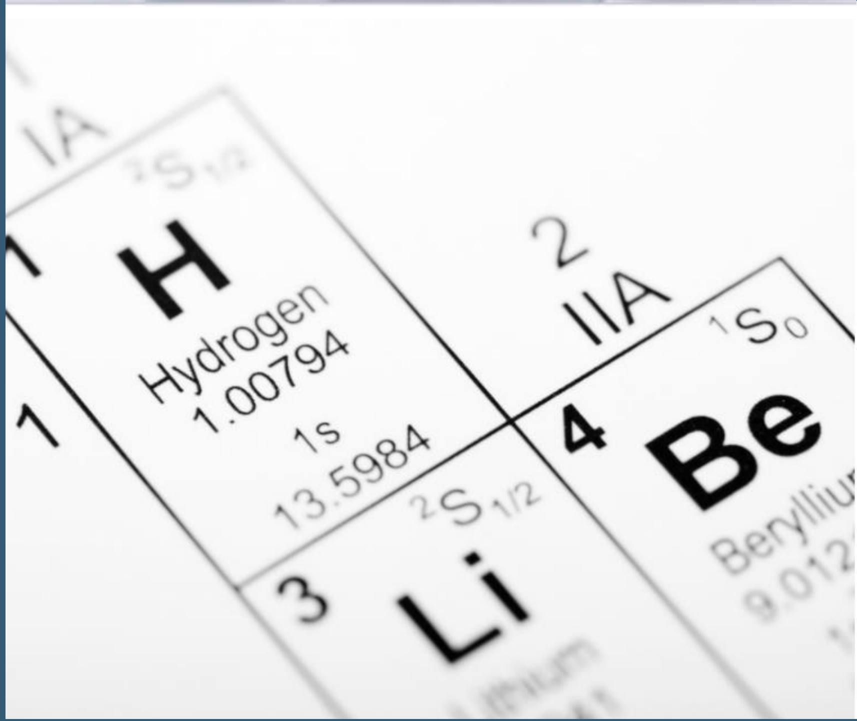
HYDROGEN COMBUSTION ENGINES (H_2ICE) IS IT NOW OR NEVER?

RICHARD PENN

JANUARY 2024



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TOPICS TO COVER

- Hydrogen ICE fundamentals
- Design and development
- Case study : JCB
- Summary
- Q&A

HYDROGEN ICE FUNDAMENTALS

HYDROGEN ICE FUNDAMENTALS

- Hydrogen ICE, the dawn of a new era or just old news??

The de Rivaz engine was a pioneering reciprocating engine designed and developed from 1804 by the Franco-Swiss inventor Isaac de Rivaz. The engine has a claim to be the world's first internal combustion engine and contained some features of modern engines including spark ignition and the **use of hydrogen gas as a fuel.**

Ford Begins Production of V-10 Hydrogen-Fueled Engines

17 July 2006

Ford has kicked off production of its dedicated hydrogen-fueled 6.8-liter V-10 engines, making it the first automaker in the world to do so. The engine is based on the same modular engine series that powers many Ford products, but is specially prepared to burn hydrogen as a fuel.

The Ford Hydrogen V-10.

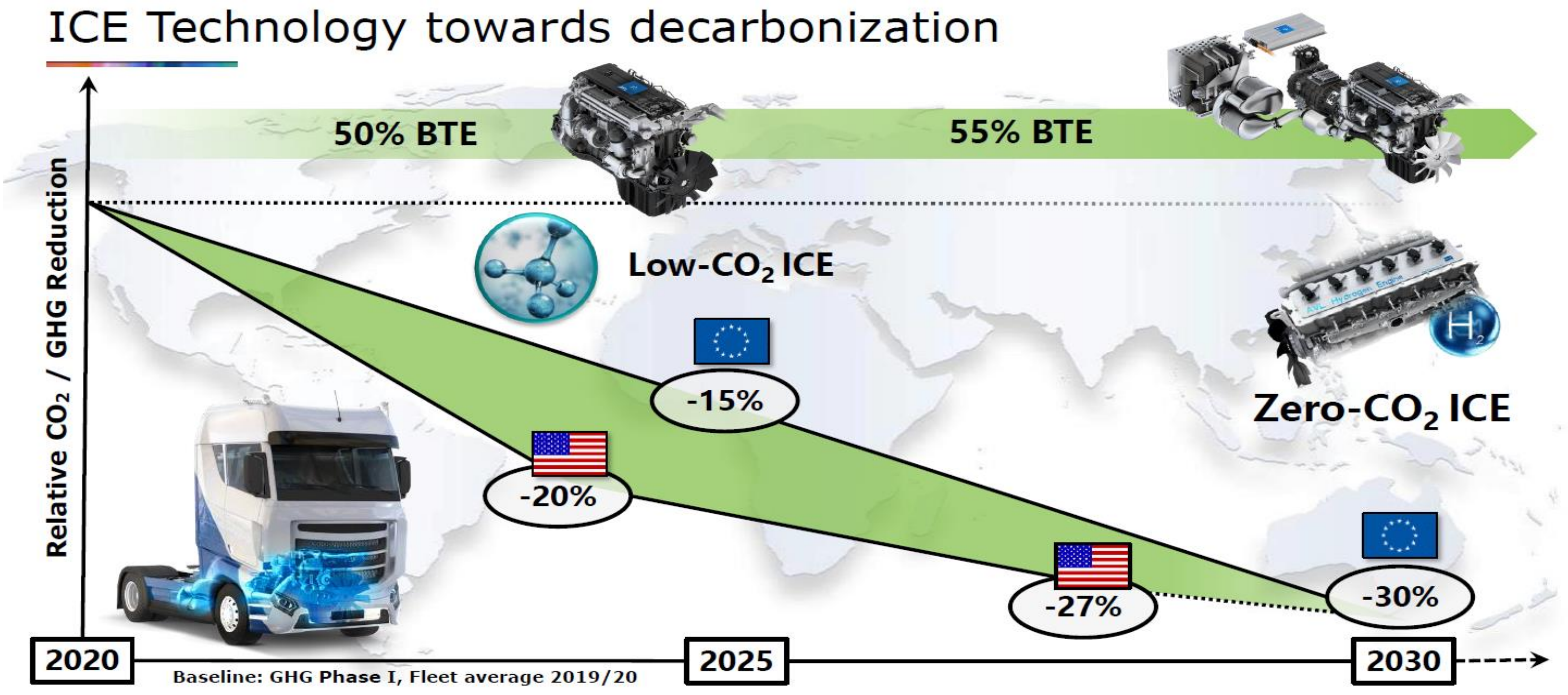
HYDROGEN ICE FUNDAMENTALS

Motivation for Alternative Powertrains

automotive engineering iav

Mission	Task	Intent	Solution
			
Preservation of the climate and environment for us and our descendants	Avoiding global warming gases	No combustion of fossil fuels	The optimal CO_2-free powertrain of each vehicle, with a clear view to all alternatives

HYDROGEN ICE FUNDAMENTALS



HYDROGEN ICE FUNDAMENTALS

Parameters	Battery Electric Vehicles	Fuel Cell Electric Vehicles	H2 Engine Vehicles
Production + infrastructure + operating costs	↓		
Suitability for daily use	→		↑
Driving Ranges	↓	↑	↑
Refueling time	↓	↑	↑
Fuel efficiency	↑	↑	→
Durability	→	↓	↑
Climate Protection	→	↑	↑

HYDROGEN ICE FUNDAMENTALS

Parameters
Production + infrastructure + operating costs
Suitability for daily use
Driving Ranges
Refueling time
Fuel efficiency
Durability
Climate Protection

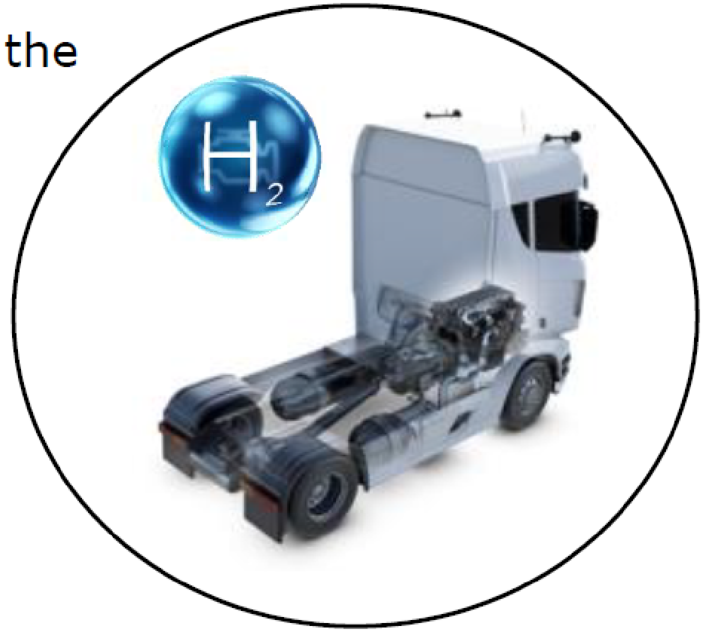
What are your thoughts on these parameters??

- Production source questionable, (public) infrastructure patchy, Hydrogen costs currently high
- Assuming infrastructure and Hydrogen costs are acceptable….
- Good with suitable size tanks and compressed to 350 / 700 bar
- Reasonable compared to petrol / diesel, typically…..
- Highly dependent upon combustion technology, can be comparable to diesel (or better…)
- Assuming base engine adaption then as good as diesel…..
- CO_2 yes, NO_x control with aftertreatment….

HYDROGEN ICE FUNDAMENTALS

Hydrogen ICE as solution for CO_2 neutral* trucks

- **Hydrogen fuel** is considered as **CO_2 neutral** & has the potential for **"zero-emission-vehicle******"**
- Hydrogen ICE for Heavy Duty vehicles come with **similar costs as diesel/natural gas** engines
- Capability to ensure **high system efficiencies** for Heavy Duty operation cycles (full load operation)
- Short **time to market**
- High **tolerance** to **low purity Hydrogen** and therefore gas **engine like reliability**
- Potential to **prolong the lifecycle of conventional powertrain** vehicles & **protect investments in existing infrastructure**

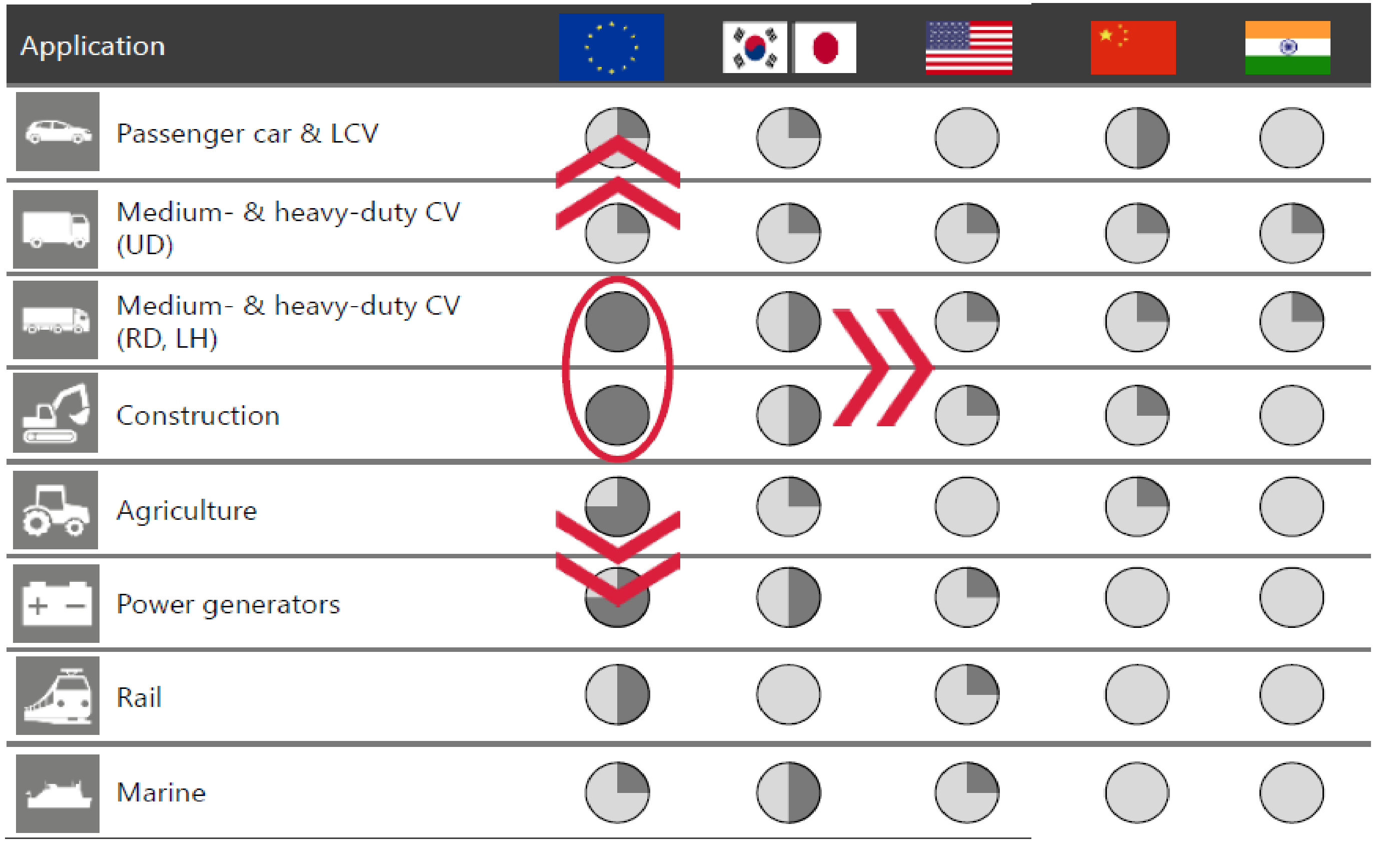


* Tank-to-Wheel
** Qualification as Z(CO_2)EV: CO_2 below 1g/kWh
CO_2 Sources: Lube Oil, AdBlue

HYDROGEN ICE FUNDAMENTALS

The interest in H2-ICE originated from HD segment in Europe has spread out to various applications and regions around the world.

FEV



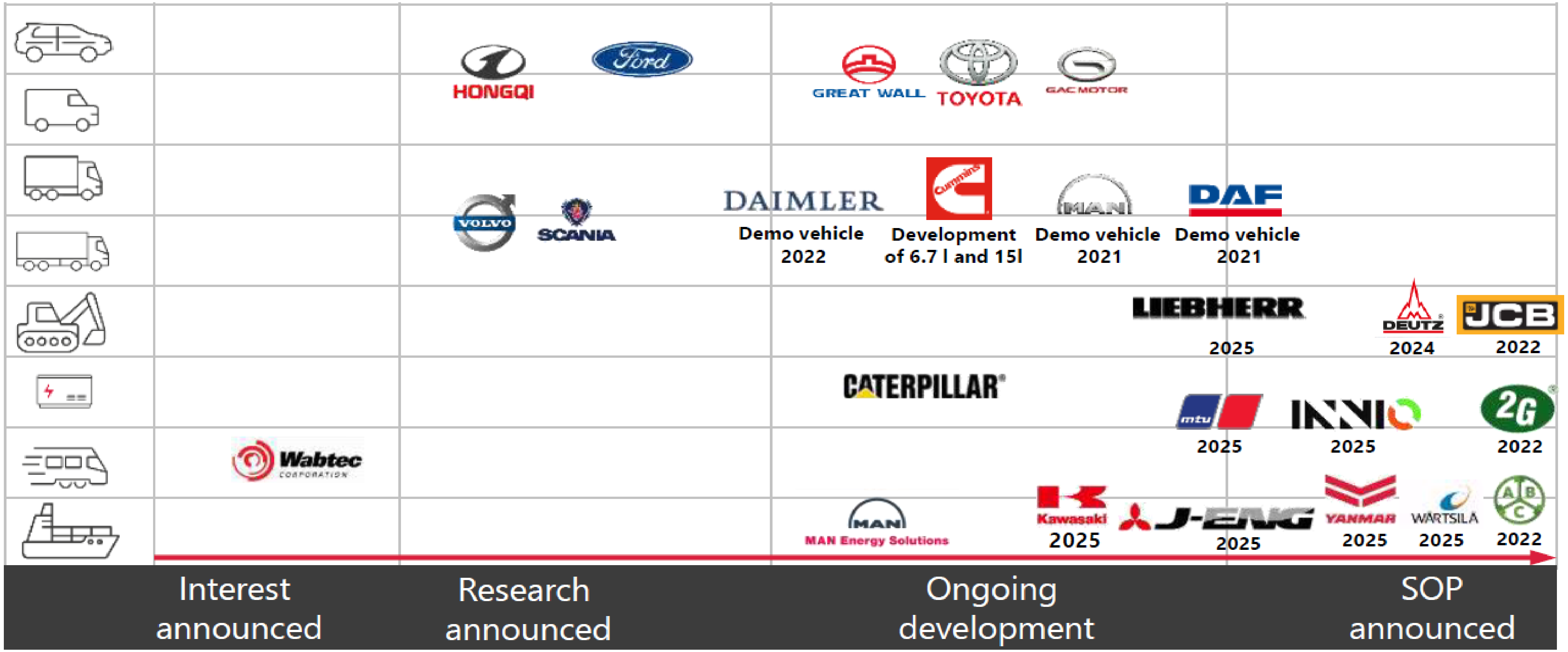
MAIN DRIVERS

- MD/HD market in Europe forcing the development of hardware (esp. Direct Injection system)
- Hardware can be used in other classes as well and makes business case attractive
- Certain applications see major drawbacks for fuel cell
  - OFFROAD
  - AGRICULTURE
- For larger bore size, dedicated injectors might be developed at a later timing but PFI solutions available soon

HYDROGEN ICE FUNDAMENTALS

Publicly announced interest and investment in H_2-Engine development is now growing strongly amongst on-and off-highway industry players

FEV



HYDROGEN ICE FUNDAMENTALS

Property	Hydrogen	Methane	Gasoline	Diesel
Minimum ignition energy in air (at 1 bar & at stoichiometry; mJ)	0.02	0.29	0.24	0.24
Stoichiometry air/fuel mass ratio	34.4	17.2	14.7	14.5
Quenching distance (at 1 bar & 298 K at stoichiometry; mm)	0.64	2.1	~2	-
Laminar flame speed in air (at 1 bar & 298 K at stoichiometry; m/s)	1.85	0.38	0.37–0.43	0.37–0.43
Diffusion coefficient in air (at 1 bar & 273 K; m^2/s)	8.5×10^{-6}	1.9×10^{-6}	-	-
Flammability limits in air (vol%)	4–76	5.3–15	1–7.6	0.6–5.5
Adiabatic flame temperature (at 1 bar & 298 K at stoichiometry; K)	2480	2214	2580	~2300
Octane number (R+M)/2	130+	120+	86–94	-
Cetane number	-	-	13–17	40–55

HYDROGEN ICE FUNDAMENTALS

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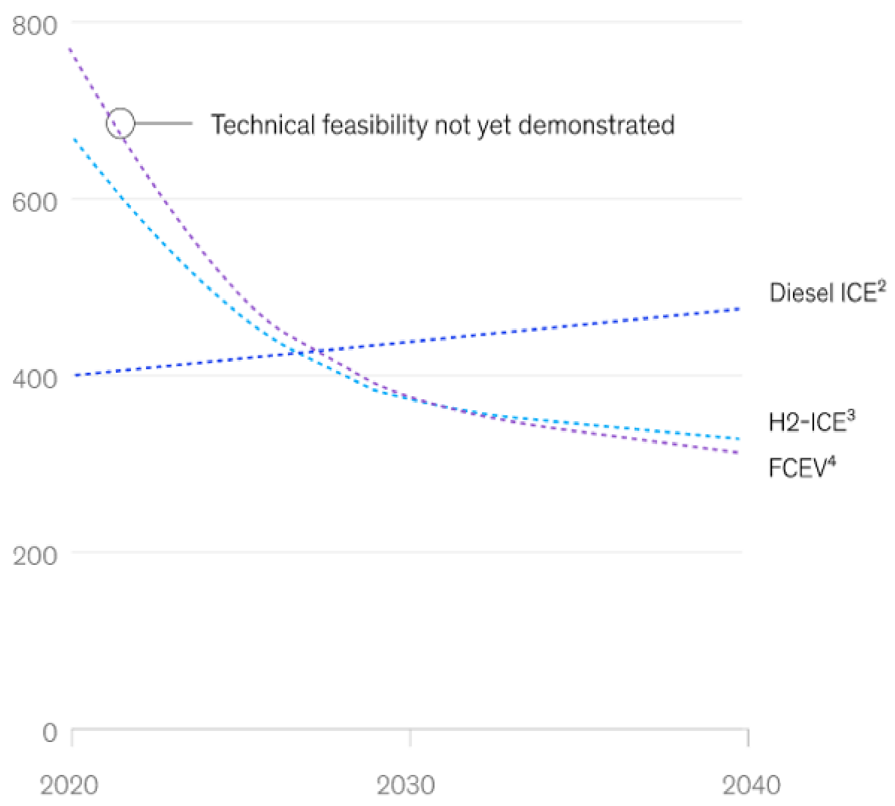
Octane number (R+M)/2	130+	
Cetane number	-	

- Typically lean mixtures utilised, full load performance approaching stoichiometry
- Short quenching distance allows combustion close to cylinder walls
- Ultra fast combustion with rapid mixing
- Low ignition energy – pre-ignition concerns

- Extremely broad range of flammability – pre-ignition concerns
- Flame temp @stoichiometry extremely high = NO_x production

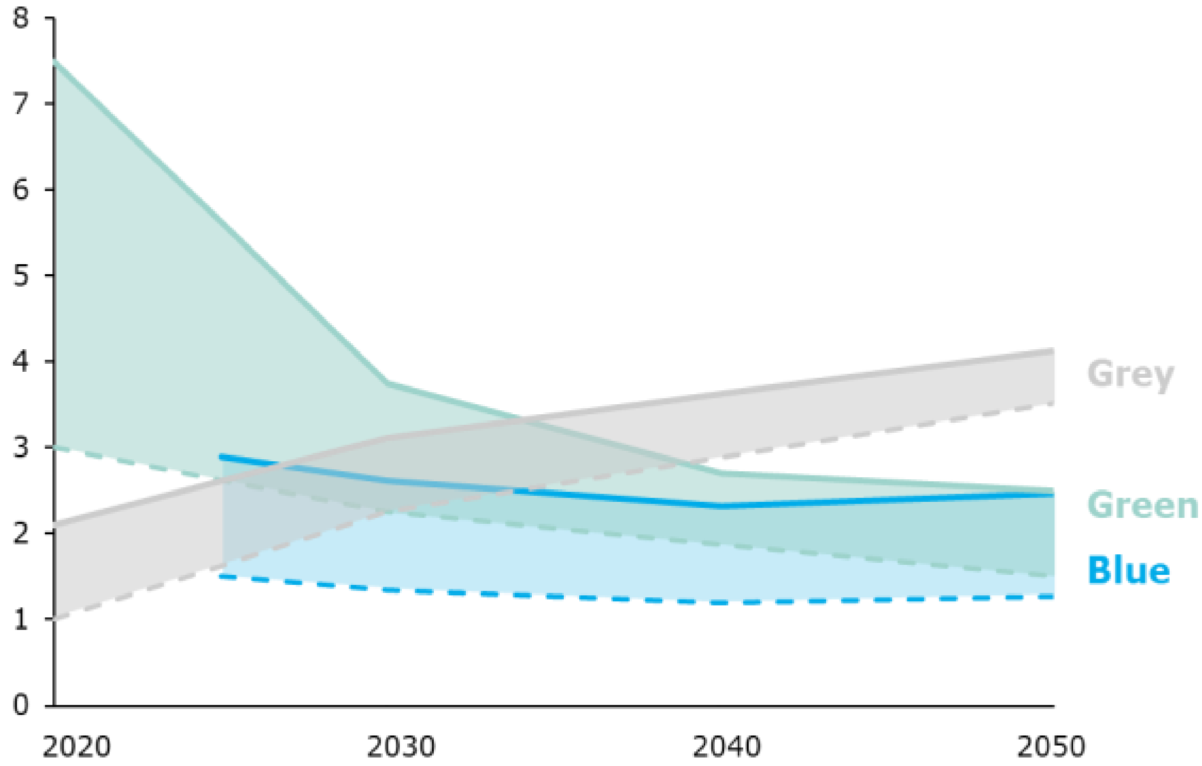
HYDROGEN ICE FUNDAMENTALS

For dump trucks, the cost of ownership for hydrogen and diesel internal combustion engines is expected to break even around 2030.



[1]Estimate is for 600-ton open-pit dump truck, such as those used in mines. Assumed CO_2 price increase from $28/ton in 2020 to $50/ton by 20 $200+/metric ton by 2050. [2]Diesel internal combustion engine. [3]Hydrogen internal combustion engine. [4]Fuel-cell electric vehicle.
Source: Expert interviews; McKinsey analysis

Estimated hydrogen cost
($ per kg H2)



DESIGN AND DEVELOPMENT

DESIGN AND DEVELOPMENT

A quick reminder on some terminology…..

- Combustion – an exothermic (heat is released) REDOX reaction between a fuel and an oxidant
- REDOX = Reduction and Oxidation occurring simultaneously
- As air is not pure Oxygen, the Hydrogen combustion equation is simplified to:

$$H_2 + N_2 + O_2 = H_2O + NO$$

NO will further react in air to create NO_2

Note: in the presence of lubricating oil and air impurities other reactions can occur at trace levels (CO, HC, PM, CO_2)

ECE/TRANS/WP.29/GRPE/2021/13 (unece.org)

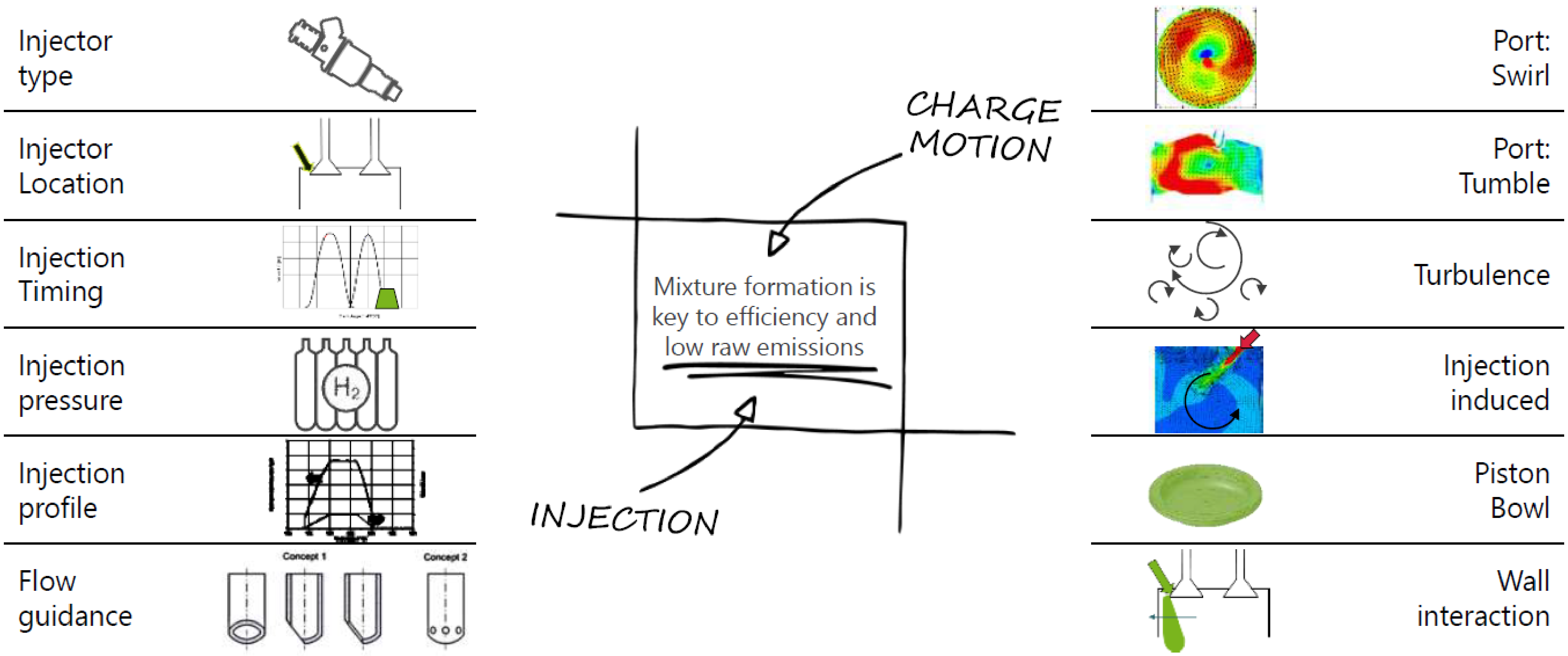
CO, THC, NMHC and CH_4 do not need to be demonstrated for engines where all of the fuels used have a molar carbon to hydrogen ratio of 0 as defined in paragraph 8. of Annex 4."

Chemical Composition of Air		
Name	**Symbol**	**% by volume**
Nitrogen	N2	78.084 %
Oxygen	O2	20.9476 %
Argon	Ar	0.934 %
Carbon Dioxide	CO2	0.0314 %
Neon	Ne	0.001818 %
Methane	CH4	0.0002 %
Helium	He	0.000524 %
Krypton	Kr	0.000114 %
Hydrogen	H2	0.00005 %
Xenon	Xe	0.0000087 %

DESIGN AND DEVELOPMENT

Mixture formation is key to efficiency and low raw emissions

FEV



DESIGN AND DEVELOPMENT

Different injection pressure levels enable different combustion process layouts with specific benefits and challenges

FEV

H_2 INJECTION SYSTEMS FOR HD ENGINES, SINGLE STAGE TURBO CHARGING (**13L CLASS**)

	External mixture preparation	Space requirement cylinder head		
	Low pressure PFI	**Low pressure DI**	**Mid pressure DI**	**High pressure DI**
Fuel Injection	Port fuel injection ~ 5-10 bar	Direct injection ~ 15-30 bar	Direct injection ~ 40-60 bar	Direct injection ~ 300 bar
Specific Power (HD) engine	< 25 kW/l	> 25 kW/l	> 25 kW/l	~ 30 kW/l
Peak BMEP (HD) engine	< 20 bar	> 20 bar	> 20 bar	> 25 bar
Combustion	Lean Spark ignited	Lean Spark ignited	Lean Spark ignited	Lean Spark ignited -- Diffusive
Knock tendency	↓	0	0	↑ (SI) -- Not existing (Dif.[1])
Boost pressure demand	↑↑	0	0	0
Transient load response	↓↓	0	0	↑
Main benefit	▪ Easy to integrate, ▪ Hardware available ▪ Low failure risk	▪ Robust against back-fire ▪ Power density ▪ Transient response	▪ Same as LP DI ▪ Smaller packaging compared to low pressure ▪ Potentially better mixture preparation	▪ Same as MP DI ▪ Diffusive combustion possible
Main challenges	▪ Boosting ▪ Safety (Backfire)	▪ Integration DI Injector ▪ Uniform mixture preparation	▪ Integration DI Injector ▪ Range	▪ Integration DI Injector ▪ High pressure generation ▪ For Diffusive combustion high NOx raw emissions

CNG engines with similar characteristics (injection pressure etc)

1) Diffusive combustion
Source: FEV

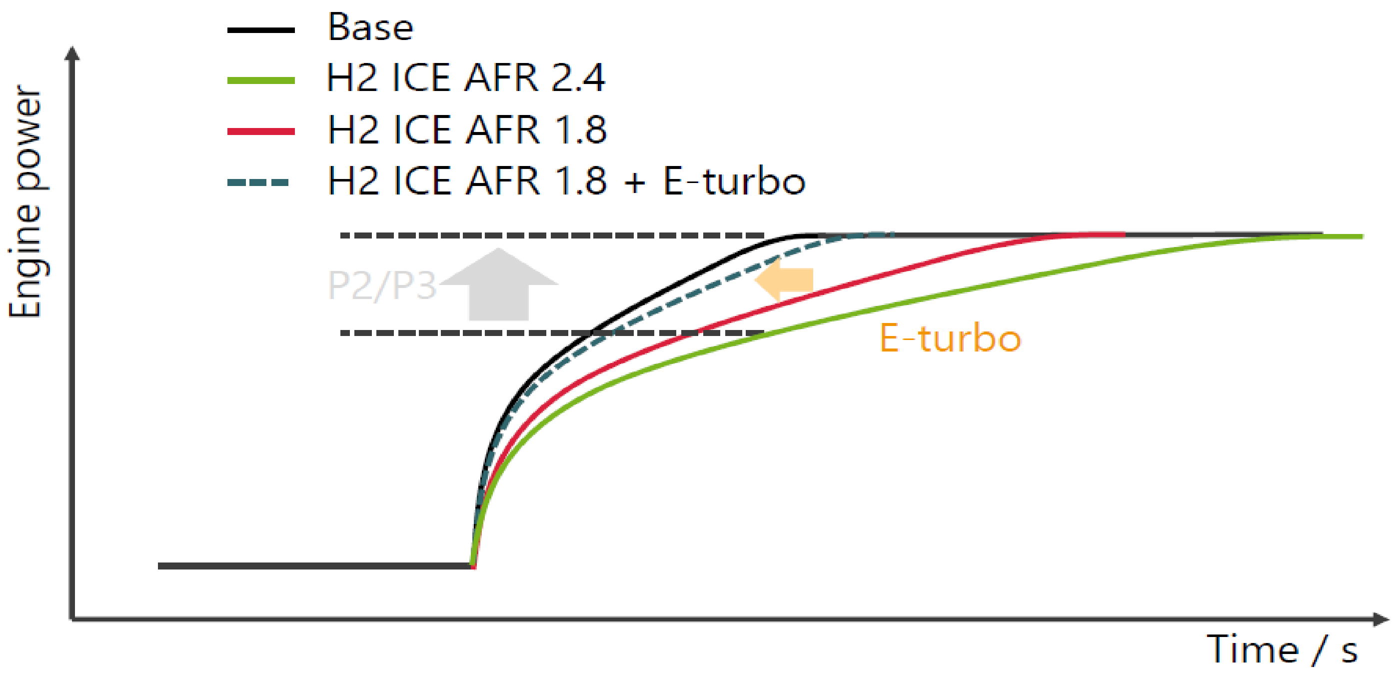
DESIGN AND DEVELOPMENT

- Taking advantage of the wide range of flammability it's possible to run extremely lean at part load conditions:
  - Excellent thermal efficiency
  - Ultra low NO_x
  - Poor transient performance without significant enrichment and then NO_x.....
- EGR used to help control NO_x formation at richer AFR's
- Sophisticated boosting, supercharging or eBoosters to improve transient performance whilst maintaining a sensible lean AFR – exhaust gas temp management can be interesting.....
- Technology content and cost starts to escalate when packaging HP DI, plus EGR, plus eBooster but equivalent or better than diesel performance is possible....

DESIGN AND DEVELOPMENT

Integration position of electrical support defines the required installed power level, less needed enrichment creates lowest NOx raw emissions

FEV



- Lag in power could be provided by the electric motor in P2 or P3 hybrid topology but would require electrical power of around 80 kW
  - If AFR > 2.4 can be maintained, extremely low NOx emissions also during transient operation can be expected
- E-Turbo solution requires less electrical power (~10kW) since it´s accelerates the boost pressure build up and air flow through the engines which emphasizes turbine power, self-reinforcing effect
  - Enables a cost-effective measure to create diesel-like drivability

DESIGN AND DEVELOPMENT

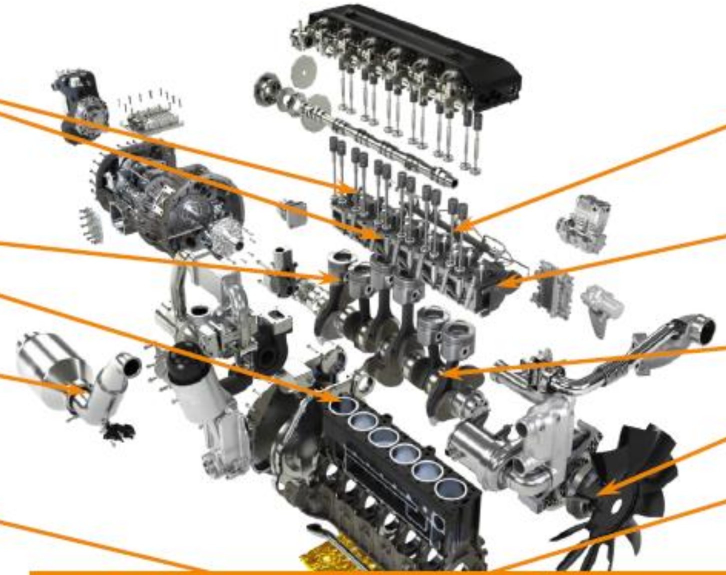
Impacts of H_2 on Mechanical Development & Validation

Injectors/Spark Plugs

Tailored Piston Bore Interface

Exhaust System & EAS

Lubrication Oil

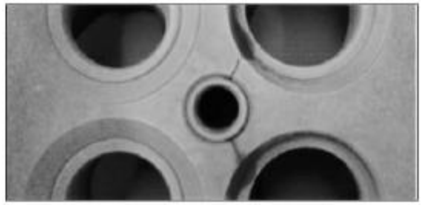


Valves & Valve Seats

Cylinder Head

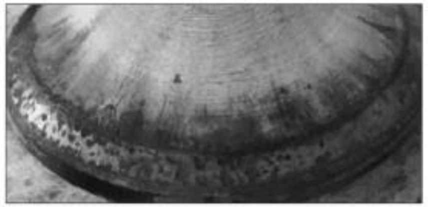
Crank Train

Crankcase Ventilation System & Oil Separation



Main H_2-failure parameters

- Combustion irregularities
- Management of water content
- Oil input into combustion
- Hydrogen slip into crankcase
- Hydrogen embrittlement



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DESIGN AND DEVELOPMENT

Cylinder block, crank, and con rod largely carry over

Main H_2-failure parameters

- Combustion irregularities
- Management of water content
- Oil input into combustion
- Hydrogen slip into crankcase
- Hydrogen embrittlement

Consideration of oil specification, ability to adsorb water / viscosity stability

Dedicated cylinder head design, spark plug integration

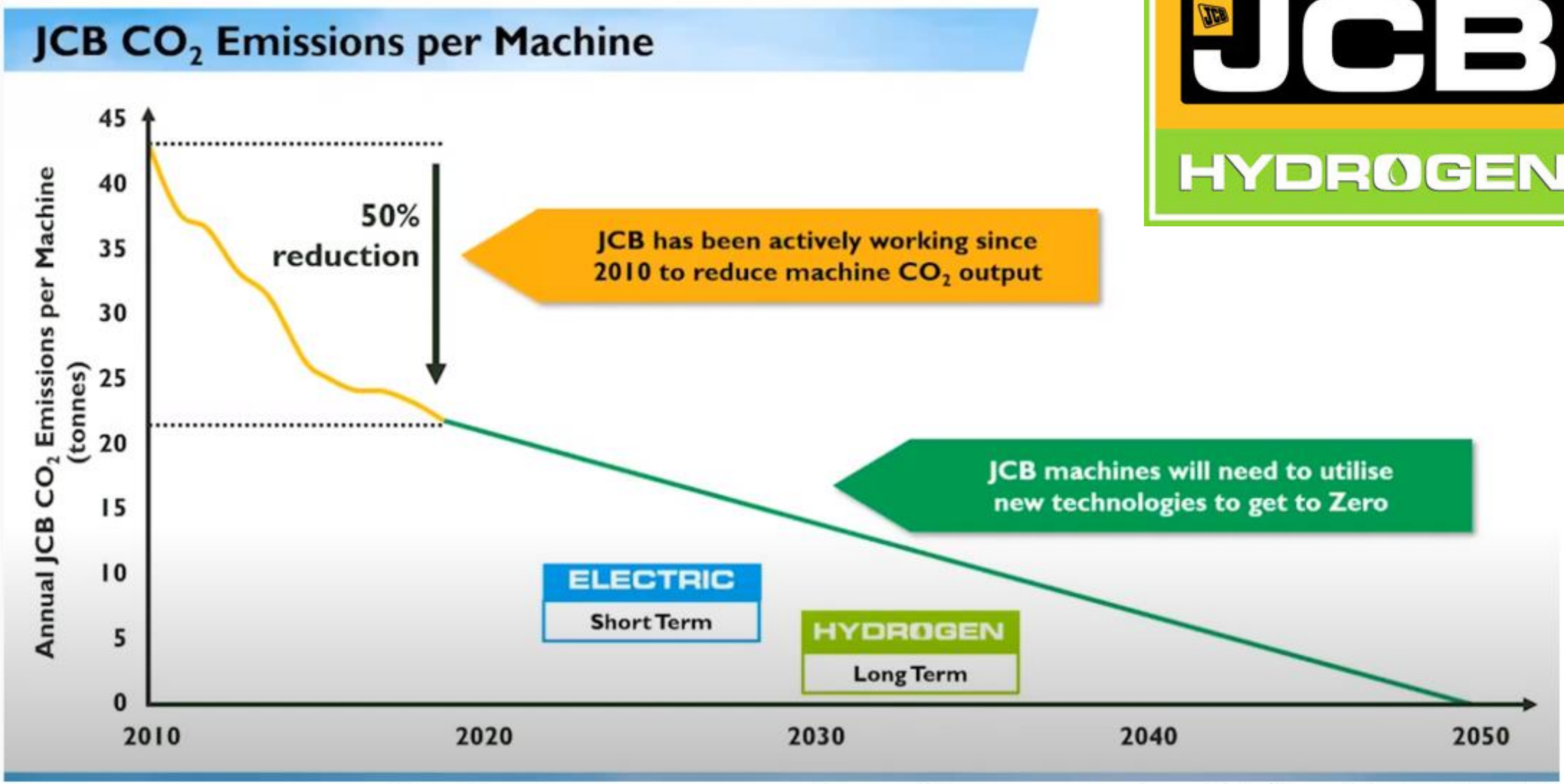
Dedicated injection system and pressure regulation

Material specification / selection of valves, piston, injector, spark plug etc

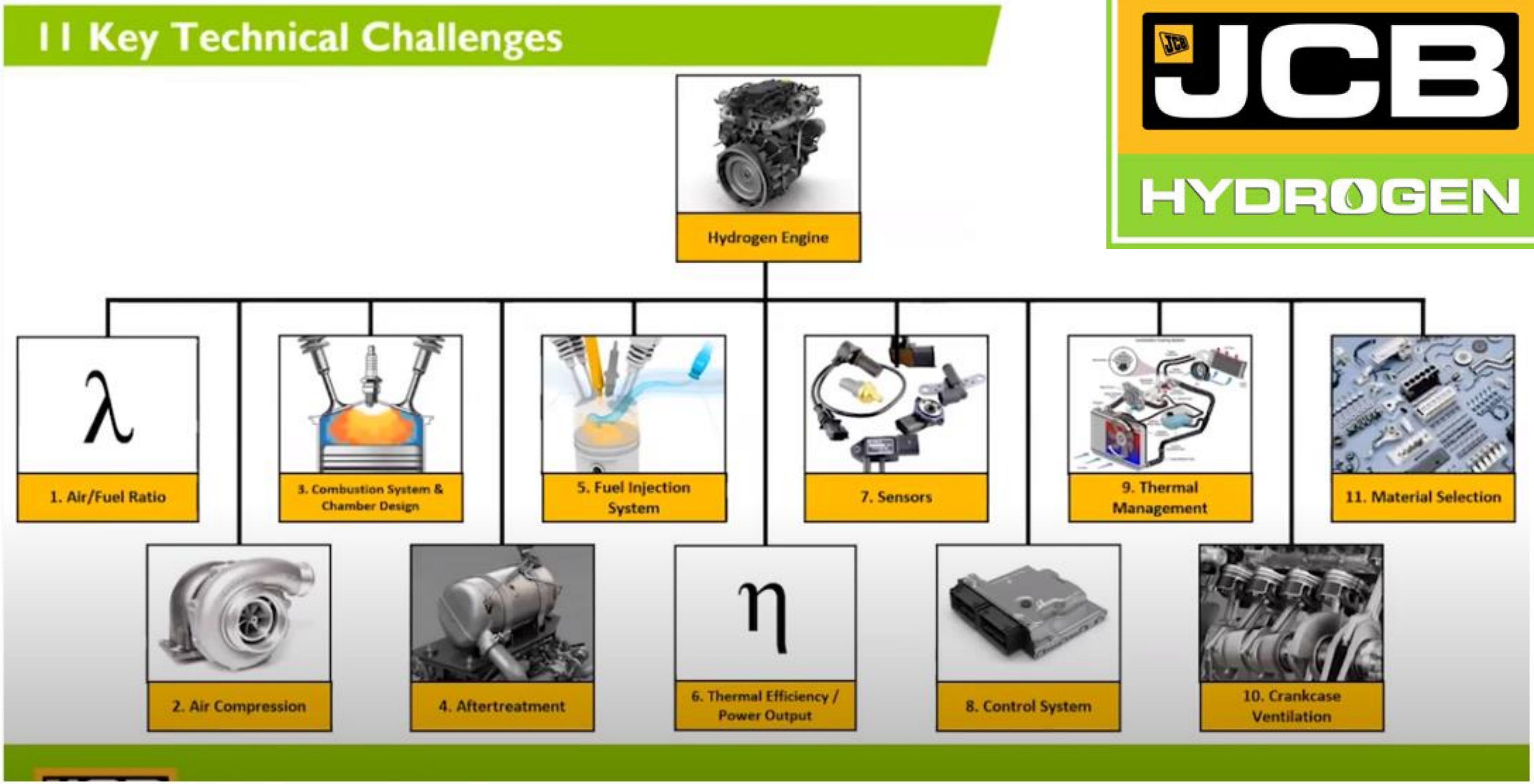
Careful specification of piston ring pack and crank case ventilation

CASE STUDY : JCB

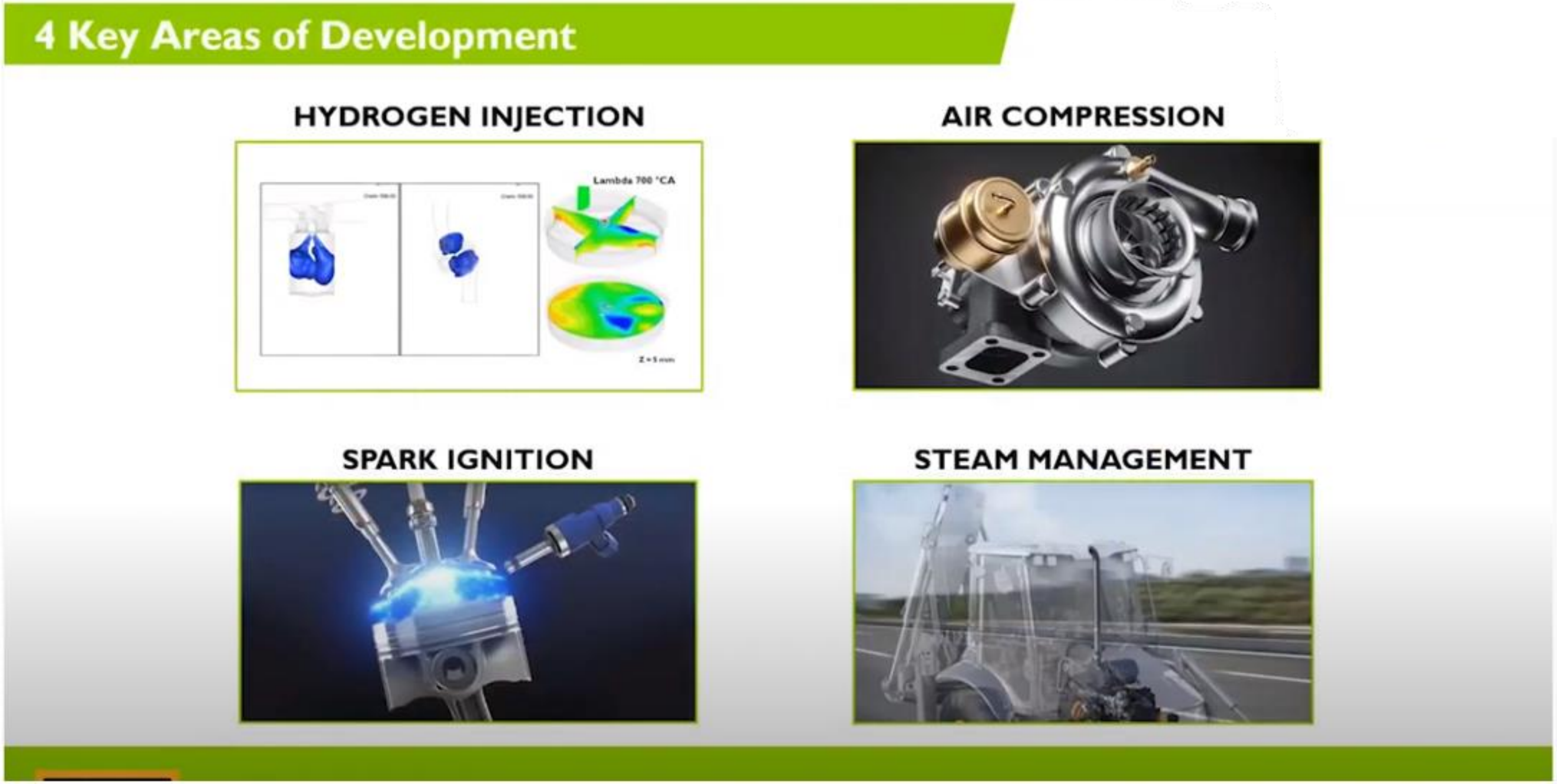
CASE STUDY – JCB



CASE STUDY – JCB

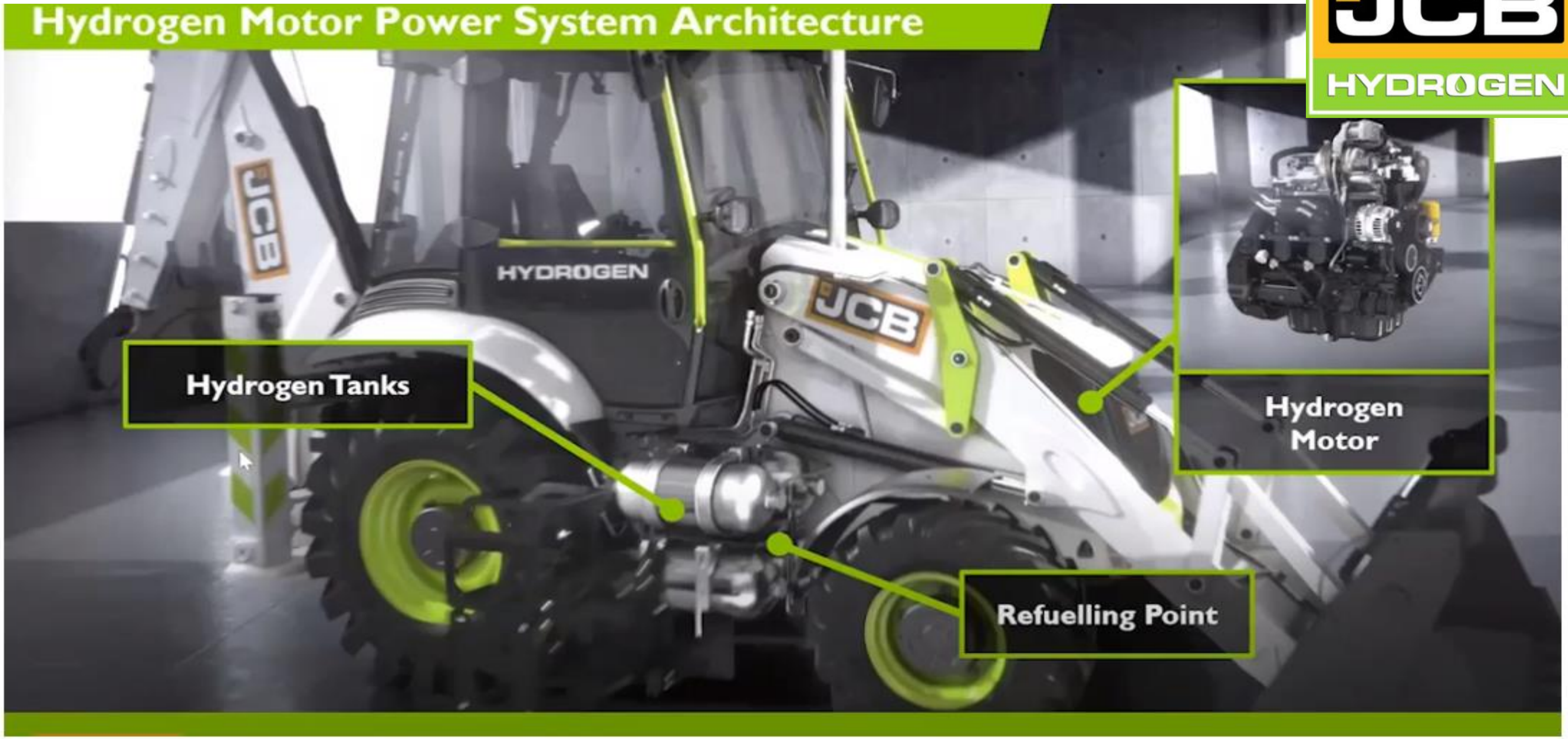


CASE STUDY – JCB

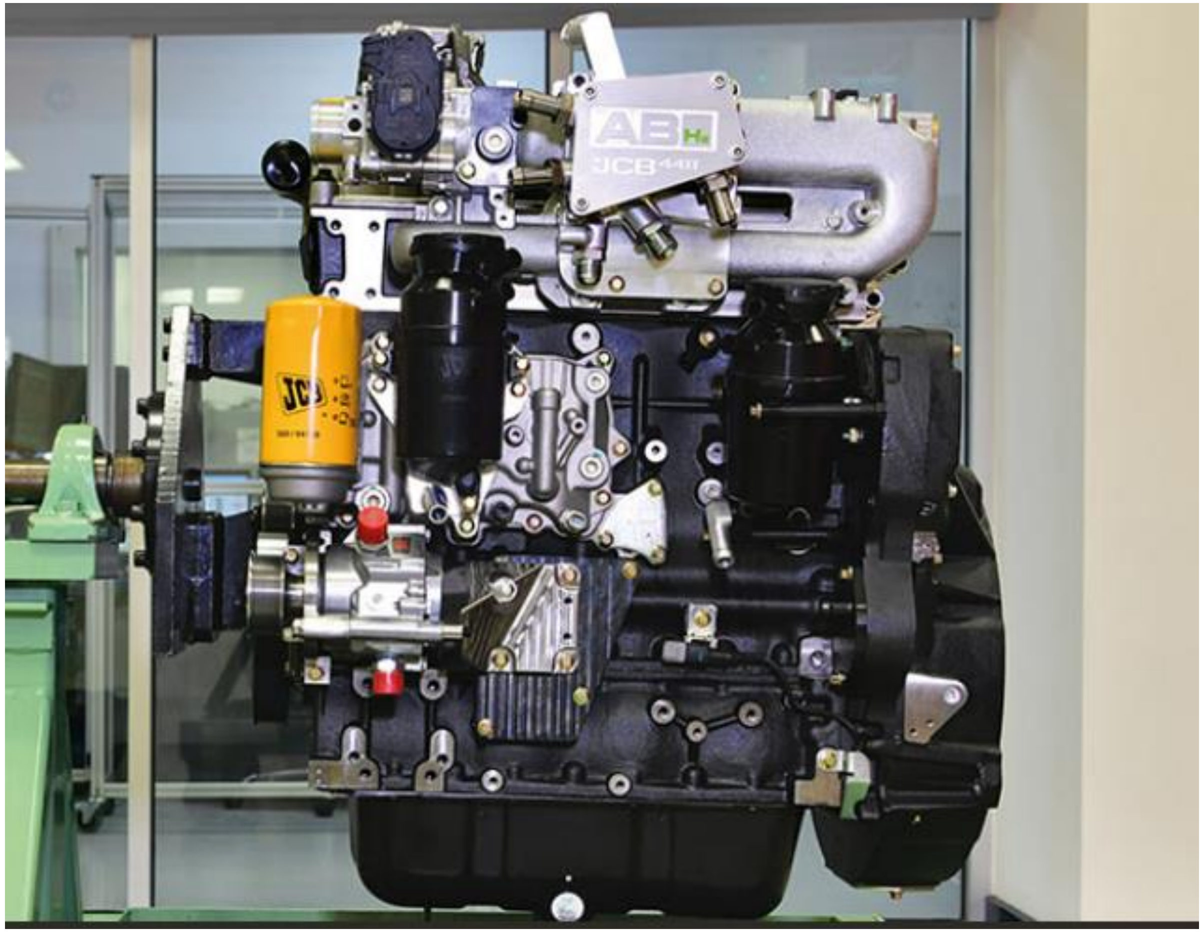


CASE STUDY – JCB

JCB
HYDROGEN



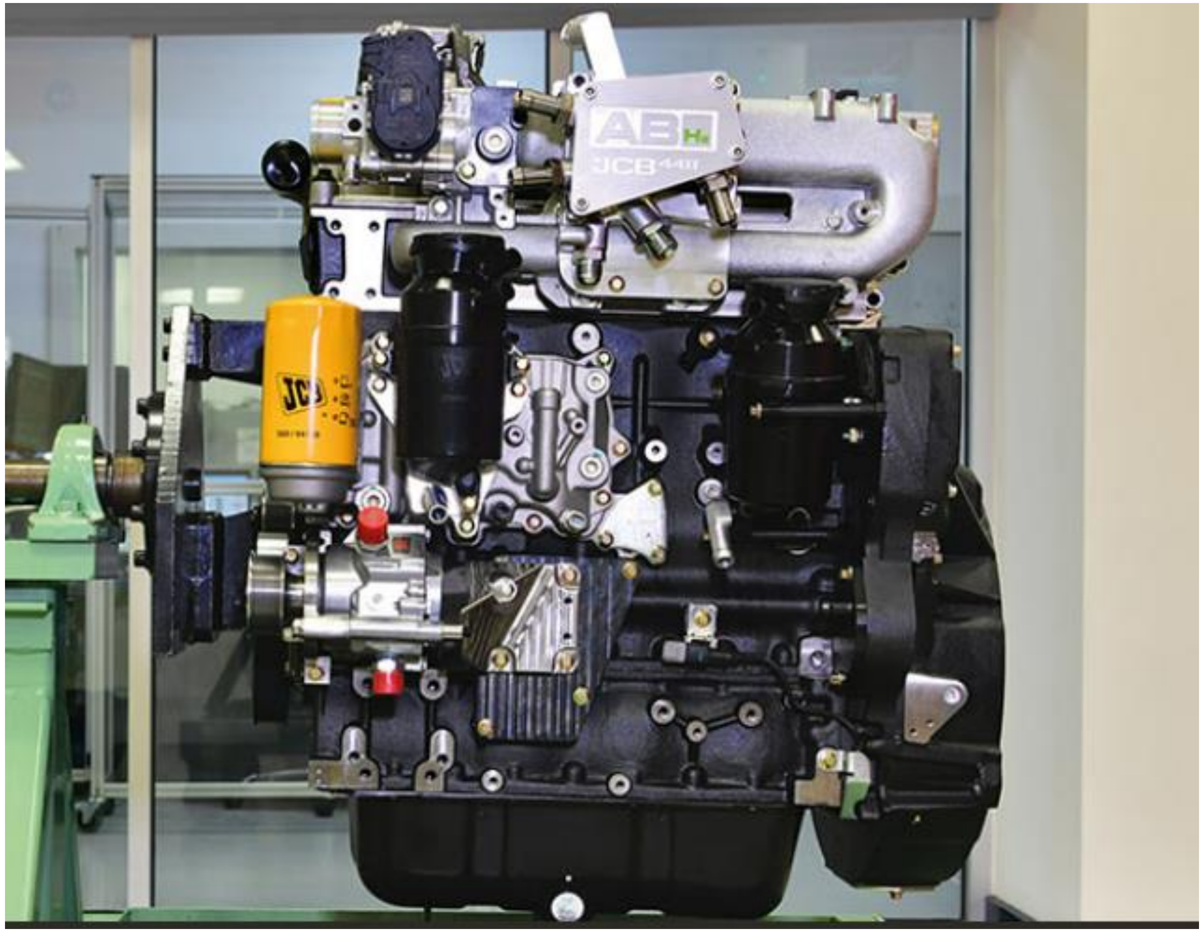
CASE STUDY – JCB



- Based off the existing 448 DieselMax engine (4.8 litre, 4 cylinder, turbocharged)

- 350 bar tank storage
- Production ready date ???
- Customer trials 2022 – 2025…

CASE STUDY – JCB



From: Department for Transport and The Rt Hon Jesse Norman MP

Published 9 February 2023

- government approves the use of the world's first digger powered by a hydrogen combustion engine on UK roads
- JCB's hydrogen-powered backhoe loaders will soon be working on UK construction sites
- hydrogen-powered technology could help decarbonise the UK construction industry, creating hundreds of jobs

SUMMARY
Q&A

SUMMARY

ET Online • Last Updated: Feb 10, 2023, 01:33 PM IST

Synopsis
According to Reliance, it is a "unique and affordable", indigenously developed technology solution that could redefine the future of green mobility.

Reliance unveils India's first Hydrogen Internal Combustion Engine tech for heavy-duty trucks

Reliance Industries on Monday unveiled India's first Hydrogen Internal Combustion Engine technology solution for heavy duty trucks, a company release said.

According to Reliance, it is a "unique and affordable", indigenously developed technology solution that could redefine the future of green mobility.

RIL and its vehicle partner Ashok Leyland, along with a few other partners, together developed the technology under its Net carbon Zero vison. The first engines run with this tech was tested in early 2022.

The race to make diesel engines run on hydrogen

20 January

Climate change

Converting mining industry vehicles to hydrogen could mean big savings in CO2 emissions

SUMMARY

PARAMETER	HYDROGEN FUELLED ENGINE (H_2ICE)	FUEL CELL (PEM TYPE)	WINNER
Efficiency	~44%+ expectation for DI H_2 fuelled ICE	~60% peak electrical efficiency (at ~25% load) ~44% at full load	**In theory – fuel cell in use – similar**
Emissions in use	Engine– out NOx [low] Trace oil derived emissions	No tailpipe emissions	**Fuel cell**
Technology maturity	ICE well understood, modification to burning H_2 in development	Existing FC system providers further optimisation to suit niche application needed.	**Similar**
Noise/vibration	Substantial NVH effort	Quiet	**Fuel cell**
Fuel purity requirement	Tolerant to fuel contaminants/ lower grade H_2 standard not yet defined	ISO H_2 purity standard (ISO 14687 Grade D)	**H_2ICE**
Air quality requirement	Robust to small particles	Sensitive to air contamination	**H_2ICE**
Durability	Diesel ICEs durable for >10,000 hours H_2 ICEs expected to be similar	Durability & reliability improved to >10.000 hours	**Similar**
Auxiliary heat output	High grade heat similar to current ICE	Thermal management of low-grade heat for PEMFC required.	**H_2ICE**


Q&A