

Decarbonizing heavy duty vehicles through hydrogen combustion

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MAHLE Powertrain

A global Engineering Services provider specialising in high performance and high efficiency powertrains



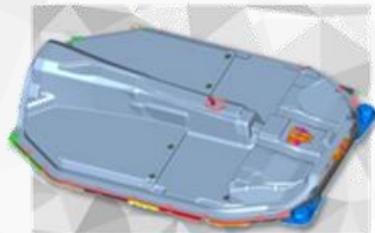
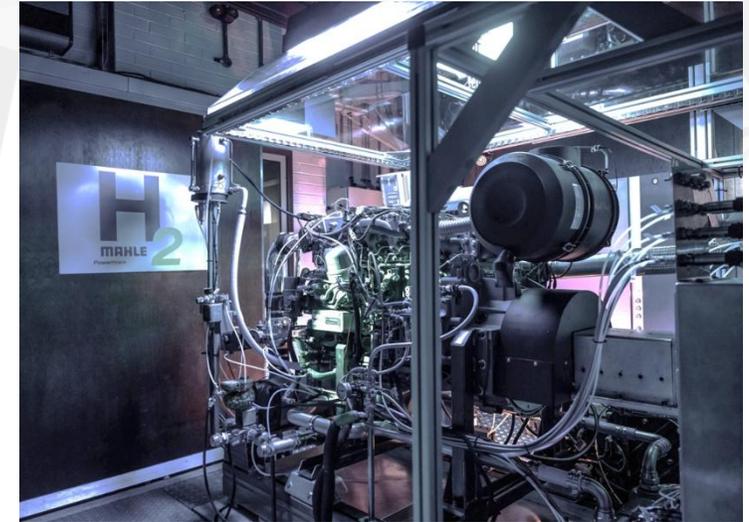
Over 60 years of heritage, innovation and experience



ICE, Electrification and Thermal Management



Whole Powertrain Solutions



Battery Systems



Advanced Engines & Hybrids



Transmissions & E-Axles



Electric Machines



Bespoke Controls & Software



Development & Validation



Vehicle Integration

The Role of Hydrogen in Decarbonisation

Hydrogen is important in the push for electrification



Hydrogen is electrification



Grid balancing for renewables



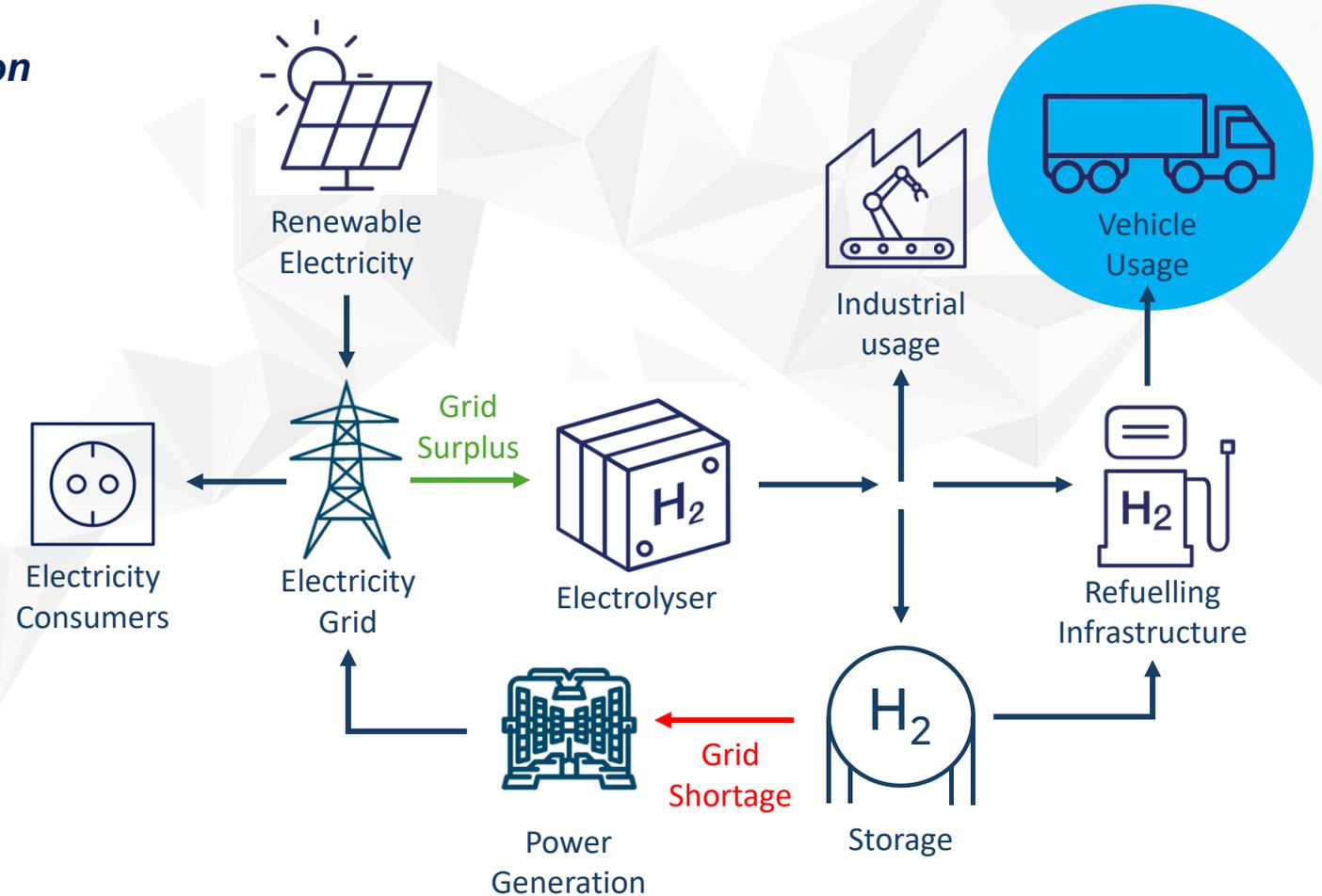
Suited for some high energy applications



Low rare-earth material requirements



Decarbonisation and ultra-low emissions



Suitability of Hydrogen ICE for Heavy Duty

Advantages



Fast refuelling



Lightweight energy storage (relative)



Existing manufacturing processes / plants



Existing repair, maintenance and recycling



High power, high torque, high robustness



Ultra-low emissions & cold (-40 °C) operation



Suitability of Hydrogen ICE for Heavy Duty

Disadvantages



Poor energy density means high pressure or cryogenics



Expensive fuel tanks with finite life



Fuel distribution infrastructure almost non-existent



Work needed to reduce cost of Hydrogen



NVH (relative to BEV)



Less efficient use of renewable electricity

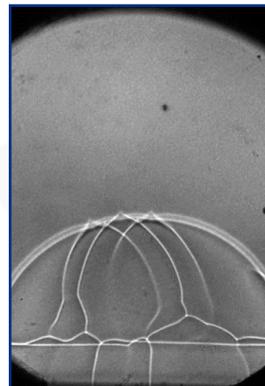


Hydrogen Engine Development Roadmap



Gen 1:

- Retrofit & OE – Port Fuel Injection (PFI)
- ~90% Diesel Performance
- Minimum hardware changes
- Existing engine architecture / prodn lines



Gen 2:

- OE – Direct Fuel Injection (DI)
- 100%+ Diesel Performance
- Carry over cylinder head architecture
- Modification to machining / prodn lines

Minimum change to production lines:

- OEM preferred approach while volumes and legislation uncertain
- No intrusive (production line) changes

Diesel type (swirl or quiescent) combustion system retained



Gen 3:

- OE - Fully optimised for Hydrogen
- High Pressure DI (e.g. Diffusion combustion)
- Tumble-based charge motion
- High efficiency (~50% BTE)

Gasoline 'pent roof' style tumble-based combustion system:

- Designed for air/fuel mixing and turbulent energy (TKe) near spark plug at ignition

Very high pressure needs special compressor

Some change to production lines:

- Cylinder head machining

Irregular combustion much reduced

Diesel type (swirl or quiescent) combustion system retained

H₂ ICE Change Components

- Spark ignition
- H₂ spark plugs
- Updated ignition coils



Ignition

Turbo

- Resizing
- Lean operation
- VTG



- Crankcase dilution
- Controlled H₂ fraction
- Maximise oil separation

CCV

Valves

- Seat insert material
- Valve material
- Revised lift profile



Piston

- Lower compression
- H₂ ring pack
- Aluminium construction

Fuel System

- H₂ specific injectors
- PFI/DI/HP-DI
- Cylinder head mods



Project Cavendish



Project Cavendish

Developing zero CO₂ hydrogen combustion systems for heavy-duty commercial transport

- Heavy Duty H₂ ICE
- Accelerate the introduction and market acceptance of Hydrogen-fuelled ICE trucks and other commercial vehicles by increasing re-use of existing HD Diesel engine architectures
- Focus on fast to market transition by leveraging existing manufacturing and supply chains
- Overall Programme Value
 - 9.78M GBP cost
 - 4.85M GBP grant funding (from APC)



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PROPULSION
CENTRE UK



MAHLE

Powertrain

BORGWARNER



OXFORD
BROOKES
UNIVERSITY

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Project Cavendish - Scope

- Single cylinder research
- Advanced combustion systems
- HP-DI incl. diffusion combustion
- Jet ignition (MJI)
- CFD combustion optimisation (OBU)

Combustion
Research

- Minimum change
- PFI injection (PHINIA)
- VTG (BorgWarner)
- HPI (MAHLE)
- Piston & ring pack (MAHLE)
- ECU (PHINIA)
- -10% performance

PFI
Engine



- MAHLE Powertrain (Northampton)
- Heavy-duty capable (500 kW)
- H₂ fuel bunkering (>600 kg)
- H₂ safety systems
- H₂ specific measurement systems
- Full emissions characterisation

HD H₂
Testbed

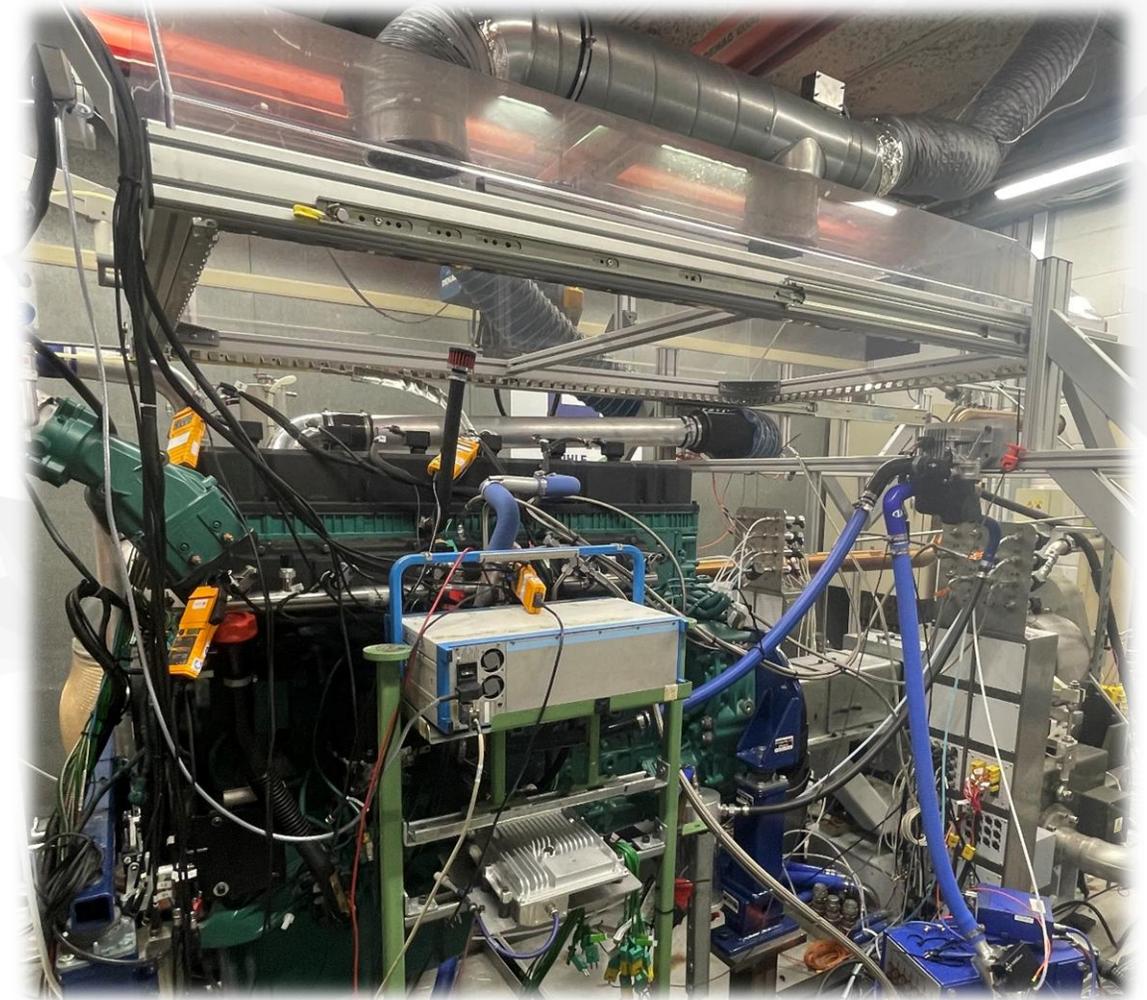
- HP-DI injection (PHINIA)
- Minor change to cylinder head machining
- Phase 2 VTG (BorgWarner)
- Full diesel performance

DI Engine

Project status

PFI Engine

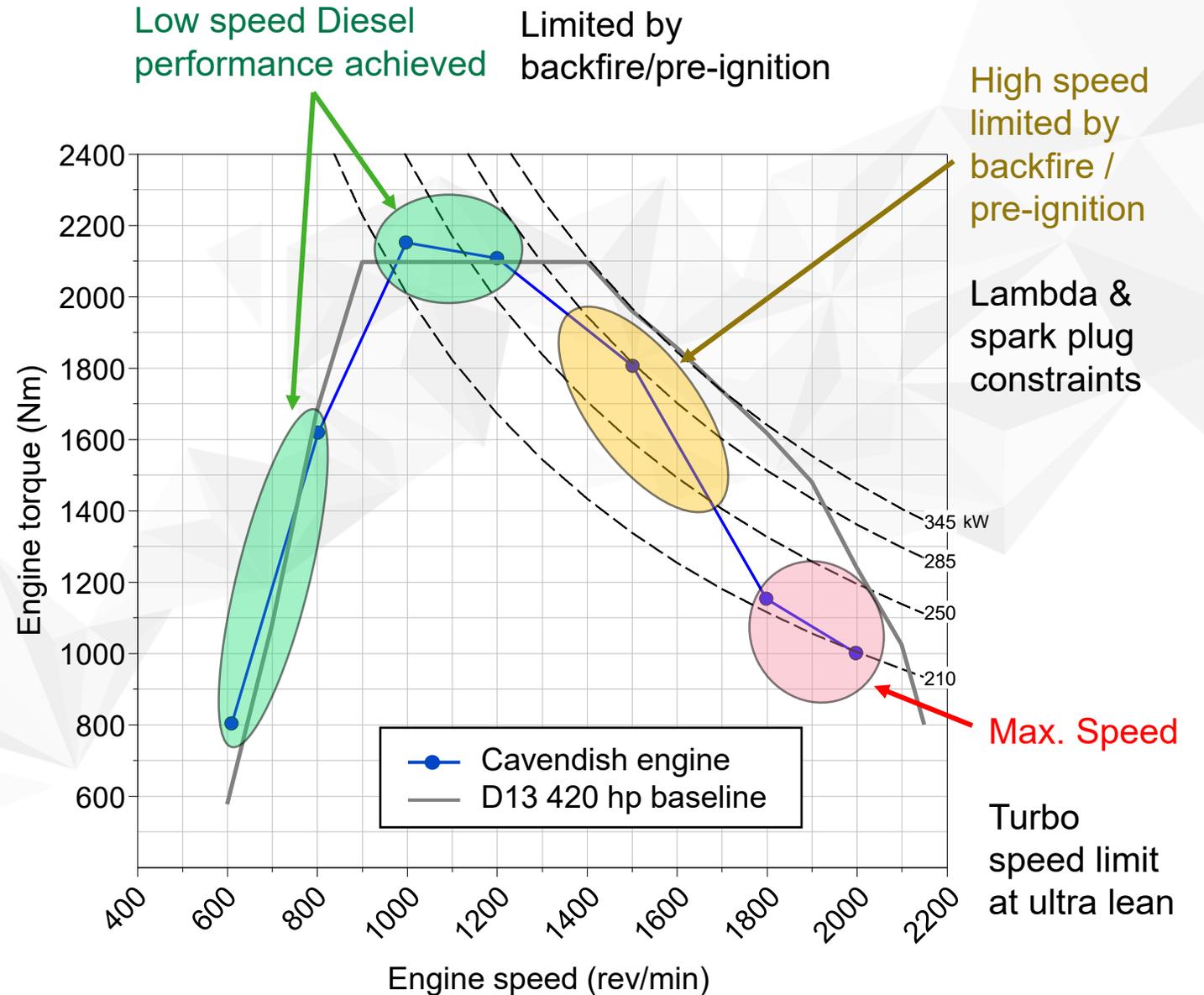
- Volvo D13 production Diesel engine conversion completed:
 - Engine conversion led by PHINIA
 - Integration of new engine components by MAHLE Powertrain
 - Fuel system and controls by PHINA
 - Turbocharger by BorgWarner
- Calibration and optimisation by MAHLE Powertrain



Project status

PFI Engine

- Volvo D13 production Diesel engine conversion completed
- **Full load** testing and optimisation completed
 - Torque
 - Target achieved
 - >2100 Nm (meets Diesel baseline)
 - Power
 - 285 kW (>90% rel. Diesel baseline)
 - Limited by irregular combustion



Project status

PFI Engine

Part load emissions

– testing and optimisation completed

NOx

– The major pollutant of interest with H₂ ICE is NOx

– Test data shows that raw (engine-out) emissions are typically below the EU7 on-highway limits

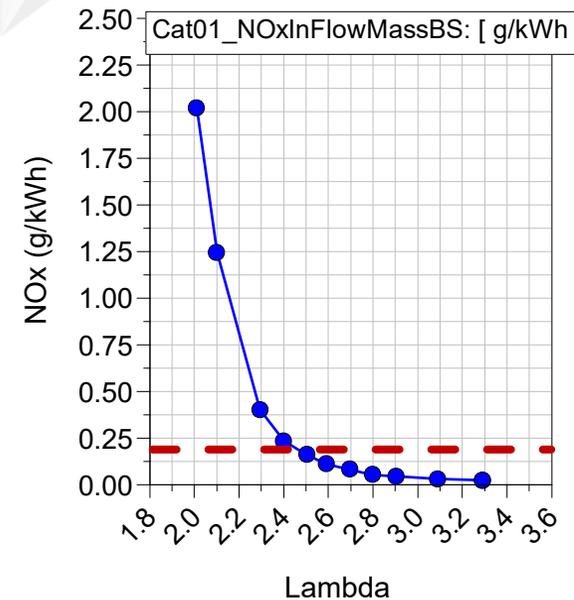
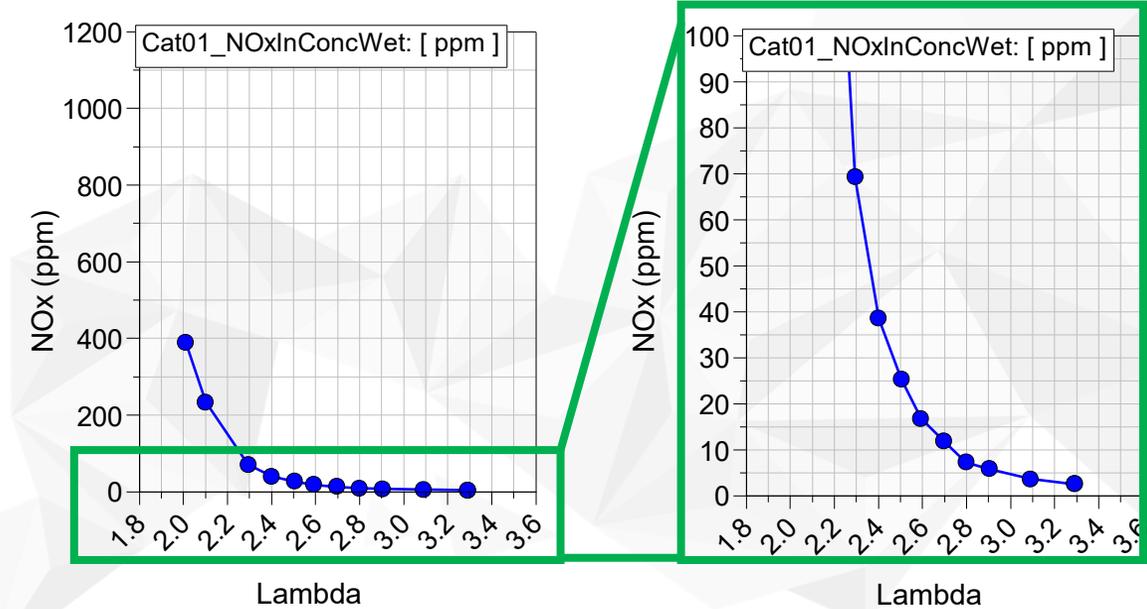
– Limits (0.2 g/kWh) are dynamic cycle-average

– Expect increases with dynamic operation

– Dependent on lambda

– Addition of a simple aftertreatment system (e.g. SCR) can reduce emissions by ~90%

– Expect tailpipe NOx emissions to be <10% of EU7 limits



Raw emissions levels are below treated cycle-average emissions limits

Euro7 cycle-average limit

Project status

PFI Engine

Part load emissions

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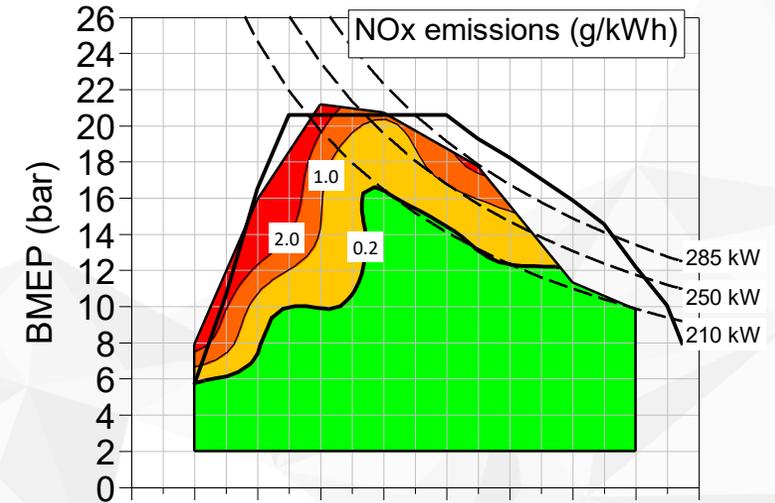
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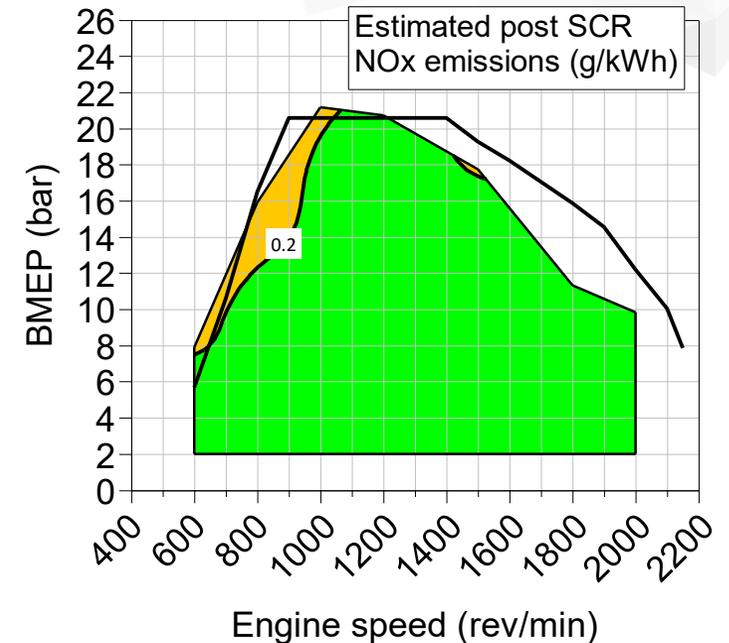
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Application of 90% effective SCR



Project status

PFI Engine

Part load emissions

– testing and optimisation completed

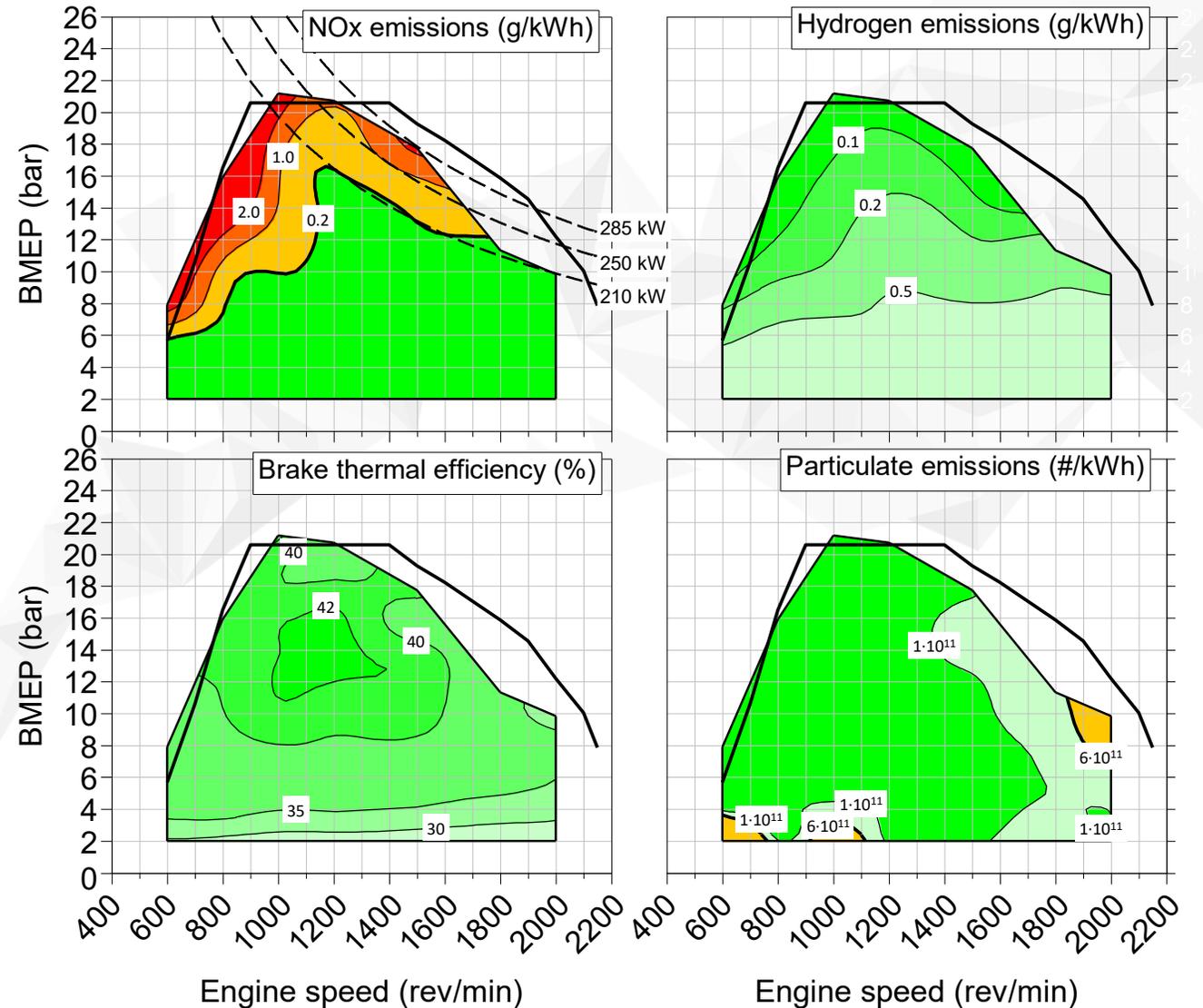
Carbon emissions effectively zero

- CO
- CO₂
- Hydrocarbons

Particulates have been shown to be negligible and also treatable with existing GPF/DPF technology

Efficiency >40% over a wide operating area, scope for further improvement

Raw emissions levels



Conclusions

Hydrogen ICE for Heavy Duty

- **Energy vector** – Hydrogen for reliable renewable energy grids to store energy – HD is one option for downstream use
- **H₂ ICE optimisation** – Essential to optimise engine for H₂, including H₂-specific parts, but still feasible as retrofit
- **Performance demonstration** – Conversion of HD engine shows performance potential – Some power loss with PFI
- **Clean emissions** – Testing shows ultra-low tailpipe emissions, below all known upcoming legislation levels
- **Hydrogen ICE: Clean, Efficient & Available**



Thanks for your attention



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