03 MARCH 2022

PROF BERNHARD BIERMANN
PROF JOERN BEHRENROTH
DR.-ING. LUKAS VIRNICH

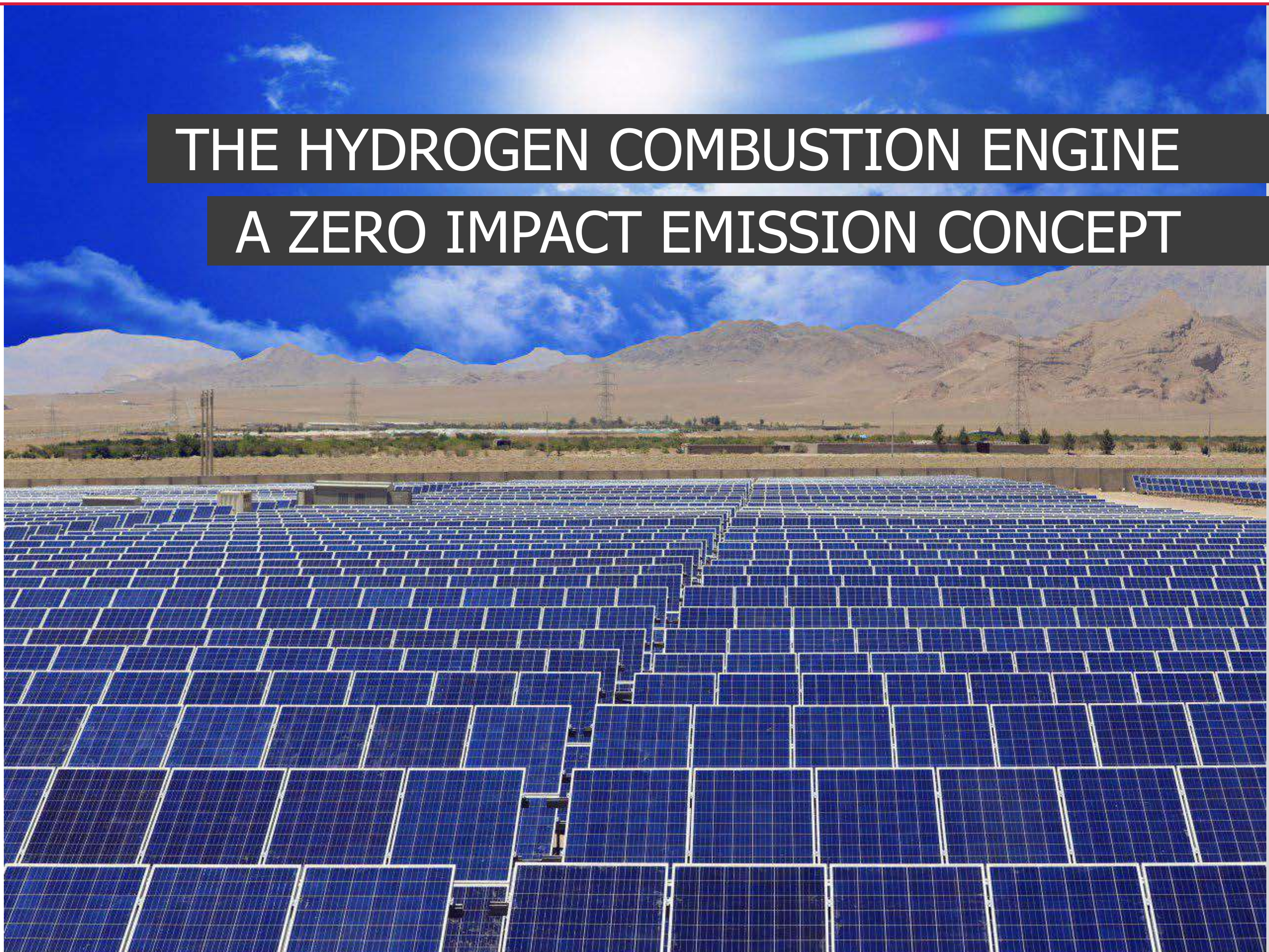
PREPARED FOR

HYDROGEN COMBUSTION SESSION

FPC2022
Future Propulsion Conference

FEV PRESENTATION @ FPC 2022

THE HYDROGEN COMBUSTION ENGINE
A ZERO IMPACT EMISSION CONCEPT



HYDROGEN COMBUSTION ENGINES

DEMAND – SUPPLY – PROJECTS – PRODUCTS

Non exhaustive excerpt of current hydrogen activities in Europe
Hydrogen is getting more and more into the focus on the way to Zero

APPROACH

1 UNITED KINGDOM

- Ten Point Plan for a Green Industrial Revolution for a world-leading hydrogen economy.
- Example: by 2030, aiming to produce 40 GW of offshore wind.

2 GERMANY

- German government has selected 62 public funded hydrogen large scale projects.
- Slogan: “Germany becomes hydrogen country”.

3 FRANCE

- French government has introduced a national hydrogen strategy in September 2020.
- Investment of 7,2 bn € planned for a production capacity of 6.5 GW.

When compared with other zero emission powertrains, H_2-ICE offers many advantages you can make use of in short term

ADVANTAGES

- High energy storage density
- Lower development and production effort, hence reduced time to market
- Fast refueling, a pre-requisite for high uptimes
- Proven powertrain durability and low sensitivity to environmental impacts
- Less stringent requirement to hydrogen purity compared to fuel cells
- Beneficial efficiency in high load operations

DRAWBACKS

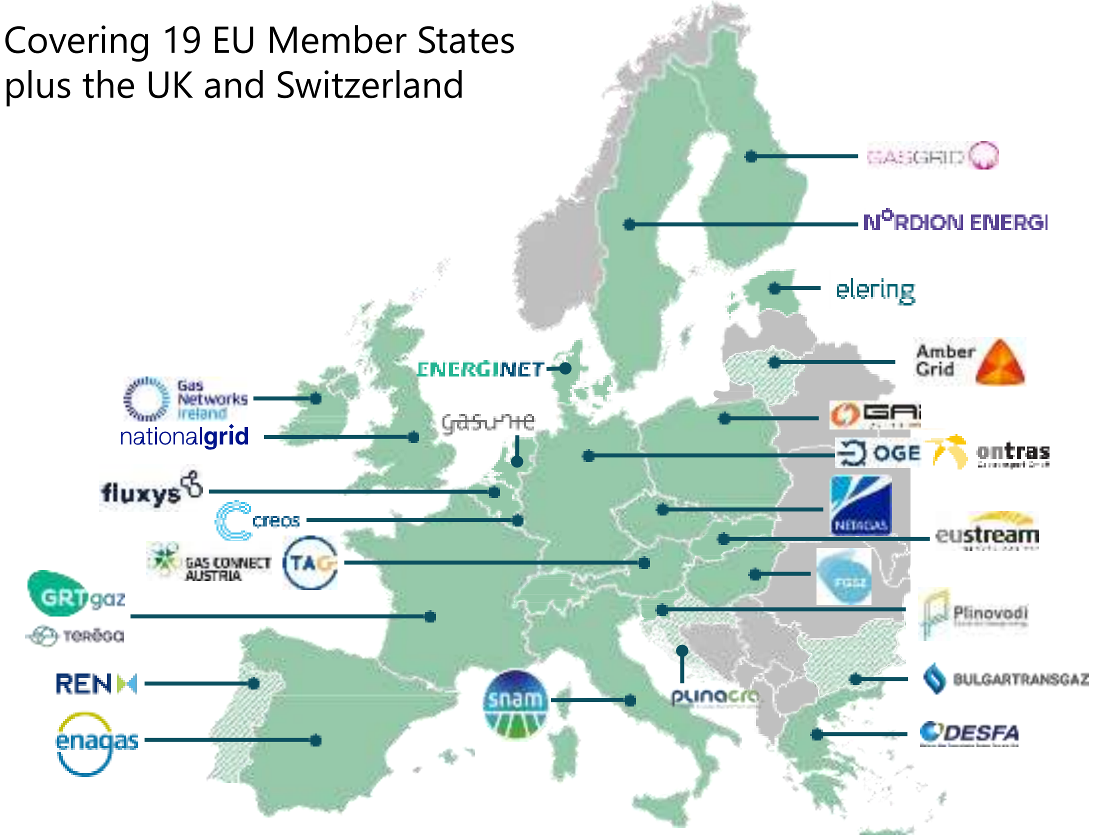
- Infrastructure and fuel cost (as of today)
- Engine out NO_x emissions require EATS
- Maintenance effort
- Powertrain noise level (still lower than diesel)

The European Hydrogen Backbone Initiative 2040 – key enabler to connect supply & demand

APPROACH

23 EUROPEAN GAS TSO'S ENGAGED

- Covering 19 EU Member States plus the UK and Switzerland

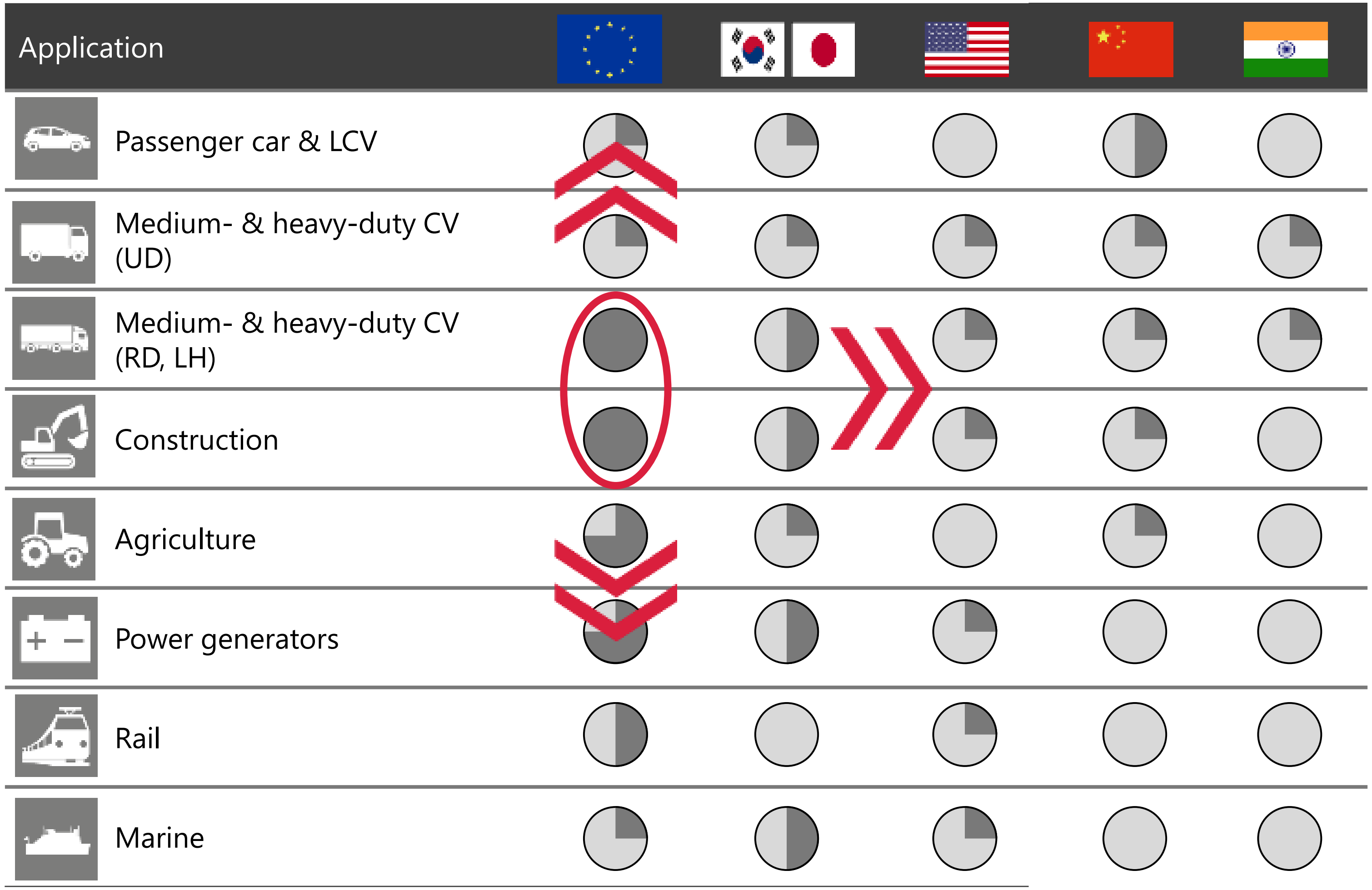


EXPANDING THE GRID WILL BE KEY TO SUCCESS

- 39,700 km grid - 69% repurposed natural gas pipelines
- ~0.16 €/kg/1000km levelized cost of hydrogen transport as competitive decarbonization option
- Europe-wide H2-Market ensuring security of supply and demand

Source: OGE presentation at 5th INTERNATIONAL FEV CONFERENCE "Zero CO2 Mobility"; 2021

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

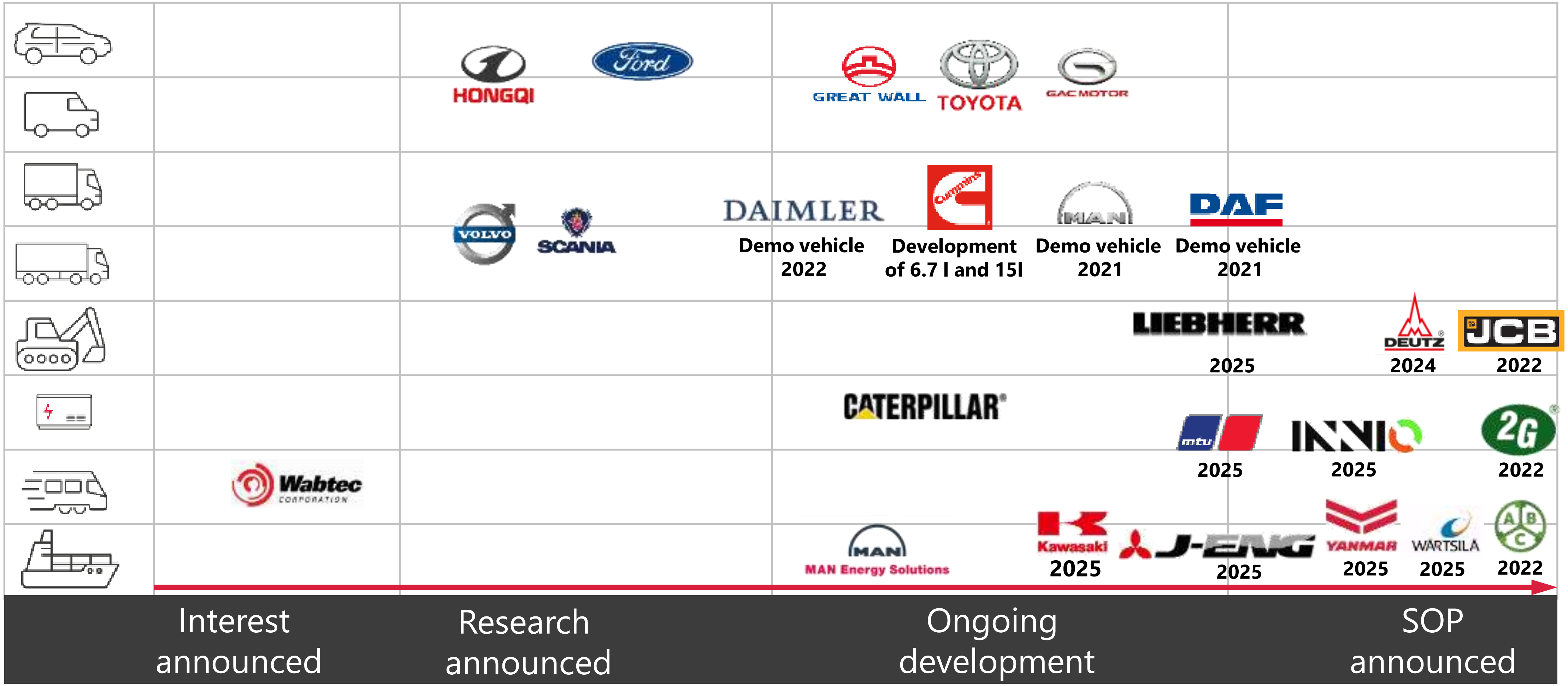


MAIN DRIVERS

- 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

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

FEV

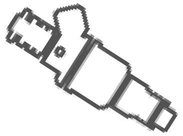


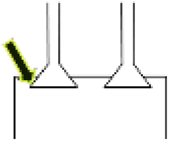
COMBUSTION SYSTEMS CONFIGURATION

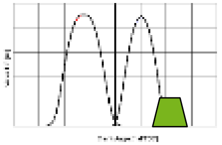
TO ENABLE HIGH EFFICIENCY AND LOW ENGINE OUT EMISSIONS

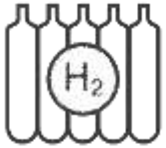
Source: Website Lavision

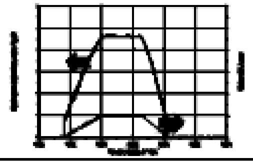
Mixture formation is key to efficiency and low raw emissions

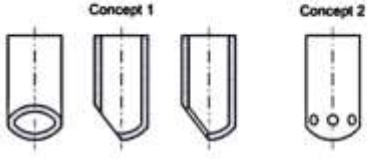
Injector type


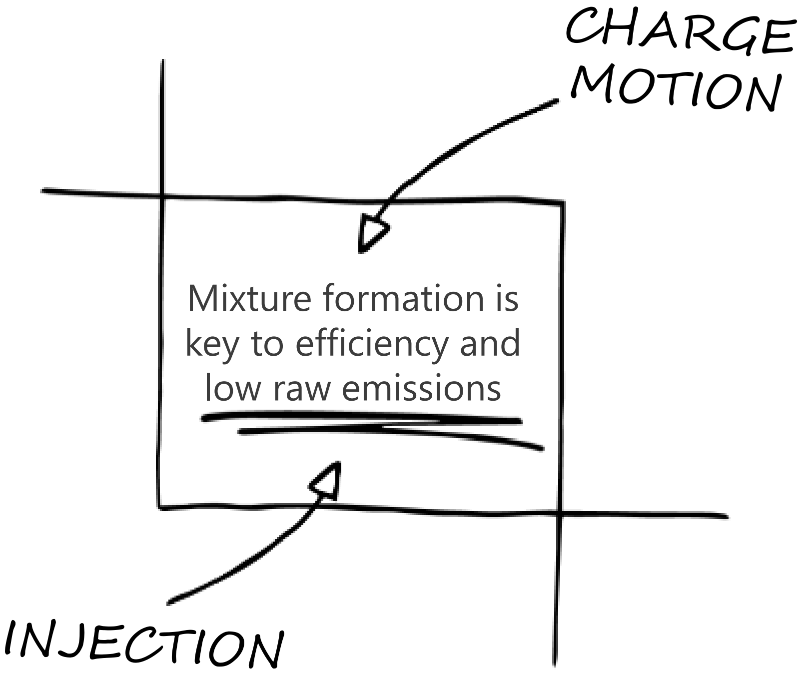
Injector Location


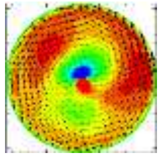
Injection Timing


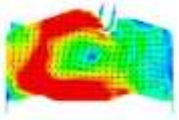
Injection pressure


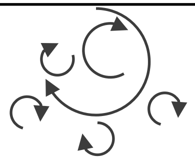
Injection profile


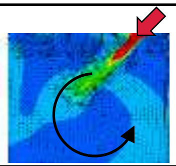
Flow guidance




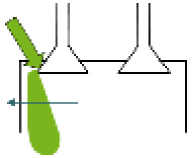

Port: Swirl


Port: Tumble


Turbulence


Injection induced


Piston Bowl

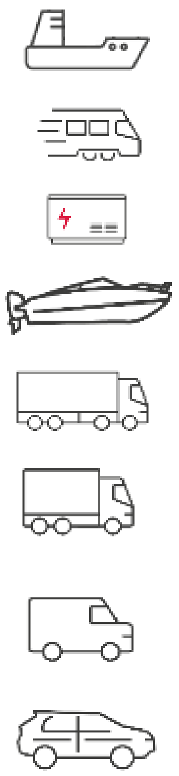

Wall interaction

Source: FEV

Hydrogen offers wide range of possible combustion system layouts in combination with different aftertreatment systems

FEV

HYDROGEN COMBUSTION ENGINES CAN BE EITHER WAY BASED ON DIESEL AND GASOLINE ENGINES



Base engine	Vehicle class	Engine size	Combustion concept	Aftertreat-ment	Boosting/ Air control	Electrification	Advantages
Diesel (Peak firing pressure)		MS Engine Bore ~ 250mm HS Engine Bore ~ 180mm	Mid/High pressure **DI SI** Low pressure **PFI** FL: Ultra Lean PL: Ultra Lean	None	1 or 2 stage	None	
		HD Engine Size ~13l MD Engine Size ~8l	Low/Mid pressure **DI SI** Low pressure **PFI** FL: Lean PL: Ultra Lean	SCR Particle Filter	Wastegate/ VTG	48 V	Durability Efficiency Range
		LCV Engine Size ~2-3l	Mid pressure **DI SI** FL: stoichiometric + EGR PL: Ultra Lean	TWC (+ LNT) Particle Filter	Throttle valve / Valve timing	Mild Hybrid	
Gasoline (Temperature)		PC Engine Size ~2l REX Engine Size ~1l	Low pressure **PFI/DI SI** FL: stoichiometric (+EGR) PL: stoichiometric	TWC Particle Filter	NA / turbo charged	Serial Hybrid	Cost Packaging

Low pressure < 30 bar, Mid pressure 40 – 60 bar, High pressure > 200 bar

For MD and HD vehicle class low/mid pressure DI in combination with lean full load and ultra-lean part load operation seems most favorable

HYDROGEN COMBUSTION ENGINES CAN BE EITHER WAY BASED ON DIESEL AND GASOLINE ENGINES

Peak firing pressure

Temperature

Base engine	Vehicle class	Engine size	Combustion concept	Aftertreatment	Boosting/ Air control	Electrification	Advantages
Diesel		HD Engine Size ~13l	Mid/High pressure DI SI Low pressure PFI FL: Ultra Lean PL: Ultra Lean	None	1 or 2 stage	None	Durability Efficiency Range
		MD Engine Size ~5-8l	Low/Mid pressure **DI SI** Low pressure **PFI** FL: Lean PL: Ultra Lean	SCR Particle Filter	Wastegate/ VTG	48 V	
		LCV Engine Size ~2-3l	Mid pressure **DI SI** FL: stoichiometric + EGR PL: Ultra Lean	TWC (+ LNT) Particle Filter	Throttle valve / Valve timing	Mild Hybrid	
		PC Engine Size ~2l					Cost Packaging
Gasoline		REX Engine Size ~1l	Low pressure **PFI/DI SI** FL: stoichiometric (+EGR) PL: stoichiometric	TWC Particle Filter	NA / Turbo charged	Serial Hybrid	

Low pressure < 30 bar, Mid pressure 40 – 60 bar, High pressure > 200 bar

For PFI higher boosting pressure is required, which can be covered by two stage turbo charger (+ 48V electrical support) or mild hybrid setup

HYDROGEN COMBUSTION ENGINES CAN BE EITHER WAY BASED ON DIESEL AND GASOLINE ENGINES

Peak firing pressure

Temperature

Base engine	Vehicle class	Engine size	Combustion concept	Aftertreat-ment	Boosting/ Air control	Electrification	Advantages
Diesel		HD Engine Size ~13l	Mid/High pressure DI SI Low pressure PFI FL: Ultra Lean PL: Ultra Lean	None	1 or 2 stage	None	
		MD Engine Size ~5-8l	Low/Mid pressure **DI SI** Low pressure **PFI** FL: Lean PL: Ultra Lean	SCR Particle Filter	Wastegate/ VTG	48 V	Durability Efficiency Range
		LCV Engine Size ~2-3l	Mid pressure **DI SI** FL: stoichiometric + EGR PL: Ultra Lean	TWC (+ LNT) Particle Filter	Throttle valve / Valve timing	Mild Hybrid	
		PC Engine Size ~2l					Cost Packaging
Gasoline		REX Engine Size ~1l	Low pressure **PFI/DI SI** FL: stoichiometric (+EGR) PL: stoichiometric	TWC Particle Filter	NA / Turbo charged	Serial Hybrid	

Low pressure < 30 bar, Mid pressure 40 – 60 bar, High pressure > 200 bar

PFI injectors will likely be available around 2023 and would offer a fast market entry; DI injectors not commercially ready before 2024/2025

OVERVIEW OF THE TECHNOLOGY READINESS LEVEL[1)] OF THE REQUIRED ENGINE CHANGES **FOR MD/HD**

Component	2021	2022	2023	2024	2025
DI injector	4	5/6	6/7	7	SOP
H_2 DI cylinder head	1	2/3/4	5/6/7	SOP	
Intake throttle	Serial part				
ECU incl. software	5/6	7	SOP		
Sensors	6/7	SOP			
Emission control system	5/6	7	SOP		
Turbocharger	5/6	7	SOP		
Spark plug & cable	5/6	7/SOP			
Spark plug module incl. wiring	5/6	7/SOP			
Fuel rail	5/6	7/SOP			
Piston group (Piston, rings, pin)	5/6	7/SOP			

1 = Proof of concept
8 = Start of production

- Lab-scale proof of concept — 1
- Prototype running — 2
- Engine installation — 3
- Engine testing — 4
- Engine performance targets met — 5
- Validation testing — 6
- Validation targets met — 7
- Start of production — 8

1) FEV definition

EXHAUST GAS AFTERTREATMENT

Source: VW presentation at 5th INTERNATIONAL FEV CONFERENCE "Zero CO2 Mobility"; 2021

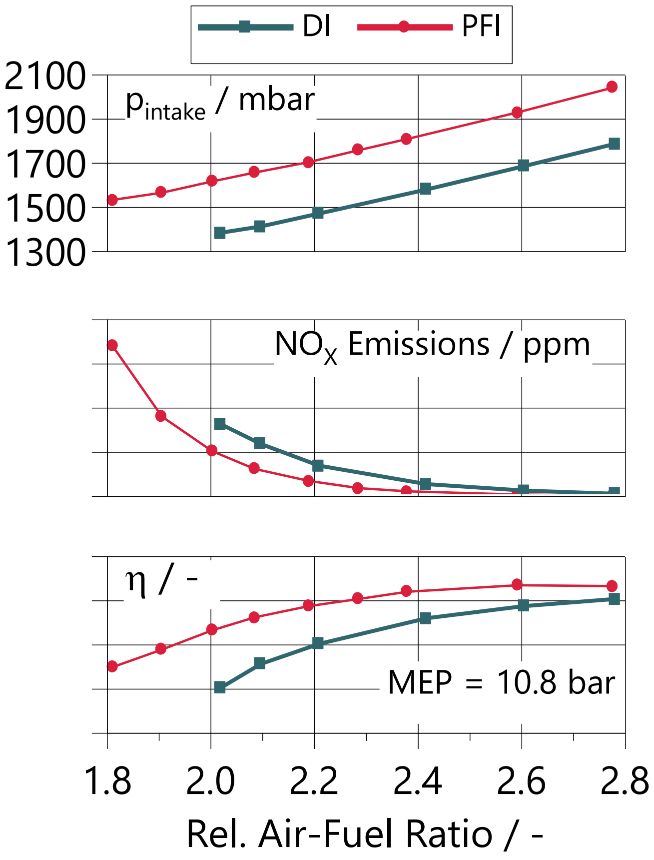
Hydrogen engine dedicated piston/piston ring and combustion chamber design is key for Diesel like BMEP level at ultra-low NOx emissions

FEV

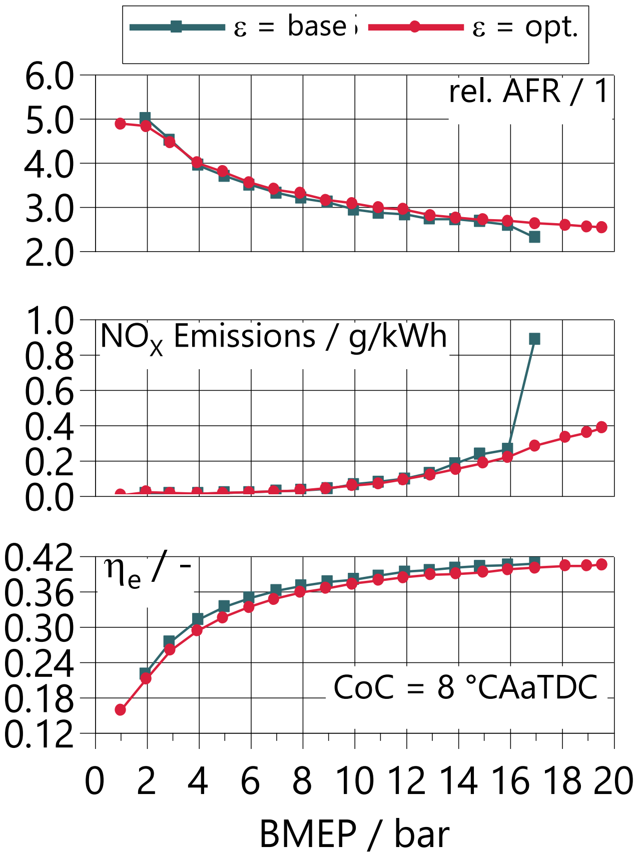
HYDROGEN DI APPLICATION REACHING **EFFECTIVE EFFICIENCIES OF 44 %**

» STATIONARY TEST

HD SCE 2.13l Fuel: H_2
1100 rpm, Bosch Direct Injector



MD-Engine 7.7l R6 Fuel: H_2
1200 rpm, 2-Stage Turbo Charger

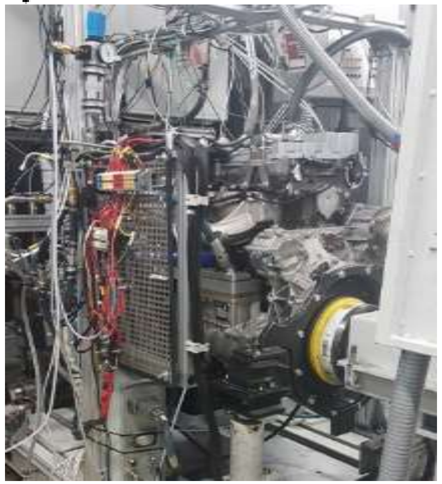


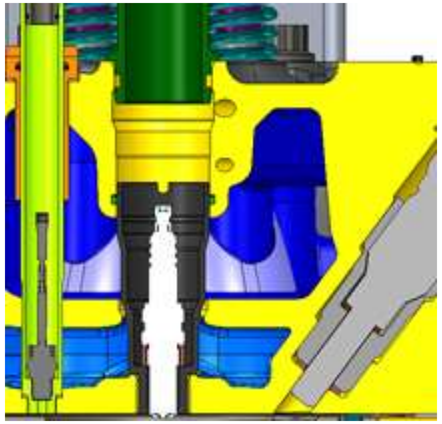
Medium duty engine 7.7l

- Base engine:
  - stochiometric natural gas with EGR
  - single point fuel injection
  - High level of charge motion
  - Miller timing
- For hydrogen operation:
  - 2-Stage turbocharging
  - Reduced comp. ratio for optimized power density
  - No miller timing

HD SCE 2.13l

- Base engine:
  - OM471 diesel engine
  - No charge motion
- For hydrogen operation:
  - Reduced comp. ratio





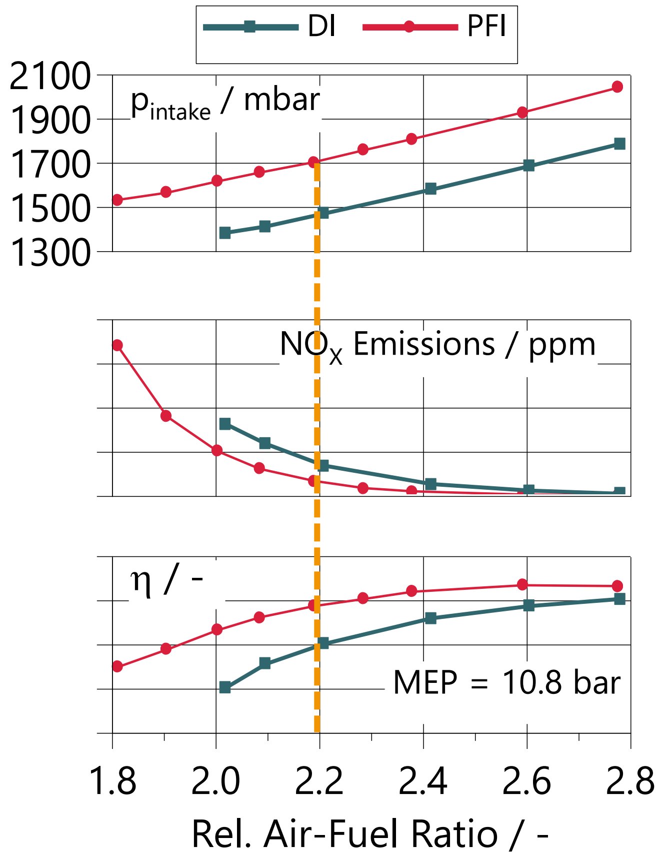
CoC: Center of Combustion

Hydrogen engine dedicated piston/piston ring and combustion chamber design is key for Diesel like BMEP level at ultra-low NOx emissions

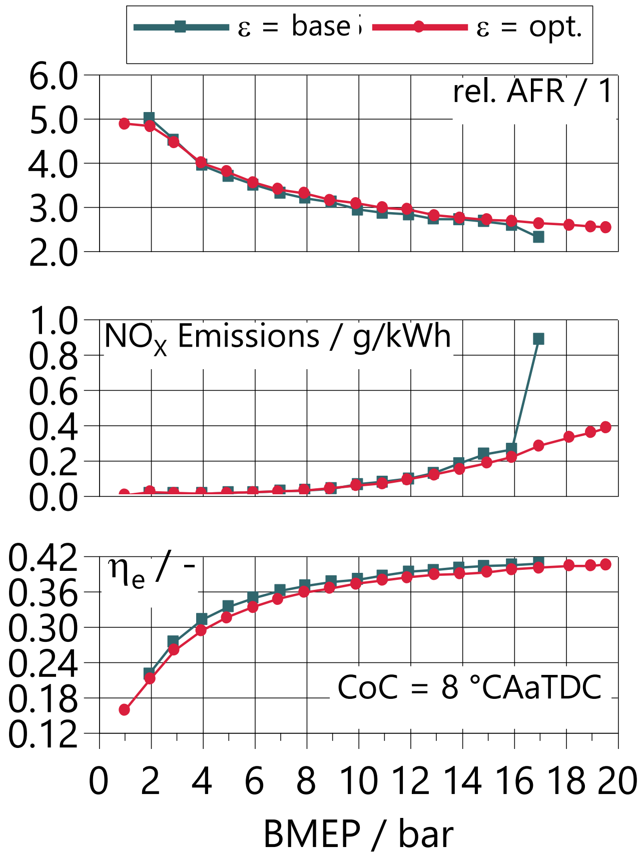
HYDROGEN DI APPLICATION REACHING **EFFECTIVE EFFICIENCIES OF 44 %**

» STATIONARY TEST

HD SCE 2.13l Fuel: H_2
1100 rpm, Bosch Direct Injector



MD-Engine 7.7l R6 Fuel: H_2
1200 rpm, 2-Stage Turbo Charger

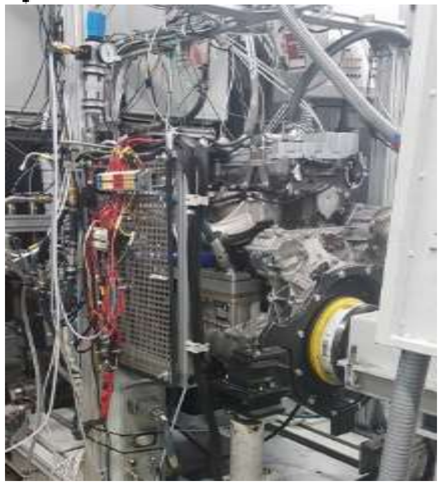


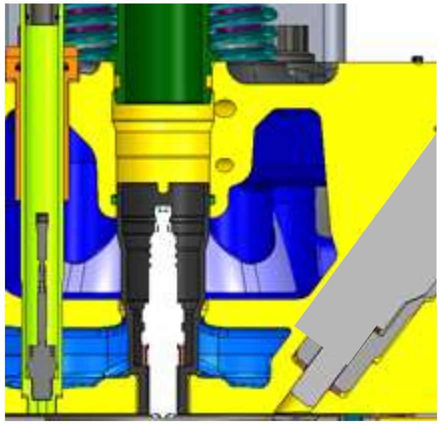
Medium duty engine 7.7l

- Base engine:
  - stochiometric natural gas with EGR
  - single point fuel injection
  - High level of charge motion
  - Miller timing
- For hydrogen operation:
  - 2-Stage turbocharging
  - Reduced comp. ratio for optimized power density
  - No miller timing

HD SCE 2.13l

- Base engine:
  - OM471 diesel engine
  - No charge motion
- For hydrogen operation:
  - Reduced comp. ratio





CoC: Center of Combustion

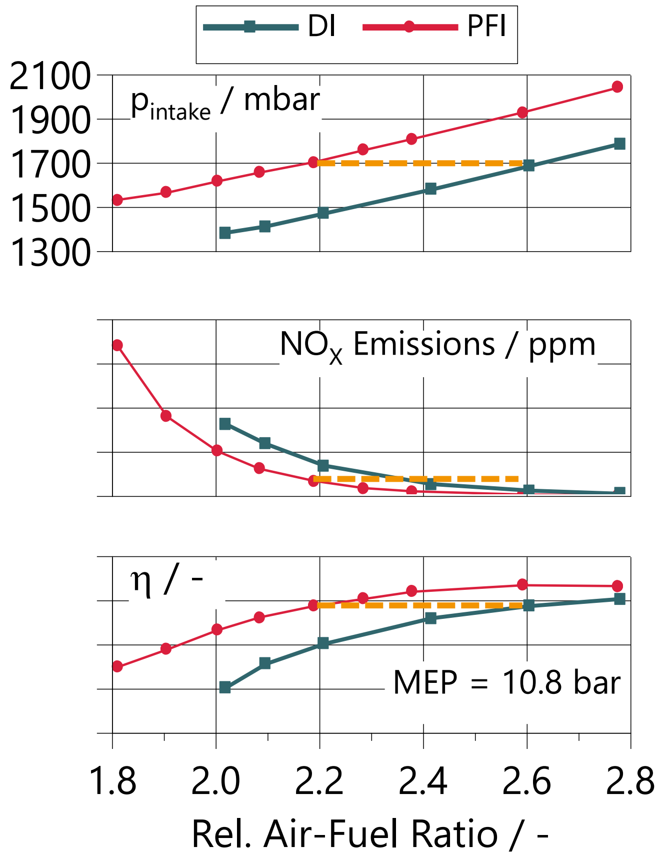
Hydrogen engine dedicated piston/piston ring and combustion chamber design is key for Diesel like BMEP level at ultra-low NOx emissions

FEV

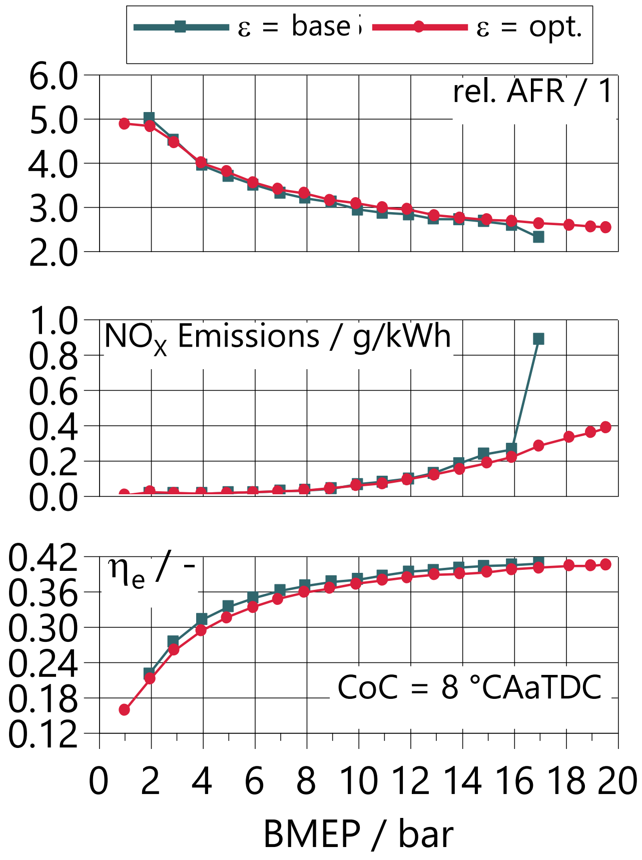
HYDROGEN DI APPLICATION REACHING **EFFECTIVE EFFICIENCIES OF 44 %**

» STATIONARY TEST

HD SCE 2.13l Fuel: H_2
1100 rpm, Bosch Direct Injector



MD-Engine 7.7l R6 Fuel: H_2
1200 rpm, 2-Stage Turbo Charger

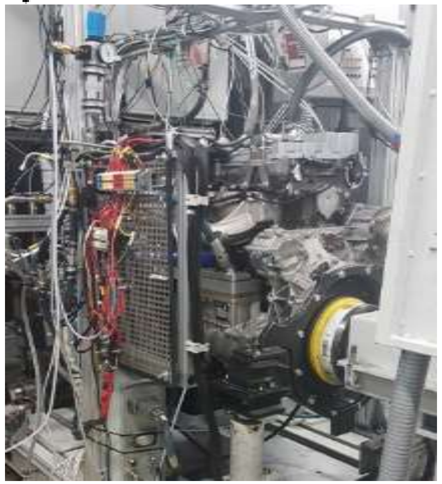


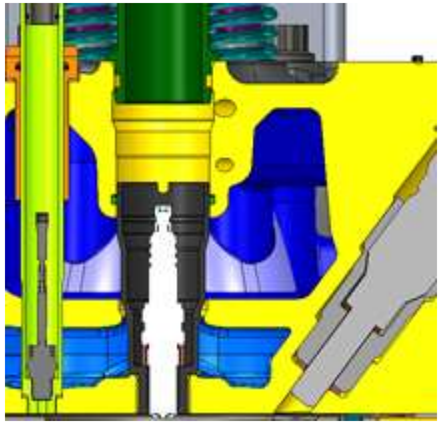
Medium duty engine 7.7l

- Base engine:
  - stochiometric natural gas with EGR
  - single point fuel injection
  - High level of charge motion
  - Miller timing
- For hydrogen operation:
  - 2-Stage turbocharging
  - Reduced comp. ratio for optimized power density
  - No miller timing

HD SCE 2.13l

- Base engine:
  - OM471 diesel engine
  - No charge motion
- For hydrogen operation:
  - Reduced comp. ratio



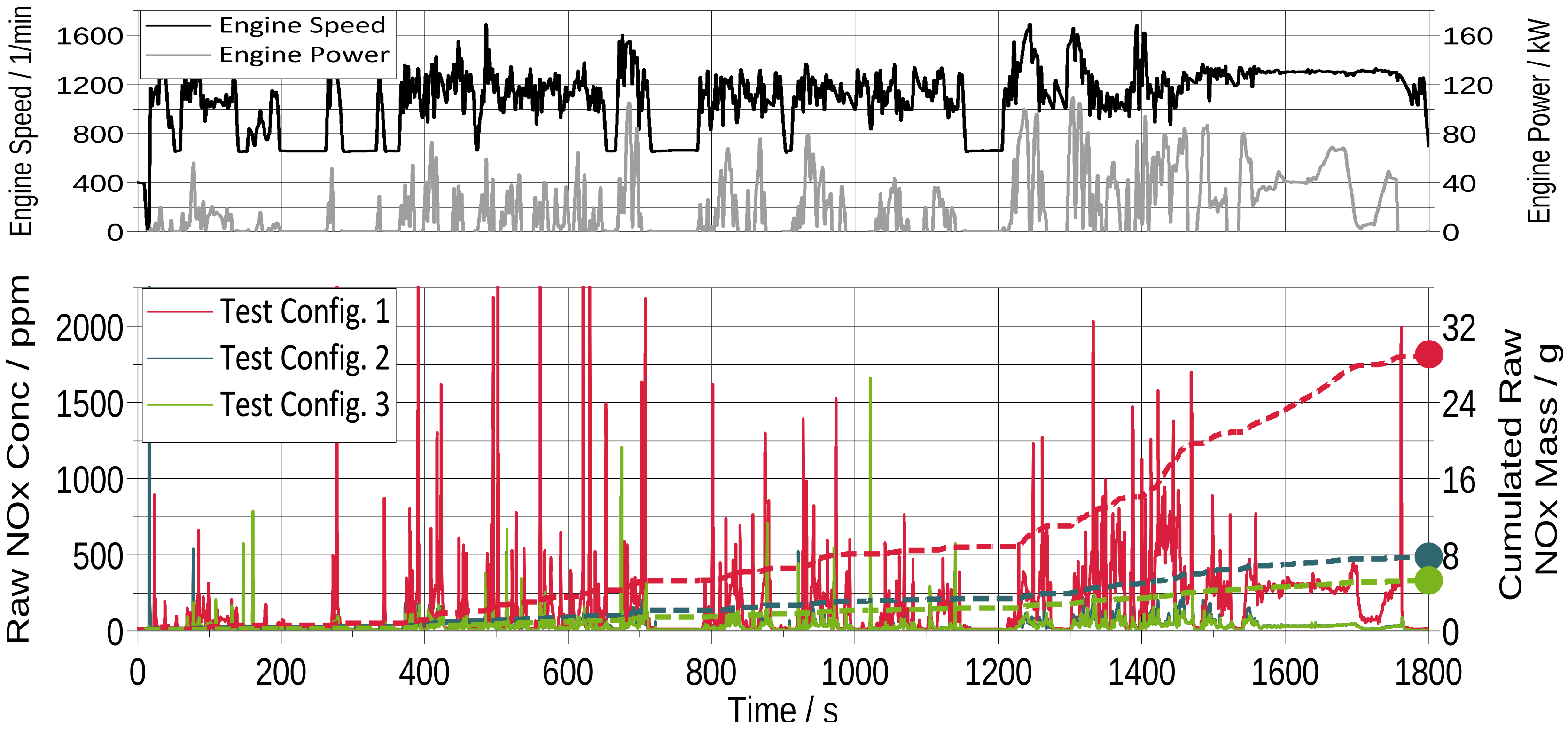


CoC: Center of Combustion

With an adapted control algorithm for lambda and ignition timing, it is possible to maintain a balance between engine efficiency and NO_X emissions

» TRANSIENT CYCLE

Test Configuration	Targeted lambda	Targeted CoC*	Ignition retardation during load step	Raw NOx emission reduction
1	2.0	≈ 8° CAaTDC	Basis	-
2	2.3	≈ 8° CAaTDC	Basis	≈ 75%
3	2.3	≈ 8° CAaTDC	Basis x2	≈ 83%



DESCRIPTION

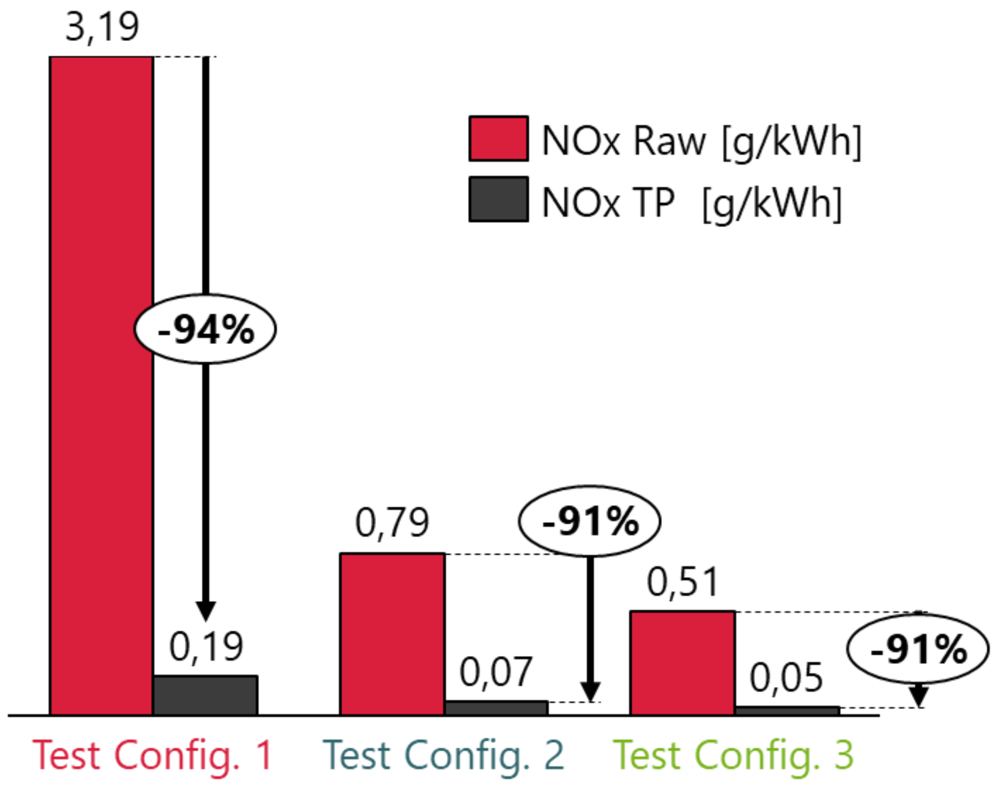
- During fast load requests, an enrichment of the air/fuel ratio supports rapid load build-up but results in higher NO_x emission
- During a fast load increase the ignition timing is retarded to avoid NO_x emission peaks and knocking combustion
- Balance can be found between engine efficiency and NO_x emission

NO_X emission reduction potential is high via a suitable combination of air-fuel ratio setting, ignition timing and properly selected SCR

VERY LOW NO_X RAW EMISSION LEVELS CAN BE ACHIEVED WITH 50 MG/KWH OVER A WARM WHTC

DESCRIPTION

- The higher exhaust gas temperatures of Test Config.1 lead to an earlier urea dosing release and increased SCR efficiencies. 94% NOx conversion can be achieved.
- For Test Config.2 and Test Config. 3, the same SCR efficiency of 91% can be achieved, as the measures taken hardly affect the temperature.
- Tailpipe emissions can be on a very low level of **50 mg/kWh** over a warm WHTC.

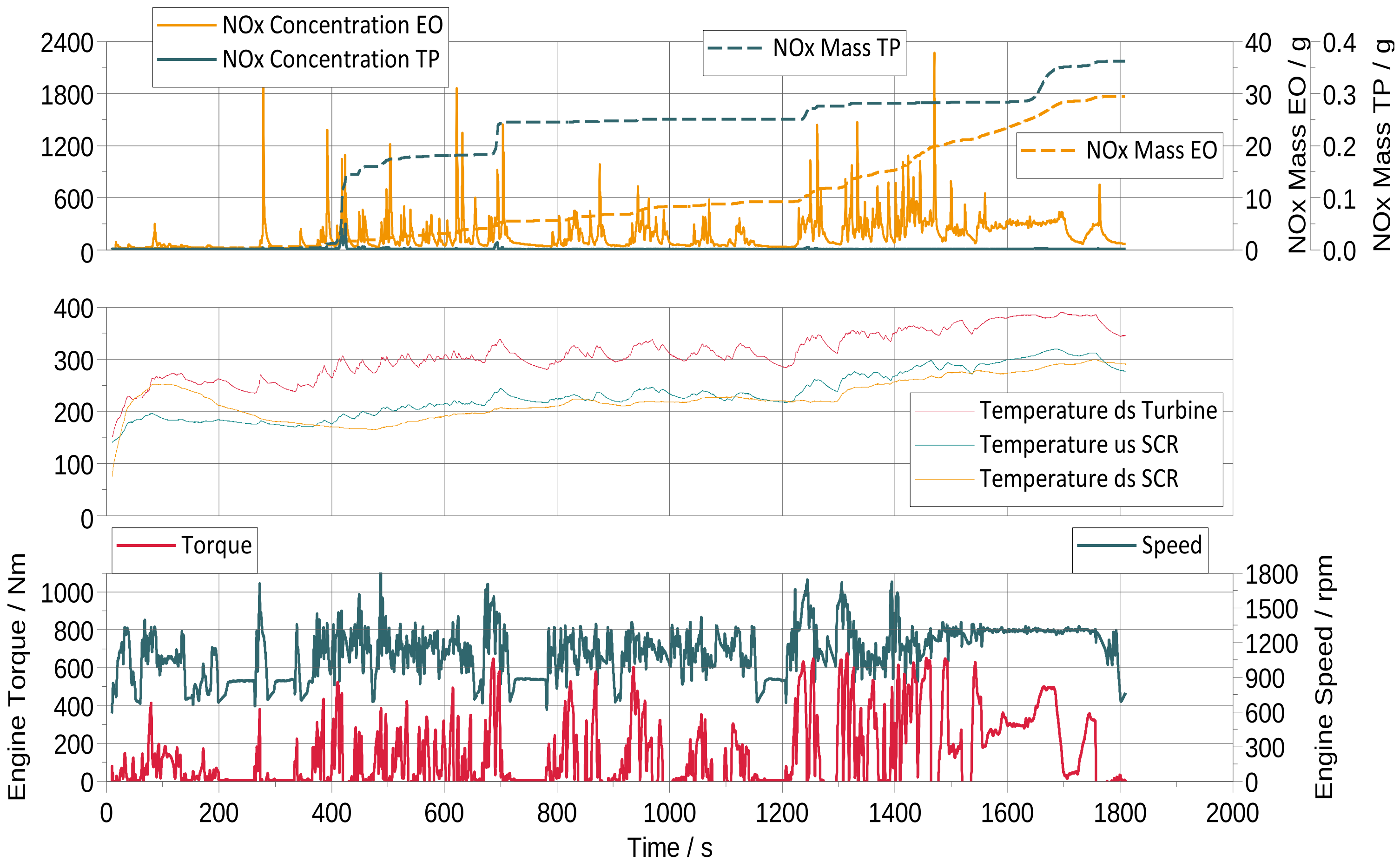


Test Configuration	Targeted lambda	Targeted CoC*	Ignition retardation during load step	Raw NOx emission reduction
1	2.0	≈ 8° CAaTDC	Basis	-
2	2.3	≈ 8° CAaTDC	Basis	≈ 75%
3	2.3	≈ 8° CAaTDC	Basis x2	≈ 83%

Ongoing screening shows, lowest NO_x Emissions can be reached with DOC-SCR Configuration, but still more configurations to come

WARM WHTC WITH H2-ENGINE (AFTER 10MIN SOAK TIME)

» TRANSIENT CYCLE



KEY FINDINGS

- Strong dependency of NO_x emissions and temperature on air fuel ratio
- With warm EATS >98% efficiency can be reached

→ Further potential of optimal alignment of calibration and aftertreatment system for lowest emissions and/or dynamic response

RESULTS

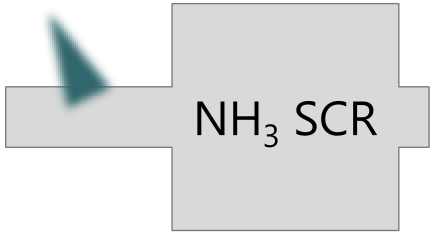
- NO_x EO: 3.25 g/kWh
- NO_x TP: 0.040 g/kWh

98%

SCR efficiency

Various possible aftertreatment configurations exist, taking over production-ready Diesel like systems is key for fast market entry

SCR ONLY



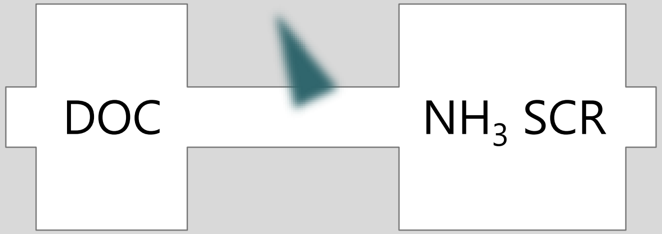
Advantages:

- NH_3 SCR can achieve high efficiencies in complete temperature range
- Fast heat up, no other aftertreatment device upstream SCR

Challenges:

- Cold start (thermal management without oxidation over DOC)
- SCR needs to work with low NO_2/NO_x ratios

DOC & SCR



Advantages:

- DOC can increase NO_2/NO_x ratio for better NH_3 SCR efficiency
- Heat up with H_2 oxidation over DOC possible

Challenges:

- Temperature loss over DOC (during heat up) vs. advantages of DOC

Benefit from FEV's experience and speed up your H2-ICE development!

- Hydrogen internal combustion engines can be used in various applications
- Operation strategy mainly depending on boundary conditions, especially fuel supply pressure level
  - PFI injection will require high power boosting systems
  - DI technology offers potential for highest power density
- Low raw emission level enables for ultra-low tailpipe emissions with dedicated aftertreatment systems
- Development has started and first products will be delivered to customers already within 2023
- Technology can be rolled out globally rather quickly
- FEV can support customers locally in its Coventry technology center

FEV UK Ltd –
Coventry based Technical Centre

ICE DEVELOPMENT

- Development of combustion for passenger cars, commercial vehicles and NRMM applications
- High dynamic engine test benches with asynchronous e-machines
  - Power range: up to 600 kW
  - Torque range: up to 3,500 Nm
- **Hydrogen capable test benches**
  - Adapted safety systems and hydrogen sensing
  - Redundant bottle and trailer storage and supply
  - Emission measurement equipment incl. EGR & H-sense
- **Engine in the Loop capability** to test engines under test cycle boundary conditions
- Test cell size ready to **set up engines with complete unchanged aftertreatment** system to comply with latest emission regulations

FEV

IMPRESSIONS