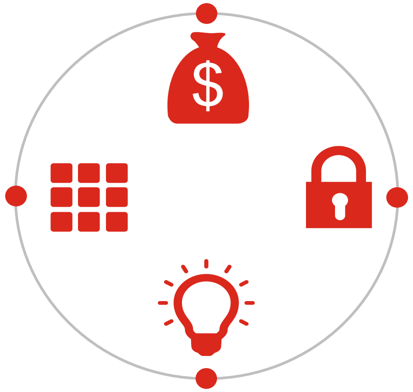
PEM Fuel Cell Engine

Internal Combustion Engine (H_2-ICE)



Total Cost of Ownership

Availability



Infra-structure

Regulations, Policy, and Goal Setting

Technology Maturity

https://youtu.be/HvPAUh-VSJ4

HYDROGEN ICE IS WITHIN REACH

THE EVOLUTION OF AN EXISTING CONCEPT IS CREATING A REVOLUTION IN SUSTAINABILITY

Supports decarbonization of the commercial vehicle industry

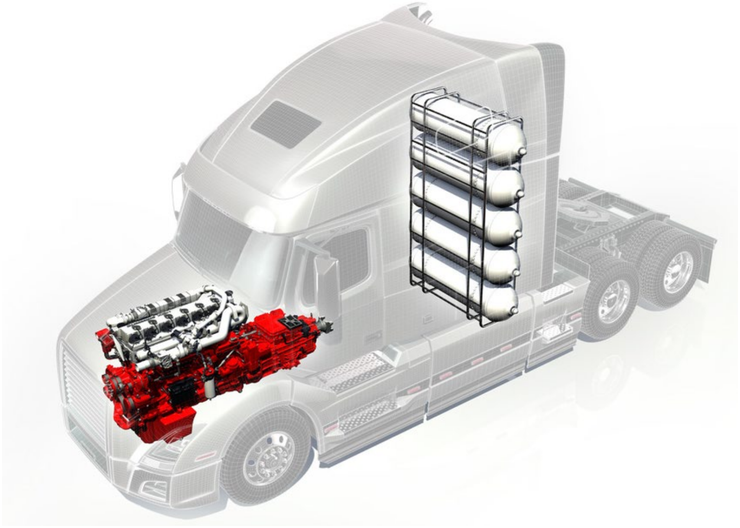
- Zero-carbon well-to-wheel with green hydrogen
- Scale production can begin within the decade

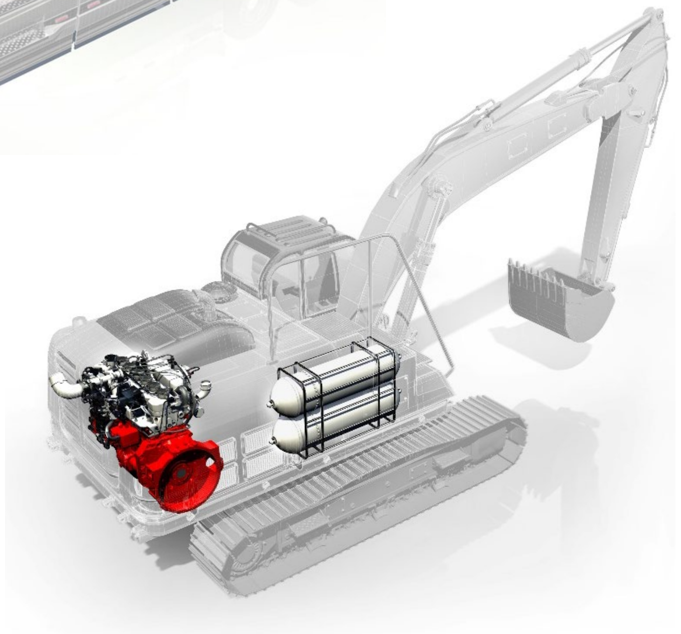
Benefits to end users

- Competitive initial cost
- Drop-in diesel replacement
- Familiar powertrain technology, vehicle/machine technology and maintenance practices
- Single fuel supply switch across a range of duty cycles

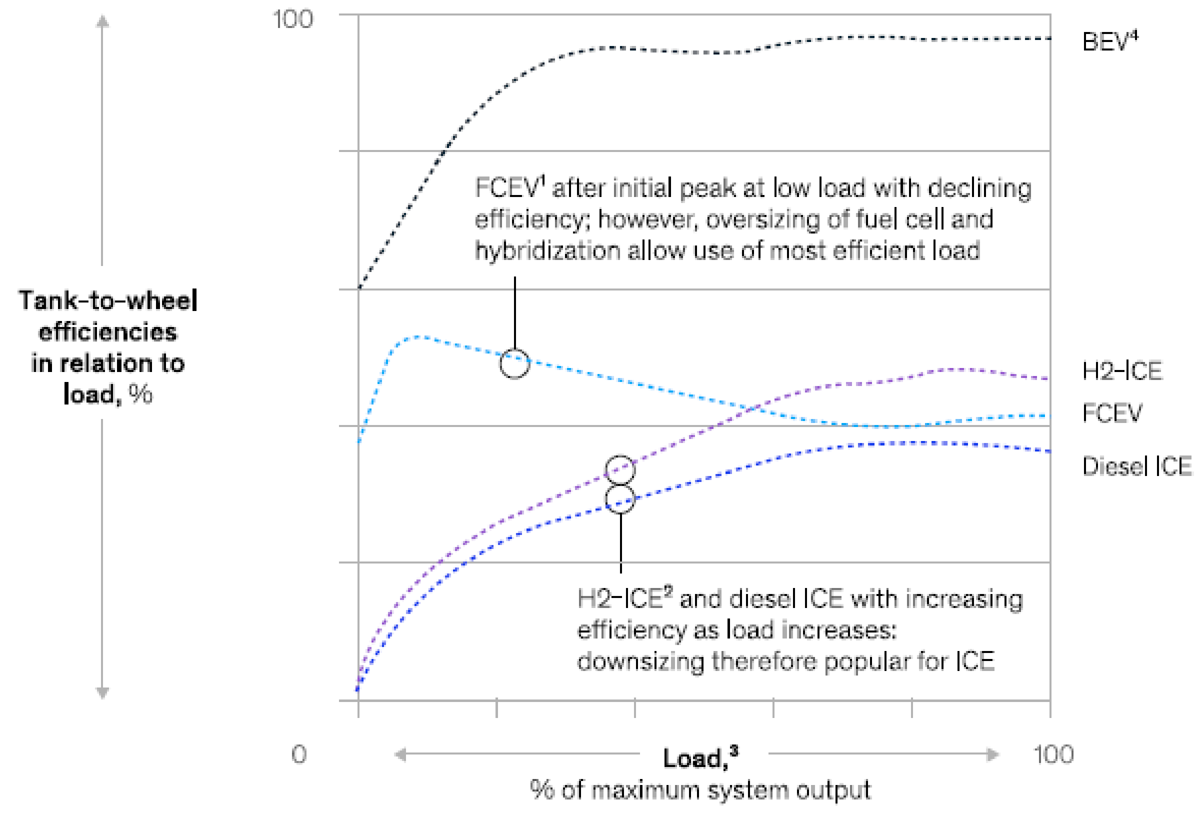
Complementary to hydrogen fuel cell

- Builds scale for hydrogen storage tanks on vehicle
- Drives hydrogen fueling infrastructure
- Common hydrogen service and support infrastructure



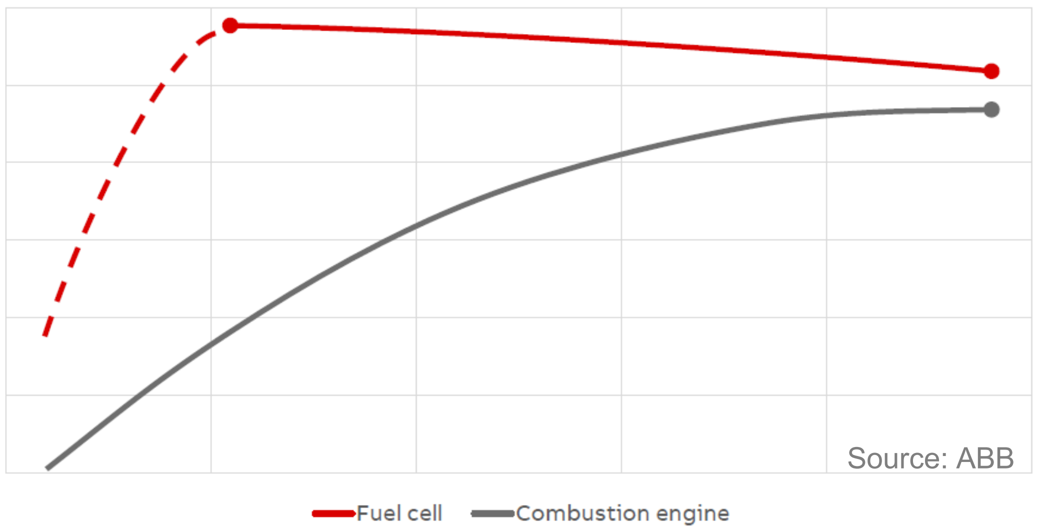


Efficiency vs. Load Trade-Offs



[1]Fuel-cell electric vehicle. [2]Hydrogen internal combustion engine. [3]Defining "maximum system output" as maximum output that system can supply continuou (including Booster), equaling 80% of FC system output. [4]Battery-electric vehicle.
Source: Lohse-Busch et al., Toyota Mirai case study (1st generation), July 2019; RL Deppmann

McKinsey & Company



Unlike ICE, efficiency of a fuel cell declines substantially with:

- Load: ~10-20 percentage points
- Aging: ~5-15 percentage points

Higher parasitic load due to cooling:

- Low temperature operation
- Limited heat rejection to exhaust

Hydrogen ICE

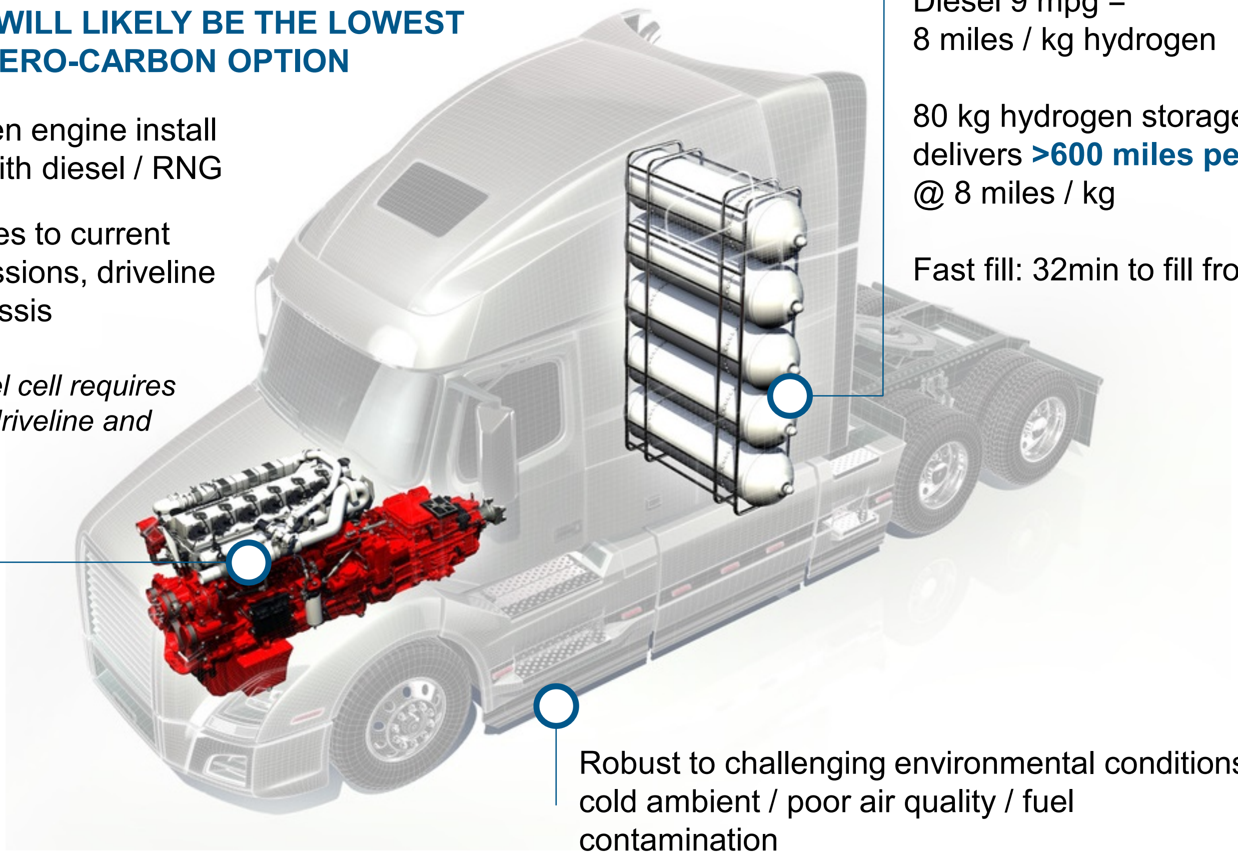
2027 / NORTH AMERICA / LINE HAUL / 120,000 MILES PER YEAR / 600+ MILE RANGE

H2-ICE WILL LIKELY BE THE LOWEST COST ZERO-CARBON OPTION

Hydrogen engine install aligns with diesel / RNG

Integrates to current transmissions, driveline and chassis

Note. fuel cell requires electric driveline and battery

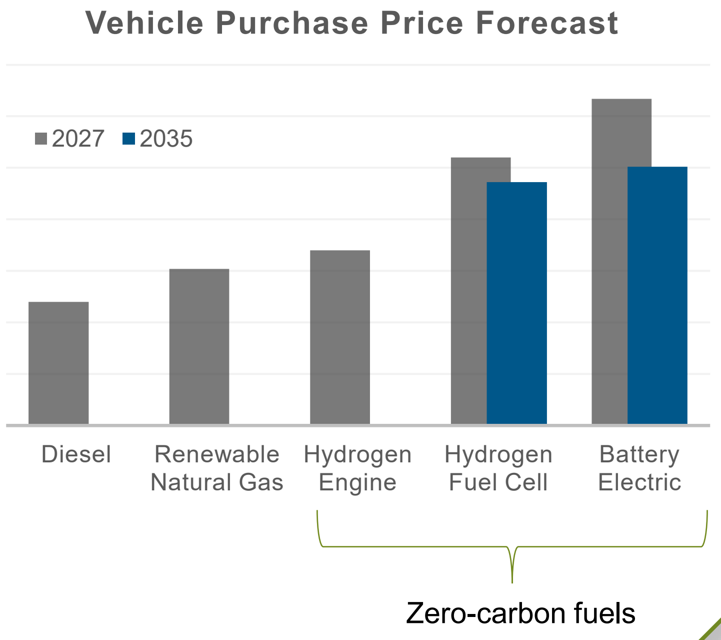


Diesel 9 mpg =
8 miles / kg hydrogen

80 kg hydrogen storage unit @ 700bar delivers **>600 miles per day range** @ 8 miles / kg

Fast fill: 32min to fill from empty

Robust to challenging environmental conditions: cold ambient / poor air quality / fuel contamination



VECTO & GEM: CO_2 score forecast to be equivalent to battery electric and fuel cell powertrains

H2-ICE CO2 Comparison to Diesel

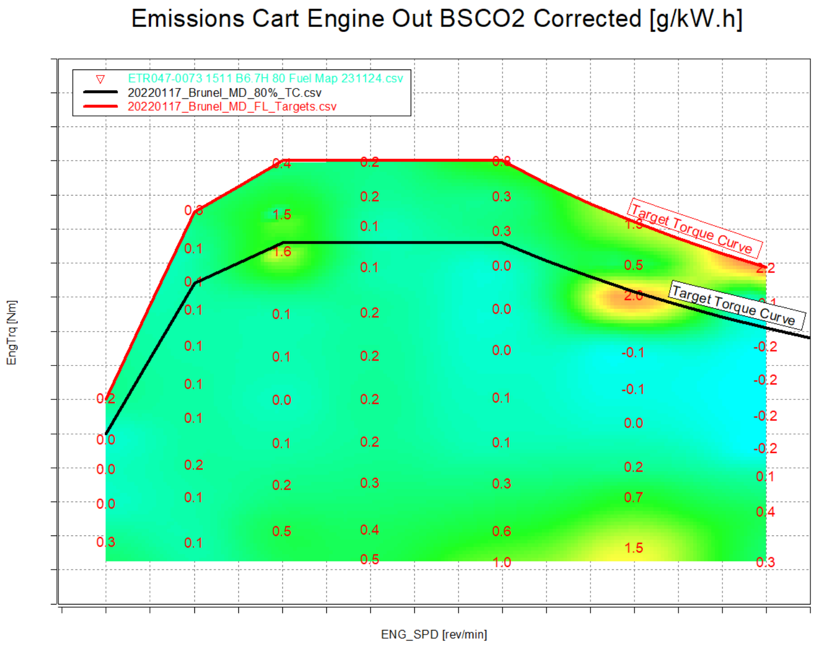
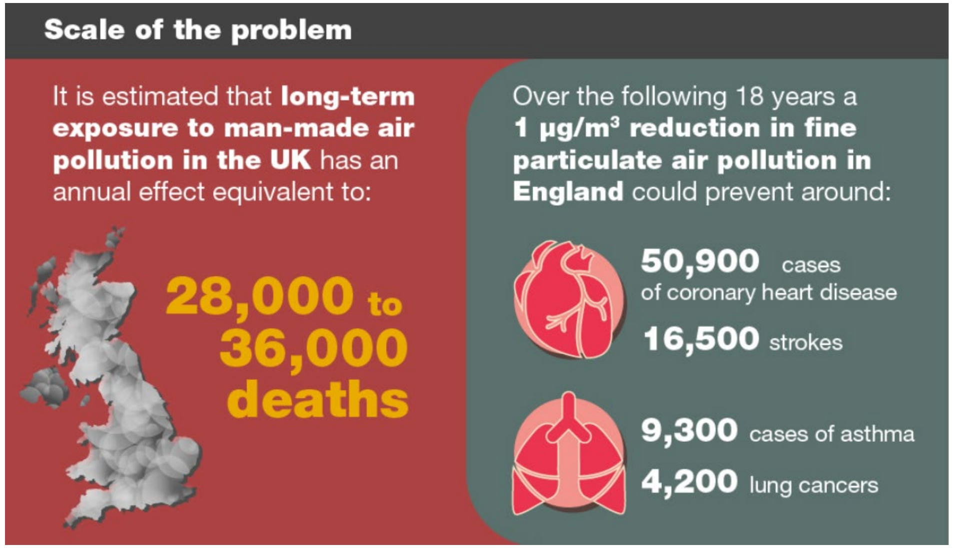
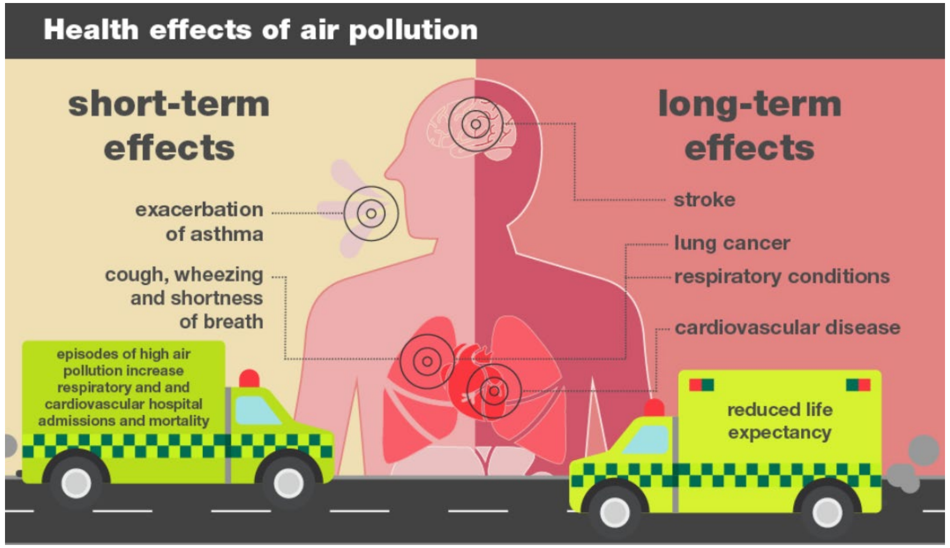


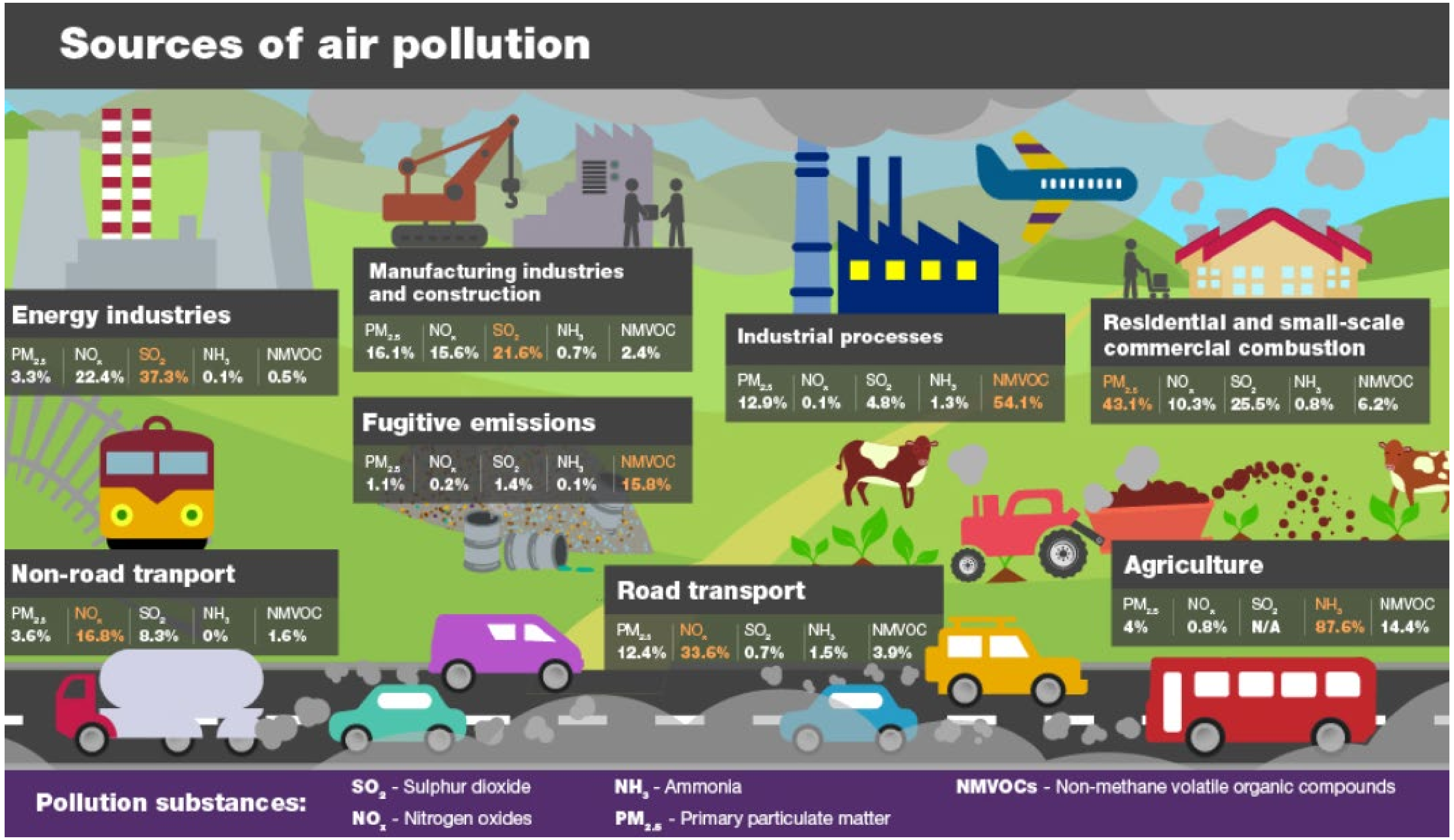
Fig 1 H2-ICE Engine out CO2 measured data

- Across the combustion map H2-ICE produces >99% CO_2 reduction compared to equivalent diesel engine range(600-1000 g/kWh).
- CO_2 values corrected for intake air CO_2, show only the incremental CO_2 produced from combustion

What about the NOx???

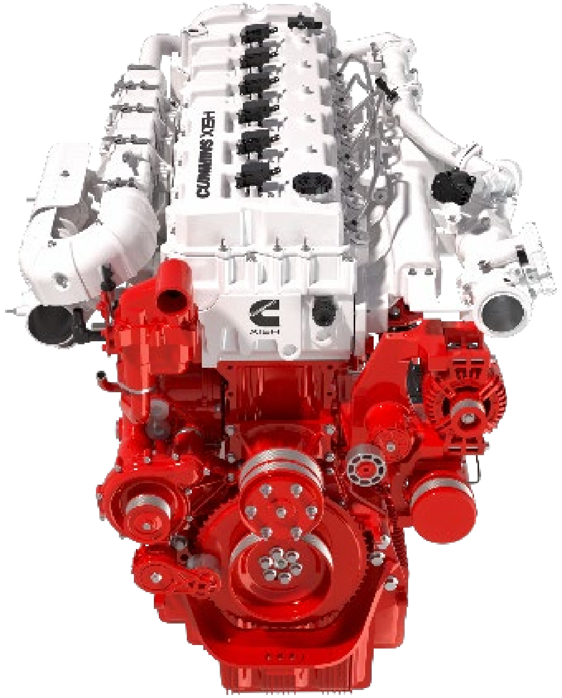


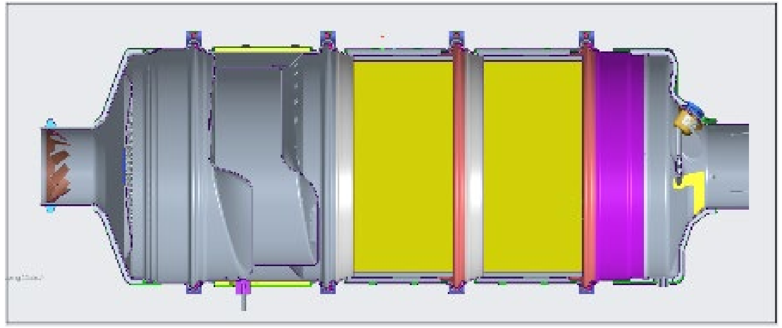




H2-ICE Aftertreatment Test Summary

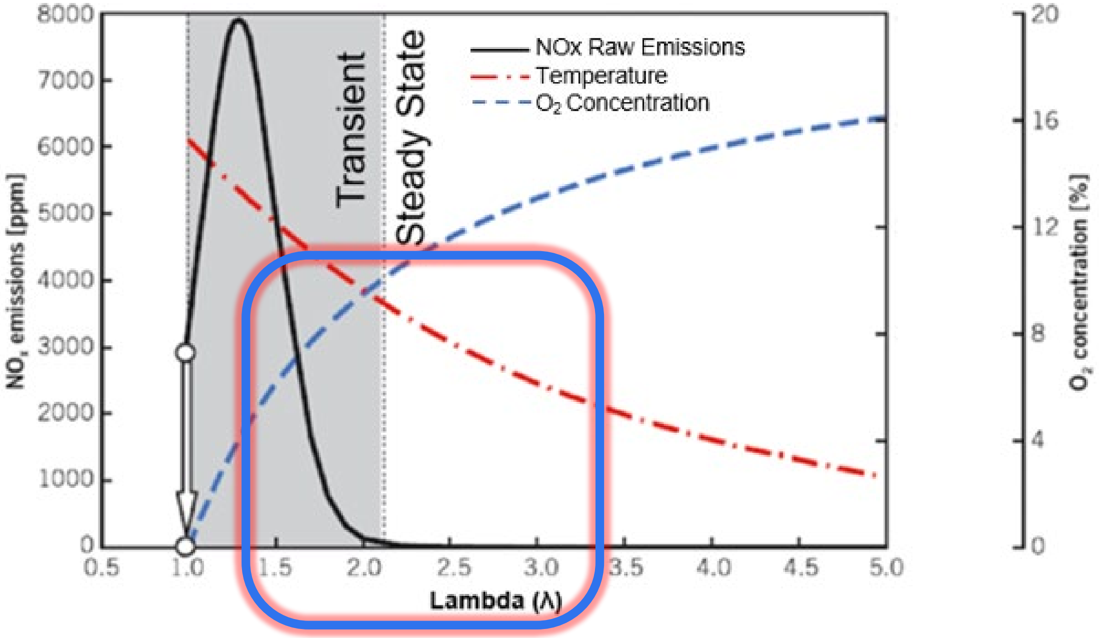
- Data Analysed: HD (15litre) 550hp
- Data uses **SCR-only** to investigate the simplest emission control system





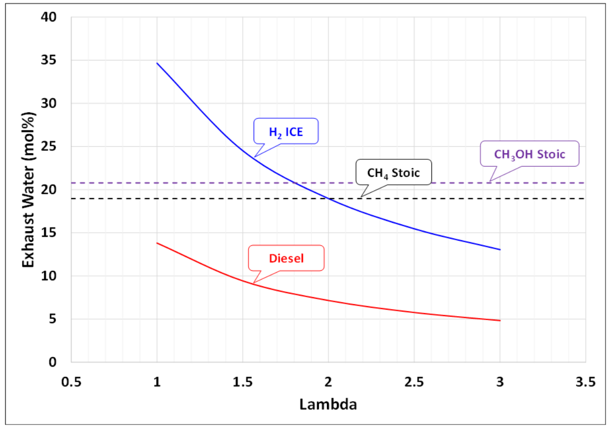
- So far work has been Euro 7 (WHTC) heavy duty on highway focused
- Non-road (NRTC) for stage V and guesstimated stage VI to follow

H2-ICE Combustion & ATS Considerations



Lean Burn (λ>2.0)

+ Very low EONOx can be achieved.
+ Higher BMEP make HD diesel performance possible
+ SCR technology is enabled.
Δ Transient NOx levels drive a need for aftertreatment.
Δ High air flows result in lower exhaust temperatures.

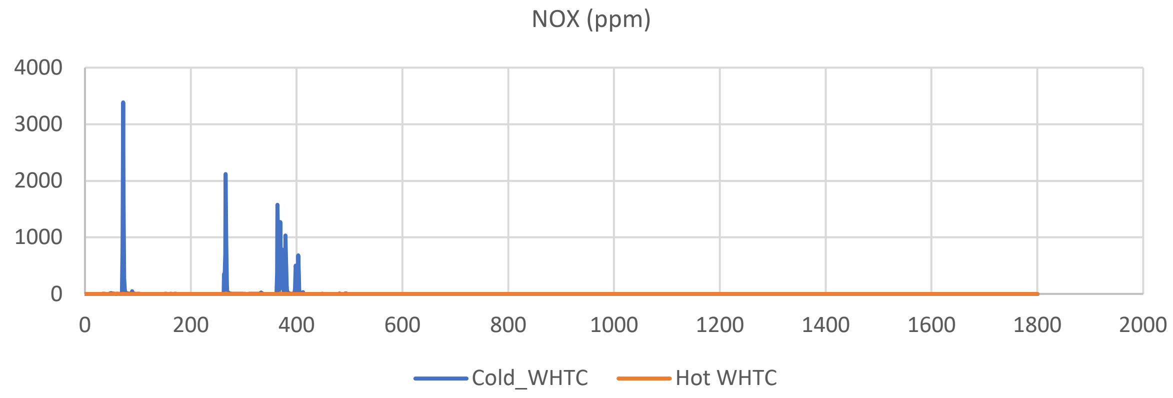


System Environment watchouts

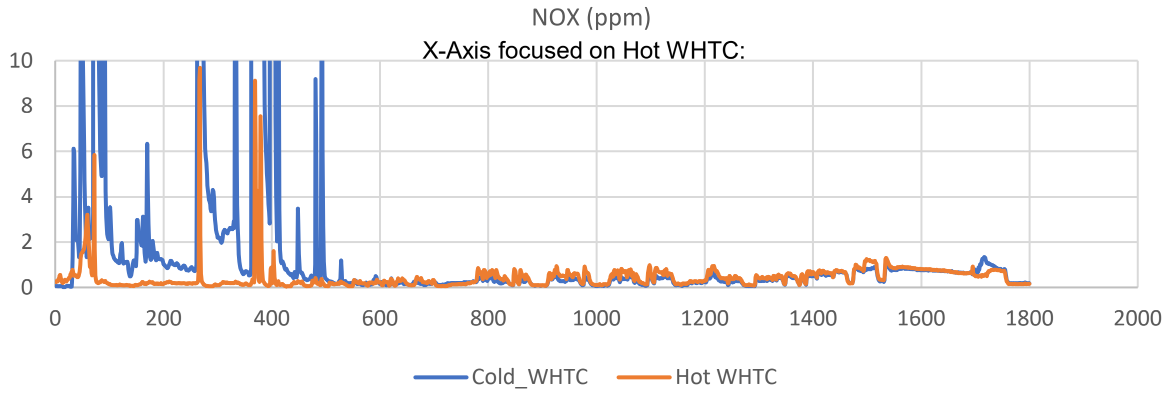
Δ Hydrogen creates a lot of water during combustion.
Δ λ≈2 creates similar water levels to natural gas.
Δ Lower exhaust temperatures in lean burn conditions create a condensation risk.
Δ Hydrogen embrittlement is possible if H_2 concentration is high enough.

Source: SAE Heavy Duty Diesel Sustainable Transport Symposium
H2-ICE Emission Control Technology – Paul Gwyther

H2-ICE WHTC System Out NOx
(WHTC)



- Real-time NOx ppm is very low after 400 seconds of Cold WHTC and throughout Hot WHTC.



- Focusing on Hot WHTC NOx ppm levels, NOx is between 0 – 1ppm with three transient excursions, peaking at 9ppm.

H2-ICE WHTC System results

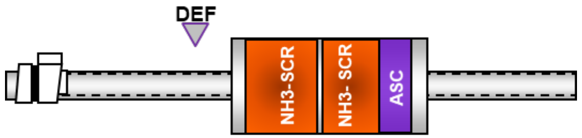
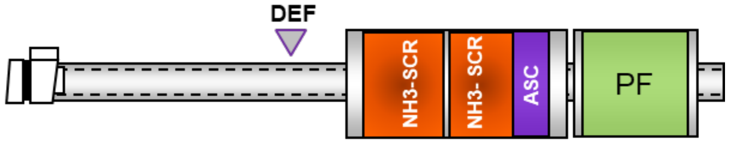
- Lambda based combustion control delivers exhaust temperature fast and consistent on cycle.

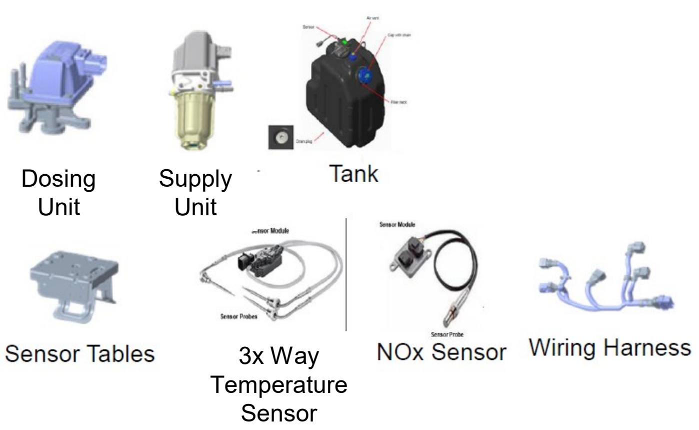
- System out NOx is controlled at 400s into Cold WHTC
  - Cold cycle achieve >90% deNOx control
  - Hot cycle achieves >99% deNOx control
  - WHTC System Out Combined Cycle NOx 35mg/kWh

Cycle	Arch.	Rating	Type	NOX (mg/kwh)	PM (mg/kwh)	PN10 (#/kwh)	N2O (mg)	NH3 (mg)
			EU7 WHTC Limit	200	8	6.00E+11	200	60
WHTC	SCR Only	550ps	Composite	35	5	~	65	18

- H2-ICE with current diesel like SCR (only) after-treatment far exceeds Euro 7 capability.
- Other after-treatment technology, including Oxi-Cat and Particulate Filter is being evaluated.
- Further Optimization will be done to improve future performance.
- Non-road cycles and operation to be evaluated.

Interim H2-ICE Aftertreatment Architectures

	Most likely Architecture	Key Drivers
Euro VI		NOx – 460 mg/kWh PN_{23} – $6x10^{11}$
Euro VII		NOx – 200 mg/kWh PN_{10} – $6x10^{11}$



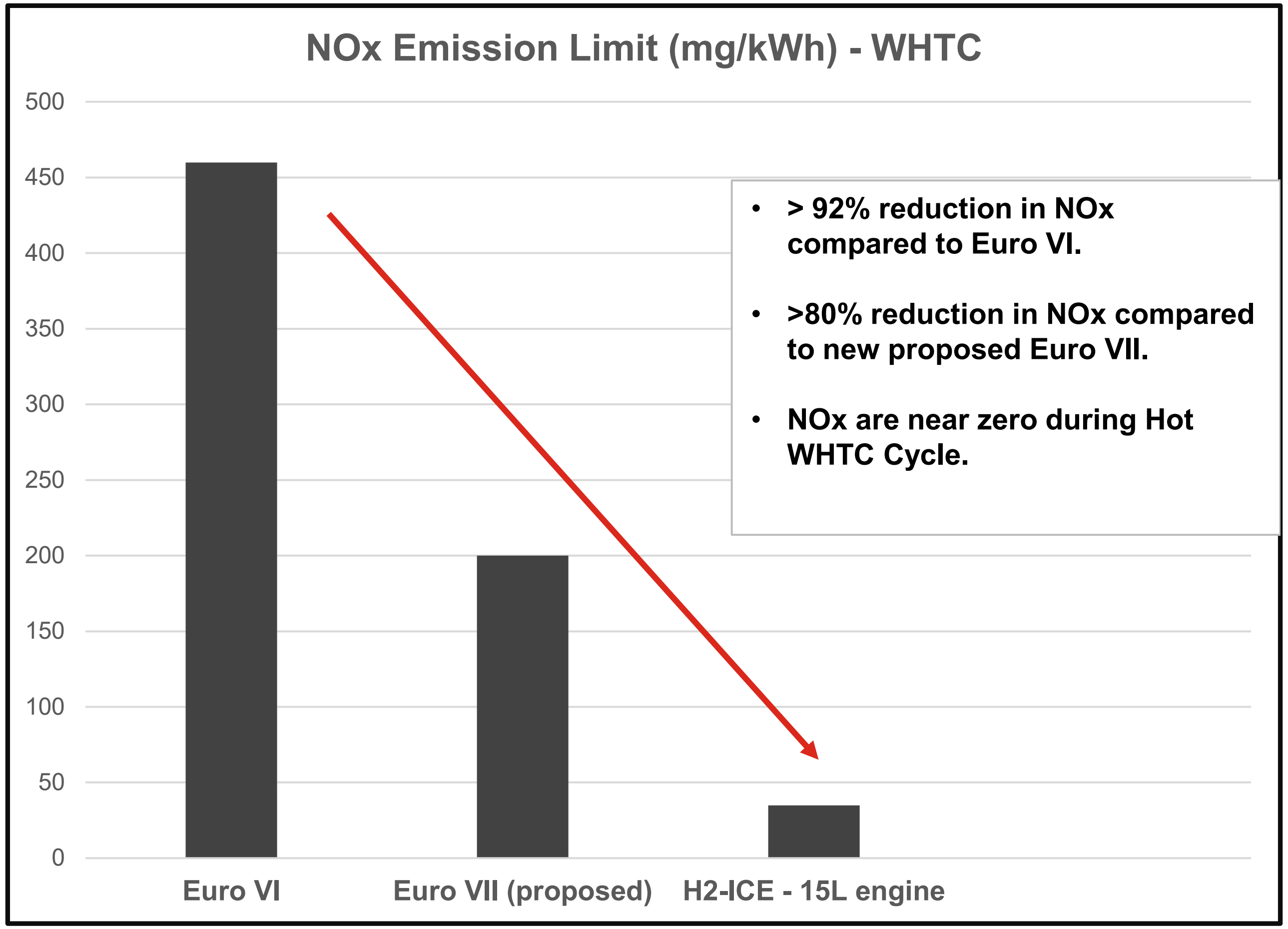
Current Status & Key Takeaway:

- Aftertreatment systems can reuse diesel technology, including packaging, catalysts, sensors and actuators.
- NOx levels are controlled well below Euro VII limits.
- N_2O levels are controlled well below Euro VII limits.
- Real-time NOx ppm is very low (near zero) after 400 seconds.
- Across the combustion map H2-ICE produce near zero CO2 (>99% reduction compared to Euro VI CO2 level).

Next Steps for System Development

- PF is being evaluated for improved PN_{10} control.
- Oxi-Cat is being assessed for additional thermal management needs (Specifically for RDE).
- Further Optimization will be done to improve future performance
- Work to optimize for non-road cycles and operation

NOx comparison - Regulation



- **> 92% reduction in NOx compared to Euro VI.**
- **>80% reduction in NOx compared to new proposed Euro VII.**
- **NOx are near zero during Hot WHTC Cycle.**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