

Driving Cleaner Performance





Agenda

1

Welcome and housekeeping items

- Fabien Redon, Chief Technology Officer, Westport
- Ashley Nuell, Senior Director IR, Westport

2

Application of Westport's H₂ HPDI™ Fuel System to a Demonstration Truck

- David Mumford, Senior Director of Heavy-Duty Product Management, Westport
- Eric Olofsson, Manager of Combustion Systems, Scania

3

Hydrogen Combustion Concepts: Comparison of Port Fuel Injection with Spark Ignition and HPDI – Power Density, Efficiency, and Emissions

- Xander Seykens, Senior Research Scientist, Powertrains, TNO

4

Q & A



Drivers of market uptake of H₂-ICE

Regulation

Positive momentum in the recognition of H₂-ICE as zero-emission powertrain.

Economics

Lower capital outlay than BEV or FCEV. A competitive solution from a TCO perspective.

OEM Resources

Uses available skill of R&D and production team, leading to lower OEM investment and faster time to market.

Technology

More mature than BEV and FCEV as H₂-ICE builds on Diesel engines.

Supply Chain

Leverages existing supplier, powertrain and vehicle production supply base.





Scania / TRATON:

A view on the H₂ economy and the outlook for H₂ ICEs

SCANIA



Scania: Why H₂ ICE?

- How does TRATON prepare – in a capital efficient way – for a possible scenario where our future customers demand an H₂ energy converter?
- This possible risk diversification/mitigation must be carried out at low cost, in order not to jeopardize TRATON's main route to CO₂ neutral road transports of heavy goods, i.e. the BEV
- **This is where the H₂ Internal Combustion Engine fits in**
- H₂ ICE facilitates:
 - Low development, investment and production costs, due to well-known and relatively mature and robust technology
 - Possibility to use existing production facilities
 - Relatively short time to market.
- **H₂ ICE is therefore a capital-efficient way to use H₂**
- H₂ ICE will consequently not cannibalize the resources allocated to BEV. Simultaneously it will make TRATON prepared for a possible future scenario where H₂ plays an important role in the HD road transport sector



The three fuels we can see – for the foreseeable future – that CBE1 with HPDI should possibly be able to convert are;

- Diesel
- Methane (CH_4)
- Hydrogen (H_2) in fossil or renewable/green form

Commonality between Diesel, CH₄ and H₂ engines will therefore be important in the future



- **Only one engine platform is needed to be able to handle all fuels i.e. diesel, H₂ and CH₄**
 - As a consequence; Which fuel is burned becomes indifferent to the external gas exchange system
- **CBE1 with HPDI offers true fuel agnosticity**
 - The same compression ratio can be used for all three fuels, i.e. 23:1
 - Pistons, cylinder head (with some reservation for packing of diesel and gas rails), external gas exchange system and crankcase ventilation become identical

Final thoughts



- There are many different driving forces for a H₂ society
 - Will it happen?
- Risky to invest in only one of the two available renewable energy carriers, i.e. electricity and hydrogen
 - Must meet CO₂ emission reductions. 45% 2030, 65% 2035 and 90% 2040
- **H₂ ICE is a cost-effective way to acquire an H₂ energy converter**
- HPDI provides the opportunity to
 - High Torque and Power Density
 - Very good efficiency, both WtT and TtW, in relation to competitive H₂ Technologies
 - Extreme Commonality for Diesel, H₂ and CH₄ from an engine and EATS perspective
 - Very competitive transient characteristics and low end torque
 - Powerful “make heat” strategies at cold starts

High Performance Hydrogen Engine Applications

Application of Westport's H₂ HPDI™ Fuel System to a Demonstration Truck



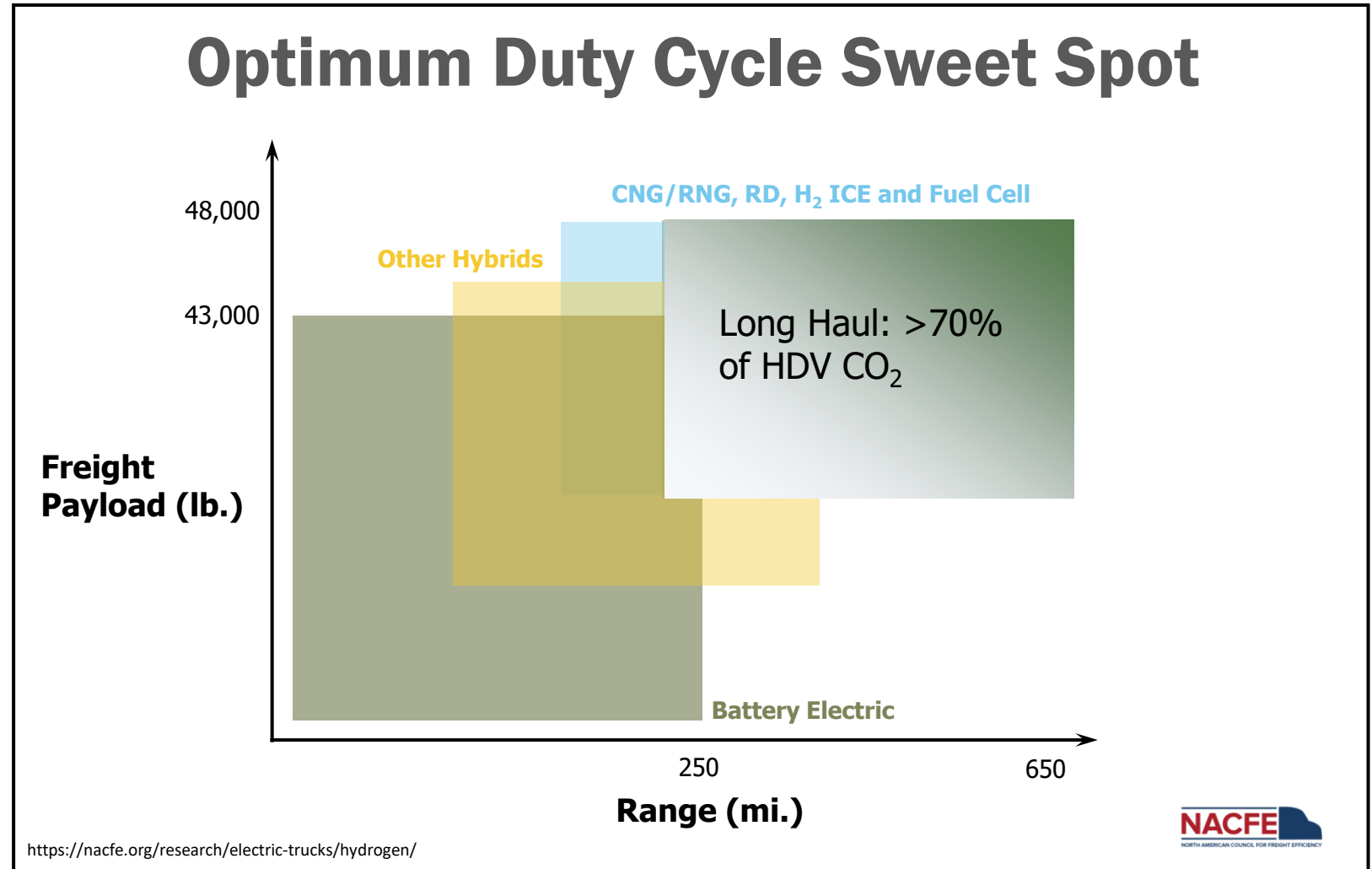
GHG Reduction: The Role for H₂ ICEs

Multiple solutions for decarbonizing transportation:

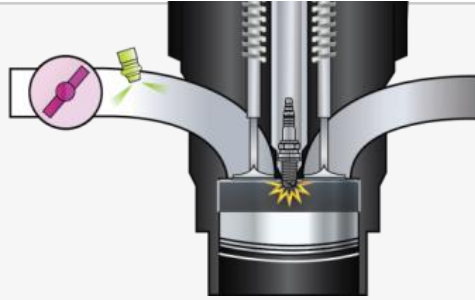
- BEVs
- FCEVs
- H₂ ICEs
- Hybrids

NACFE Study:

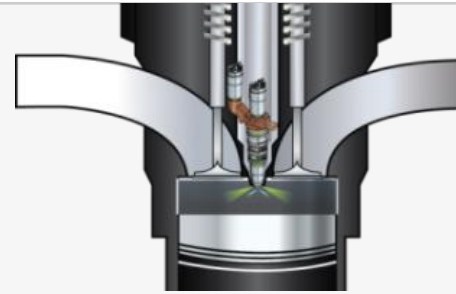
- BEVs & hybrids - short haul
- FCEVs & H₂ ICEs - long haul



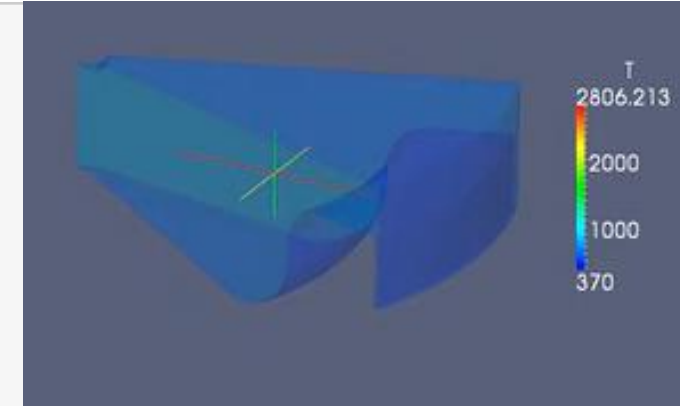
NG / H₂ ICE Technologies



Spark Ignited



Compression Ignition



How it works

- Fuel & air pre-mixed at low pressure
- Dedicated natural gas (100%)
- Ignition from spark plug
- Reduced compression ratio to avoid knock
- Simple 3-way catalyst
- Otto cycle (Stoichiometric)
- **Power / torque / efficiency typically lower than base diesel engine**

- Direct injection of high pressure gas into combustion chamber
- **Same base diesel engine can be used equipped with Westport's HPDI fuel system**
- Compression Ignition from diesel pilot
- Same piston / compression ratio as diesel to retain high efficiency
- SCR & DPF (same as diesel)
- Diesel cycle - high substitution (~94% on typical road cycle)
- **Power / torque / efficiency can exceed base diesel engine on Hydrogen**

An Overview of Westport's HPDI™ Fuel System

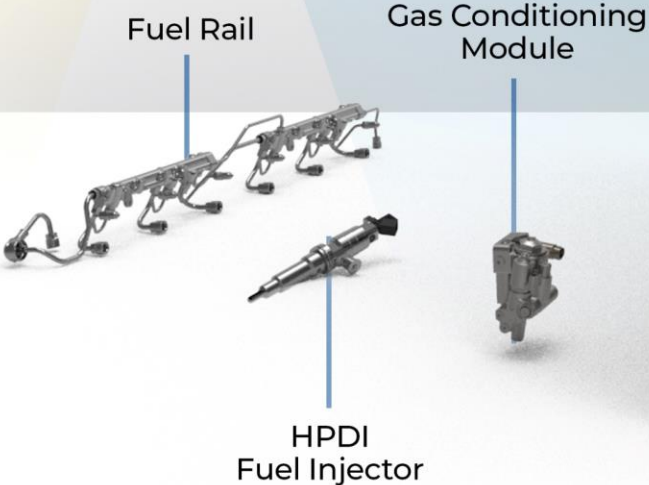
- Westport's **HPDI™** fuel system was conceptualized ~30 years ago with the goal of creating a more efficient natural gas engine.
- The “heart” of the system is a **unique fuel injector** which features a small pilot injection and a larger primary injection of the main fuel – initially natural gas.
- The rest of the system falls broadly into two categories:
 - **Fuel conditioning** – accurate control of the fuel
 - **Fuel supply** – storage and supply of the appropriate fuel
- Two important takeaways:
 - The **base diesel engine remains the same – just switch out the fuel system**
 - While Westport's HPDI fuel system was first developed with natural gas, **the system allows a number of primary fuels to combust on the Diesel cycle**



**CURRENT HPDI
FUEL SYSTEM**

www.westport.com

ON ENGINE

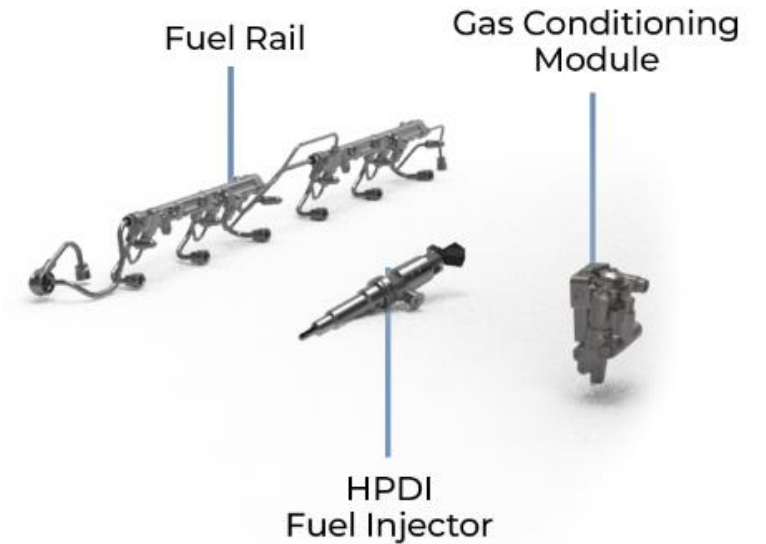


OFF ENGINE

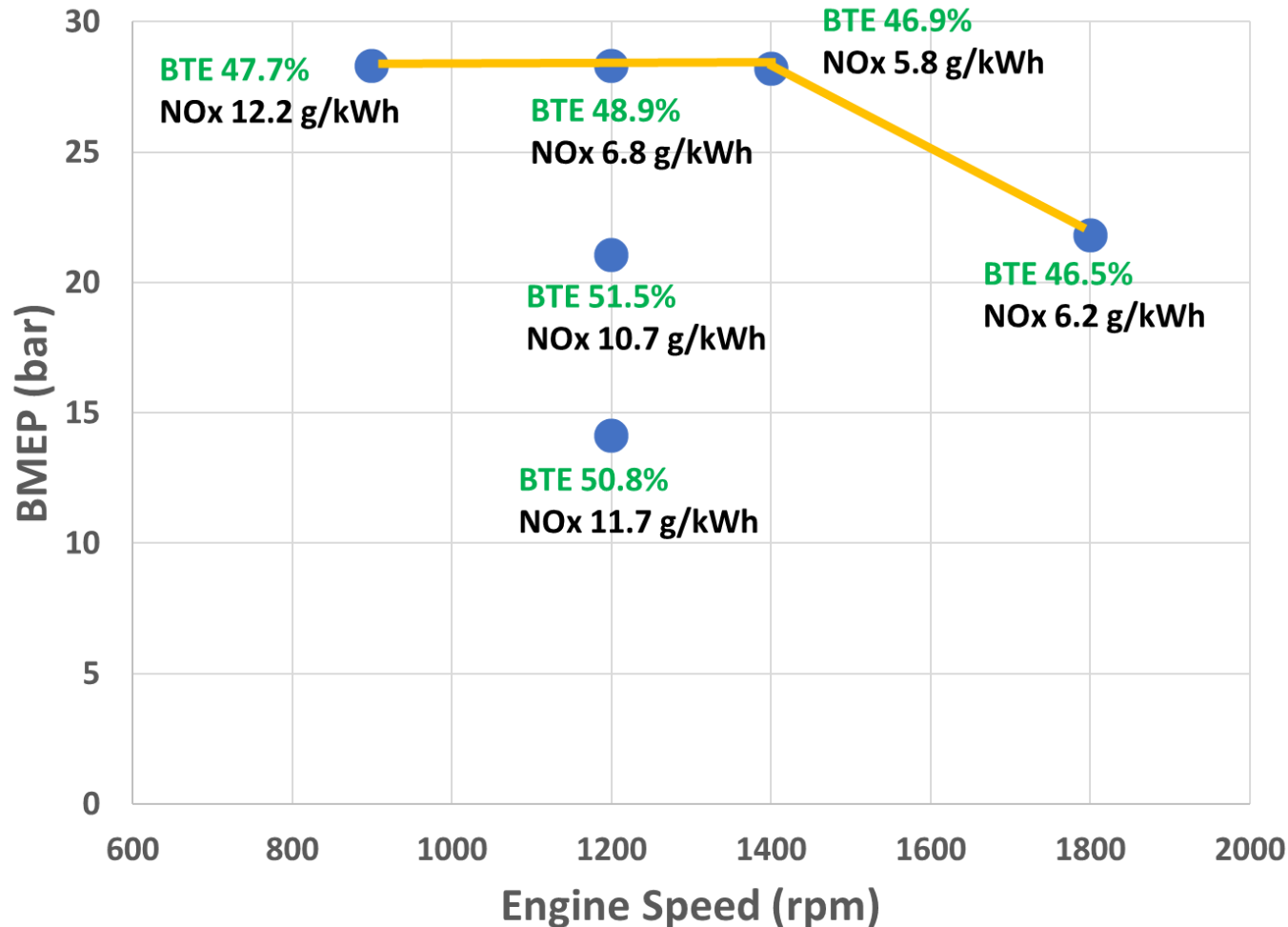


H₂ HPDI Combustion Overview

- The following results will focus on the initial calibration of Scania's state-of-the-art 13-litre CBE1 platform
 - Commercially available HPDI fuel system hardware was used for the initial calibration and demonstration of the H₂ HPDI fuel system
- In parallel, hydrogen work continues on several other HPDI fuel system-equipped engine platforms – both Single and Multi-Cylinder.

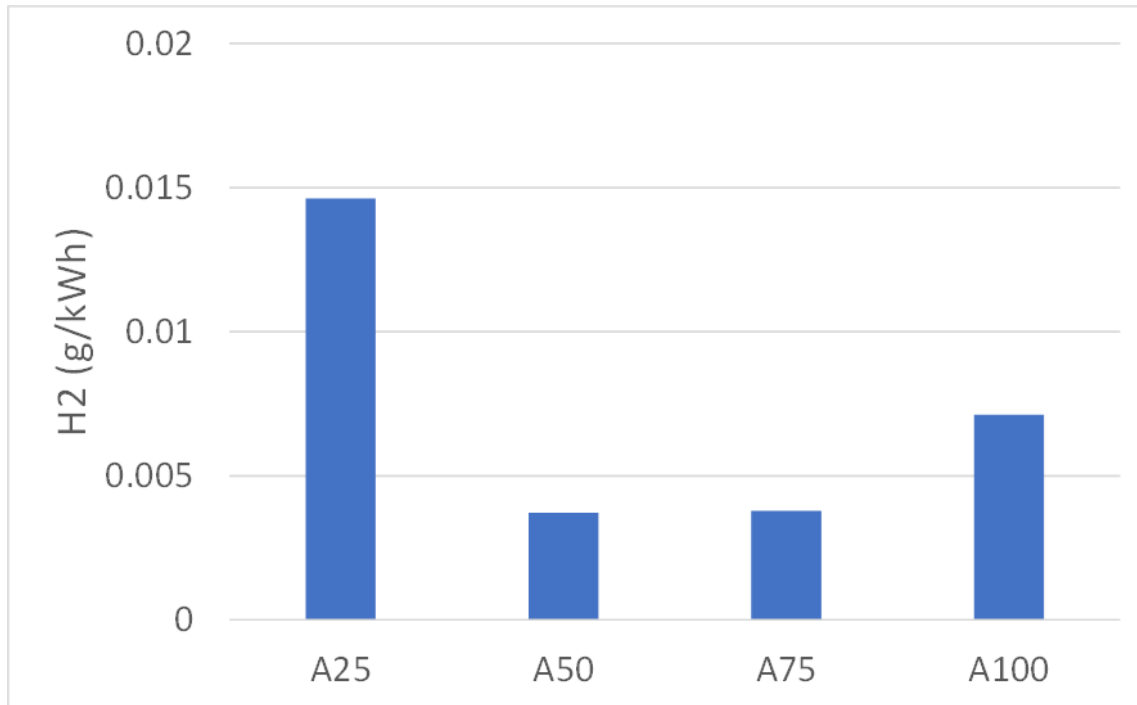


H₂ Combustion on Scania CBE1 Engine

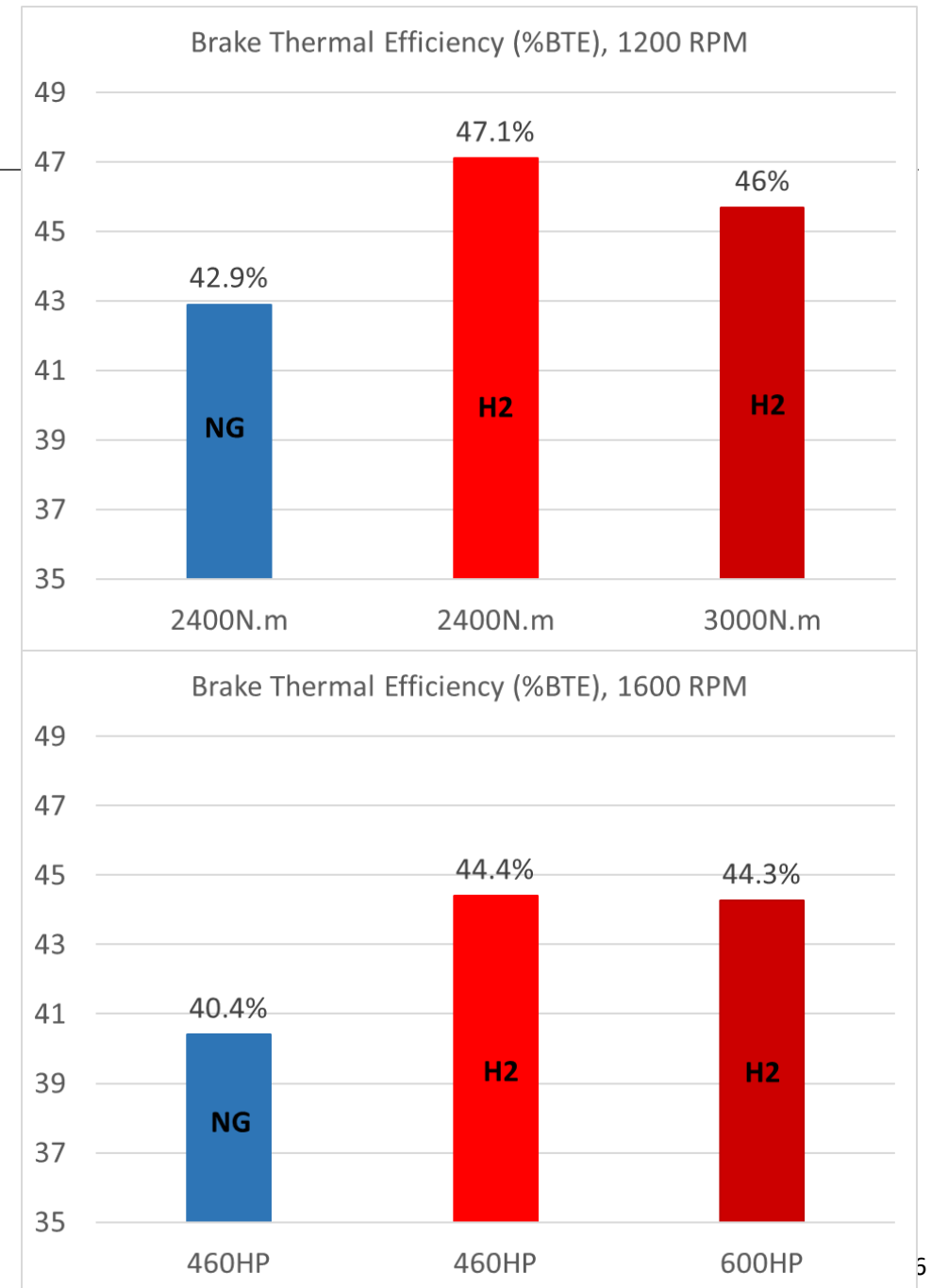


- BTE on torque curve of ~47-49%
- **Peak BTE at 51.5%**
- Engine-out NOx levels calibrated to ~6-12 g/kW.h to reflect EATs strategy
- Note: EGR can be used to reduce NOx further to ~3g/kW.hr
- Pilot quantities as low as 2-3mg have been tested, equating to **near-zero CO₂ emissions**

H₂ HPDI



- No measurable slip infers a low risk of H₂ interaction with combustion chamber
- Capable of exceeding base engine power and torque

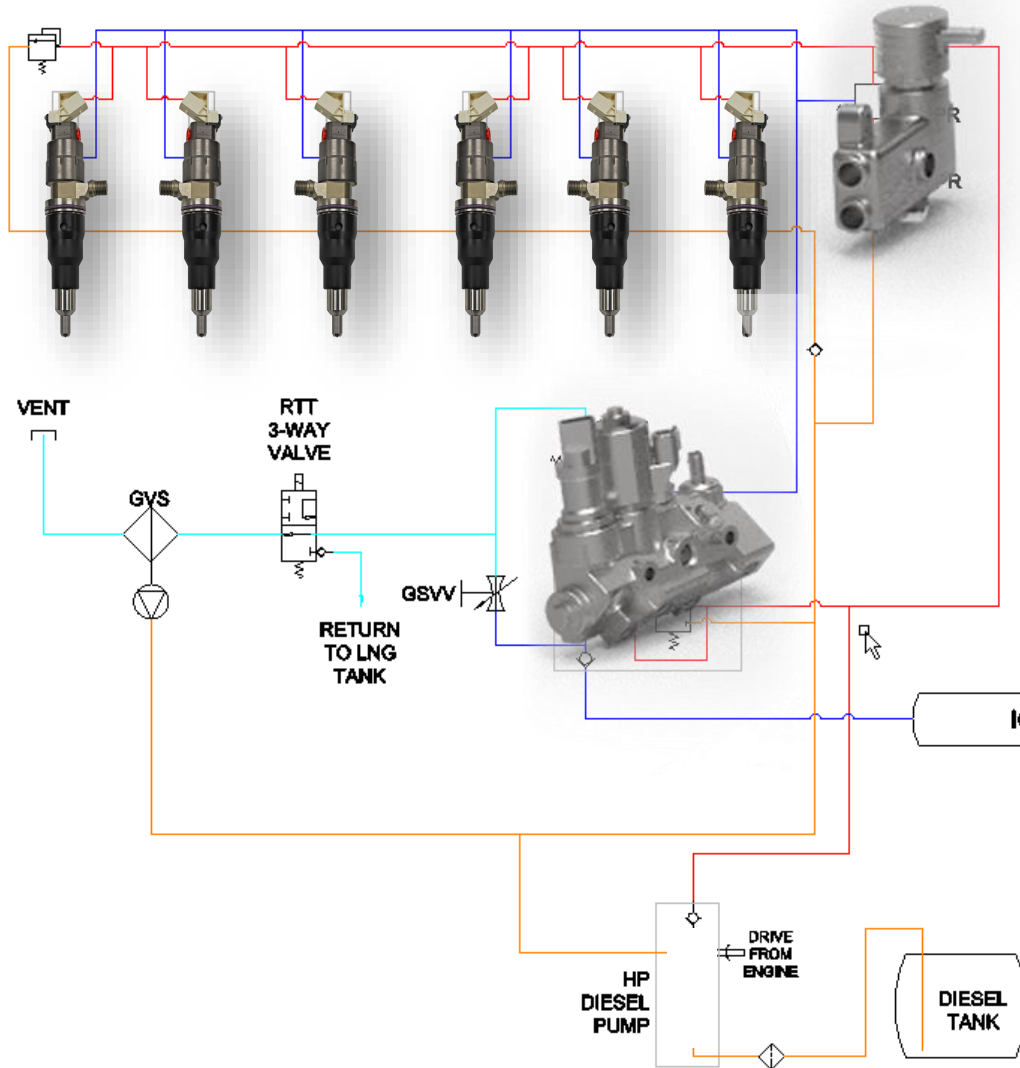


ON ENGINE

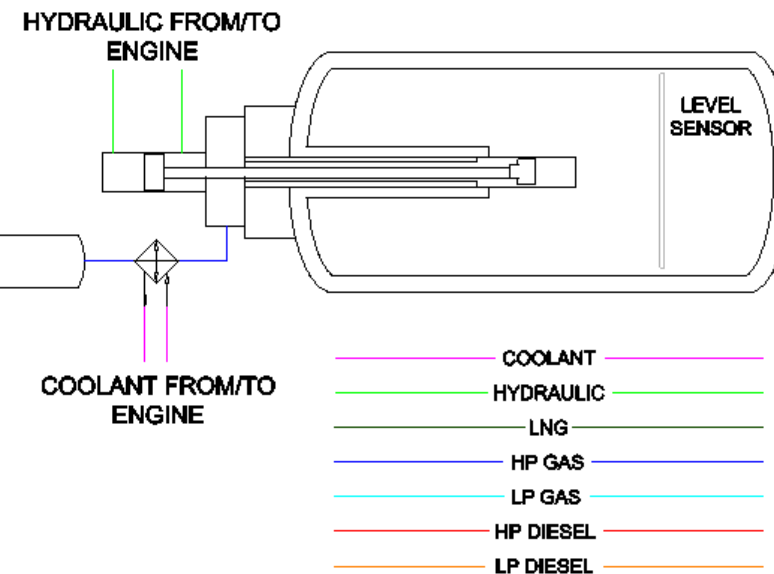
OFF ENGINE



Next Generation Fuel System Architecture (LNG Shown)

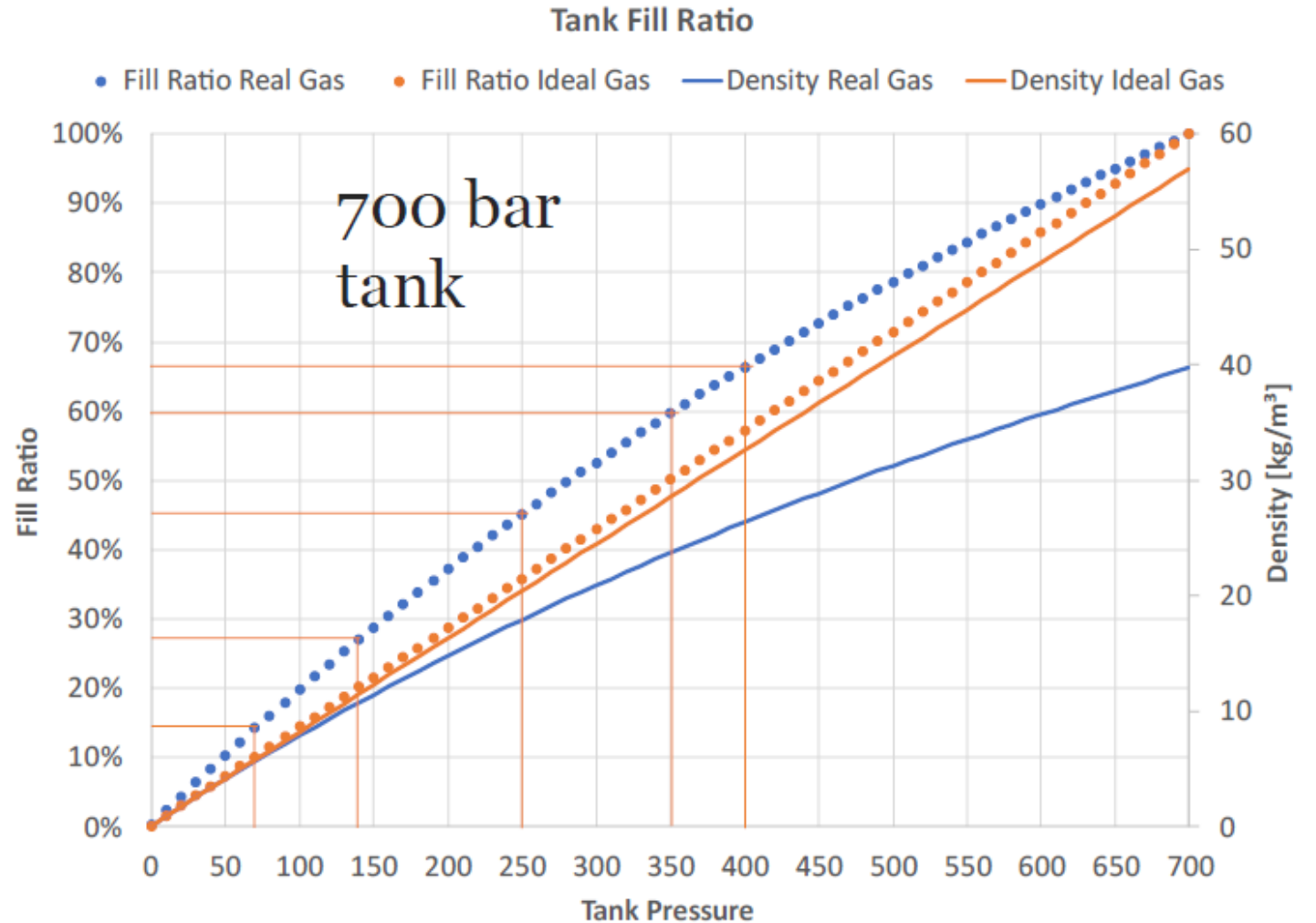


- Revised approach to gas pressure control
- Eliminates dynamic venting
- Facilitates higher pressures (eliminates non-metallic seals)
- Capable of OBFCM for EU VII

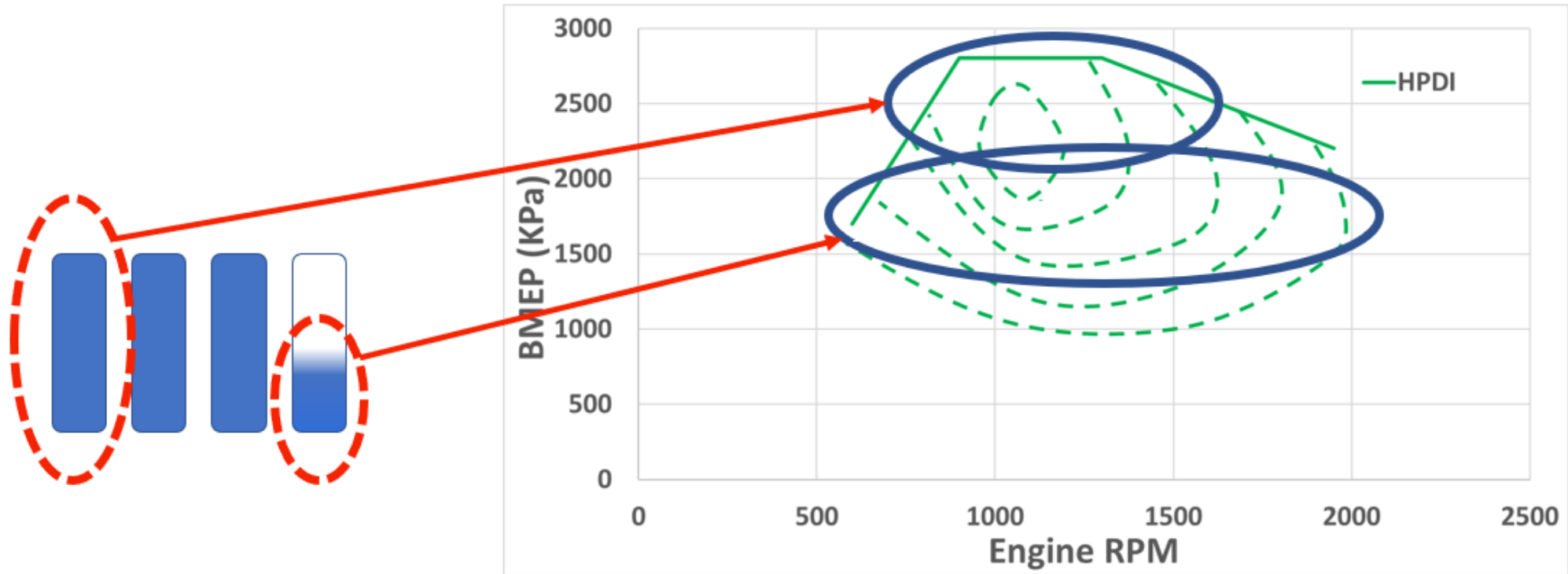


H₂ Fuel System Off Engine Approach

- Target for onboard fuel is 80kg – equates to ~2050-litres of storage
 - Note: H₂ does not follow ideal gas law at higher pressures: 40% over-estimate for ideal gas calculation
- Range without compressor is less than 600km

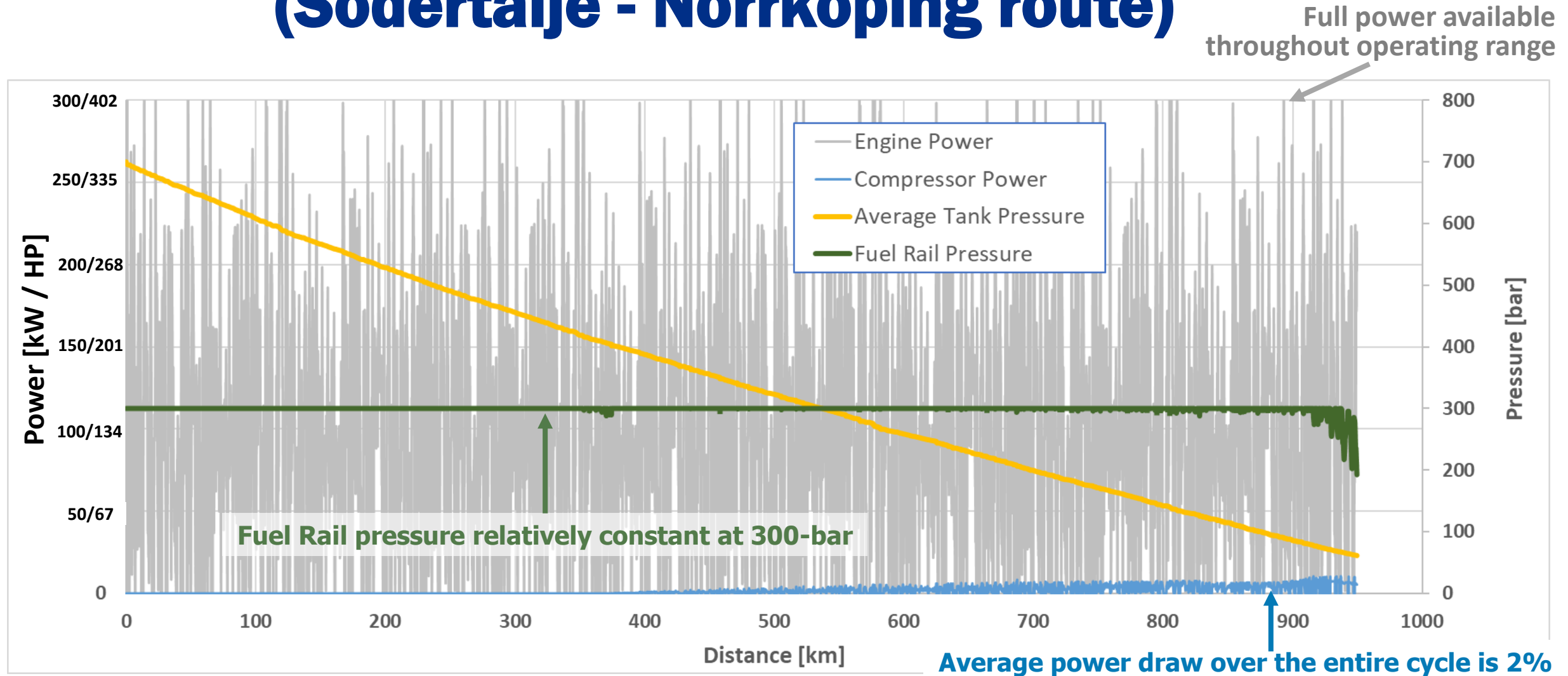


H₂ Smart Tank System



- Compressor required for ranges greater than 500km
- Smart Tank strategy evolved to maximize efficiency and minimize compressor flow
 - Able to reduce size, weight and power requirement.

Smart Tank Simulation Results (Södertälje - Norrköping route)



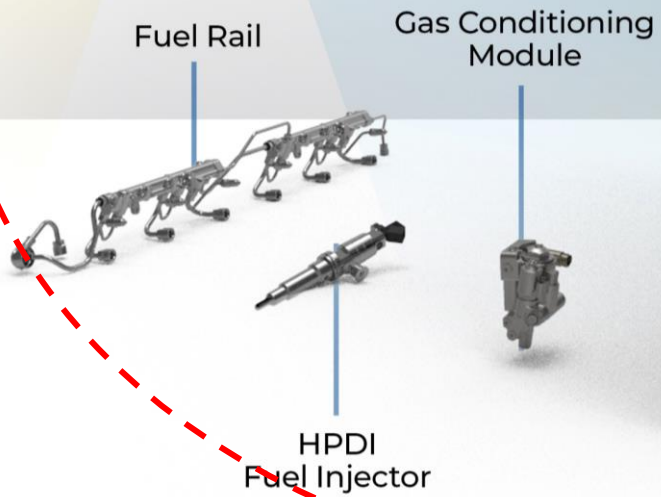
General Simulation Results

Routes	Load (Tonnes)	Predicted H ₂ Consumption (kg/100km)	Average Speed (km/h)	Range with 80kg of H ₂	Tonnes-Km with 80 kg of H ₂
Södertälje – Norrköping Highway, moderately hilly	20	7.4	84	970	19,400
München, Trucker magazine testrunde Highway and rural, moderately hilly	40	11.3	85	590	23,600
Koblenz - Trier Highway, hilly and Scandinavian vehicle load	60	16.3	81	370	22,200

- A typical truck cycle will allow approximately 800-km of range.
- Cycles which require significant power (i.e., high loads or steep climbs) will clearly impact total range for fixed fuel storage.

Demonstration trucks use current hardware

ON ENGINE



OFF ENGINE



DEMONSTRATION TRUCKS



Hydrogen
Station



Changing the way w

H₂ Demonstration Trucks – Challenges & Next Steps

- Challenges:
 - Permitting
 - Fueling
- Next steps:
 - Increase fuel storage:
 - 80kg of fuel with no compressor will allow up to ~600km range* with Smart Tank strategies
 - Add compressor:
 - 80kg of fuel w/ compressor will allow up to ~900km range*



* Cycle/load dependent

H₂ Demonstration Trucks

- Westport has built two H₂ HPDI demonstration trucks
 - Both trucks are converted from commercially available NG European models
 - Truck #1 is US-based
 - Truck #2 is European based
- Onboard storage is currently 16kg in a four-tank array with no compressor





Summary

- Westport's HPDI fuel system can be used with the same base diesel engine – same engine architecture for Biomethane or Hydrogen.
- Interest in Westport's H₂ HPDI fuel system is growing from OEMs, with **multiple development projects** recently announced and underway.
- The SCANIA CBE1 engine equipped with Westport's H₂ HPDI fuel system reached a **peak BTE of 51.5%**.
- H₂ HPDI fuel system equipped engines have demonstrated **near-zero CO₂** emissions.
- The next generation HPDI fuel system will provide improved **fueling accuracy, reduced emissions,** and **higher performance** capability while meeting the new EU VII regulations.
- The Smart Tank off-engine system is predicted to allow up to ~900km range with 80kg of H₂ storage and a small compressor.
- Demonstration vehicles with H₂ HPDI fuel system equipped engines are running in both Europe and the US.

Only at Westport... ...hydrogen with compression ignition

HPDI: Cost-effective

HPDI is the most cost-effective way to reduce CO₂ in long-haul trucking and other high-load, long-haul applications.

H₂ HPDI

- 20% more power, 15% more torque
- **Near zero CO₂ emissions**
- **Lower cost CO₂ abatement than fuel cell vehicles**
- Preserve existing engine manufacturing



H2 HPDI Webinar: Vienna Motor Symposium, Advancing the Research on H2 HPDI

Hydrogen Combustion Concepts: Comparison of Port Fuel Injection with Spark Ignition and High Pressure Direct Injection (HPDI™)

Power Density, Efficiency and Emissions

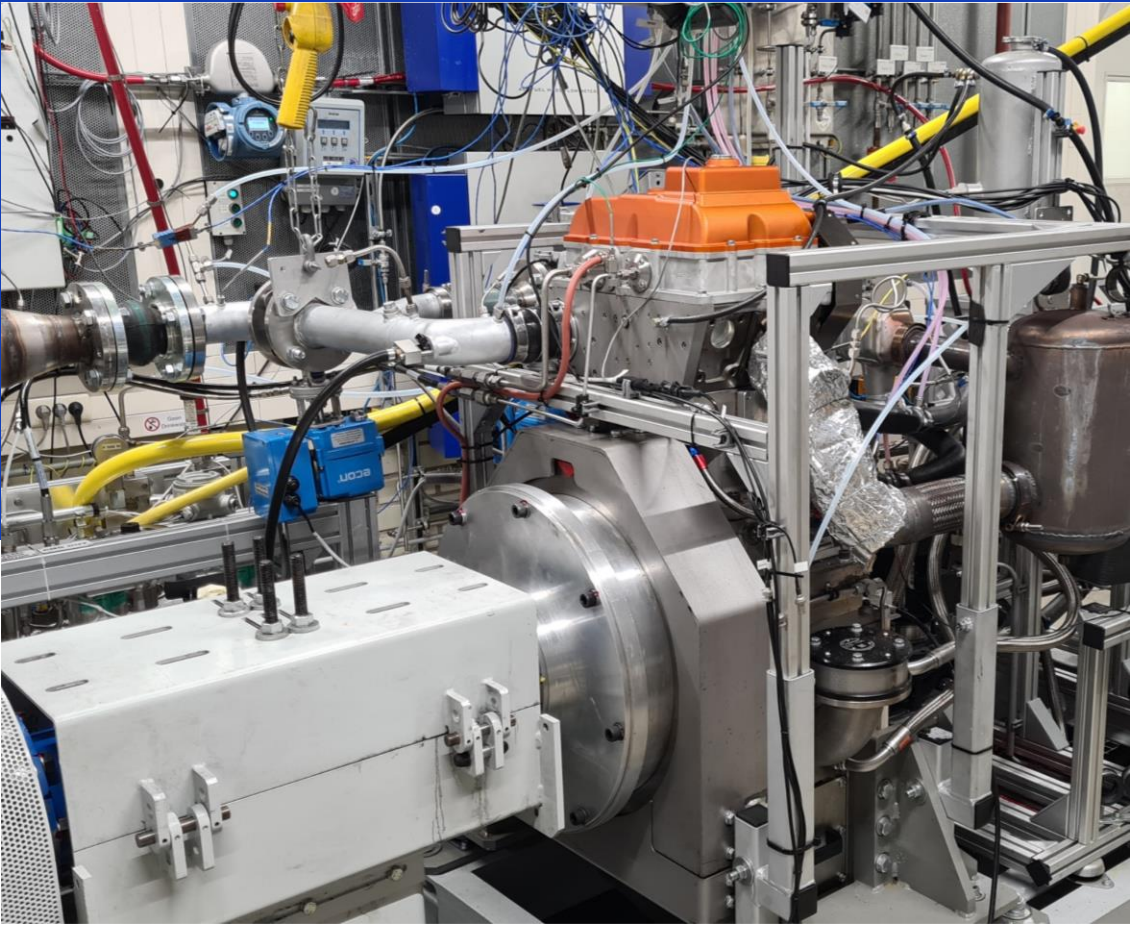
Xander Seykens, Erik Doosje, Cemil Bekdemir, Peter van Gompel
| June 6th 2023, Helmond, The Netherlands



Positioning of TNO paper

- Paper targets to present a fair comparison between two different combustion concepts for H2-ICE
 - Lean burn Spark Ignited (SI) concept with port fuel hydrogen injection (PFI)
 - Westport Fuel Systems HPDI concept (HPDI™)
- Both concepts investigated using one and the same base single-cylinder heavy duty engine
- Considering key performance indicators: power density, efficiency and NOx emissions
- Unique data: No such data available in literature

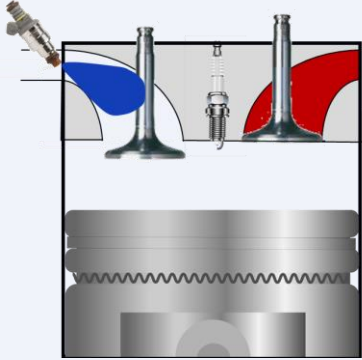
Agenda



- Single-cylinder setup & H2-ICE concepts: PFI SI and HPDI™
- PFI SI results overview
- HPDI™ results overview
- Comparison PFI SI and HPDI
- Summarizing conclusions

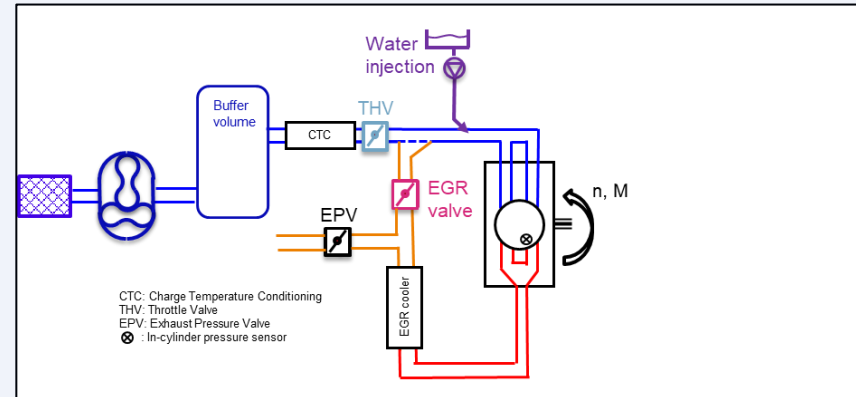
PFI SI and HPDI on same base 1-cylinder engine

PFI SI



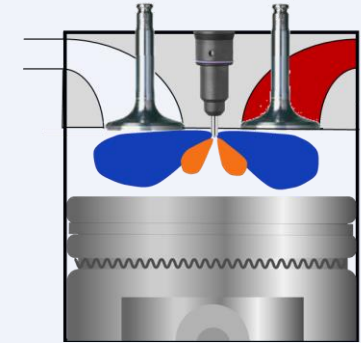
Fuel	hydrogen
Combustion mode	Premixed, flame propagation
fuel injection system	Port Fuel Injection into intake runners, pressure max.10 bar
H2 Ignition	Spark Ignited
Piston, Compression Ratio (CR)	CR 10 – 12.5 

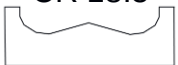
Single-cylinder research setup



Swept volume	1.8 L
Charging system	External compressor, max. boost pressure 4.5 barA, intake throttle
EGR system	High pressure, cooled EGR
Max. p_{cyl}	230 bar
Charge Temp. Cond.	Variable charge temperature [15 – 70 °C] Port Water injection

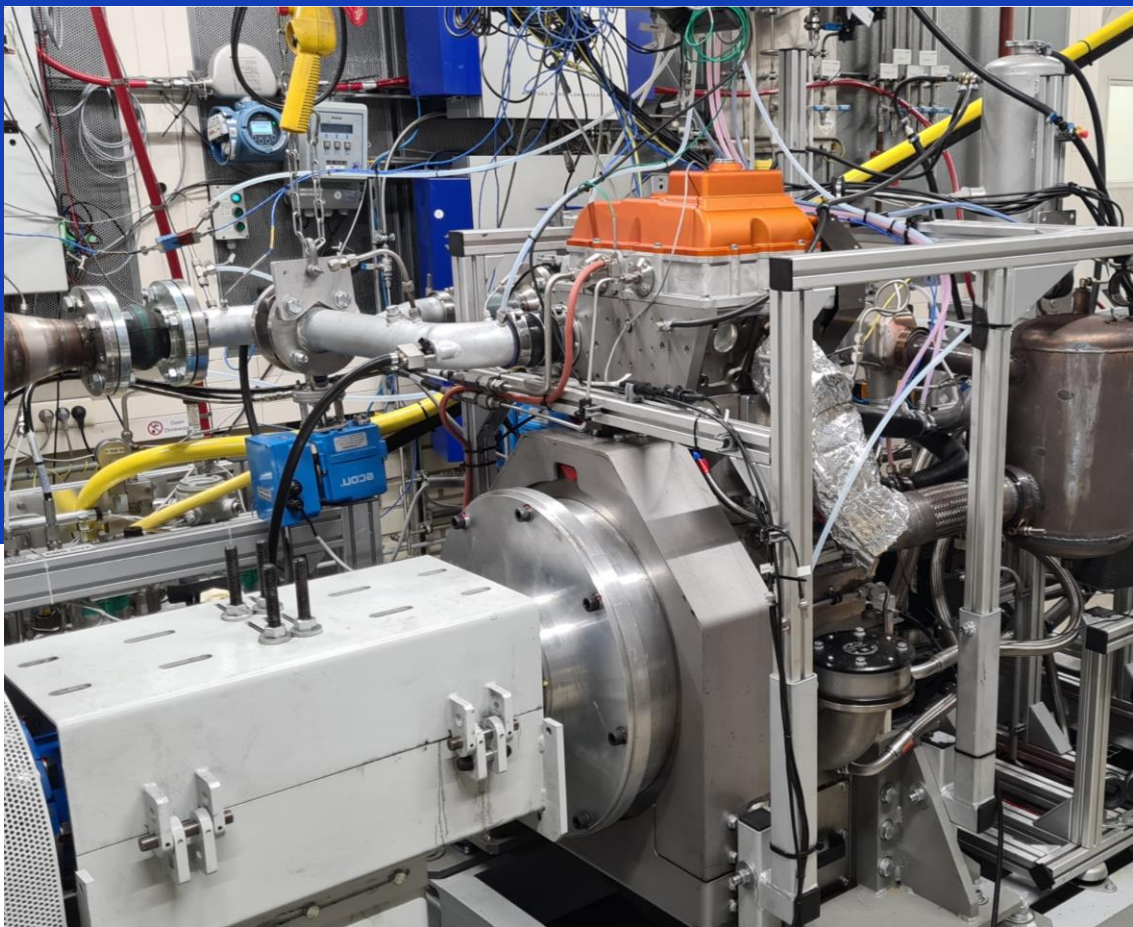
HPDI



Fuel	Hydrogen, pilot fuel
Combustion mode	Mixing-controlled
fuel injection system	DI fueling, max. 350 bar injection pressure
H2 Ignition	CI, initiated by pilot fuel (3% energy share)
Piston, Compression Ratio (CR)	CR 18.5 

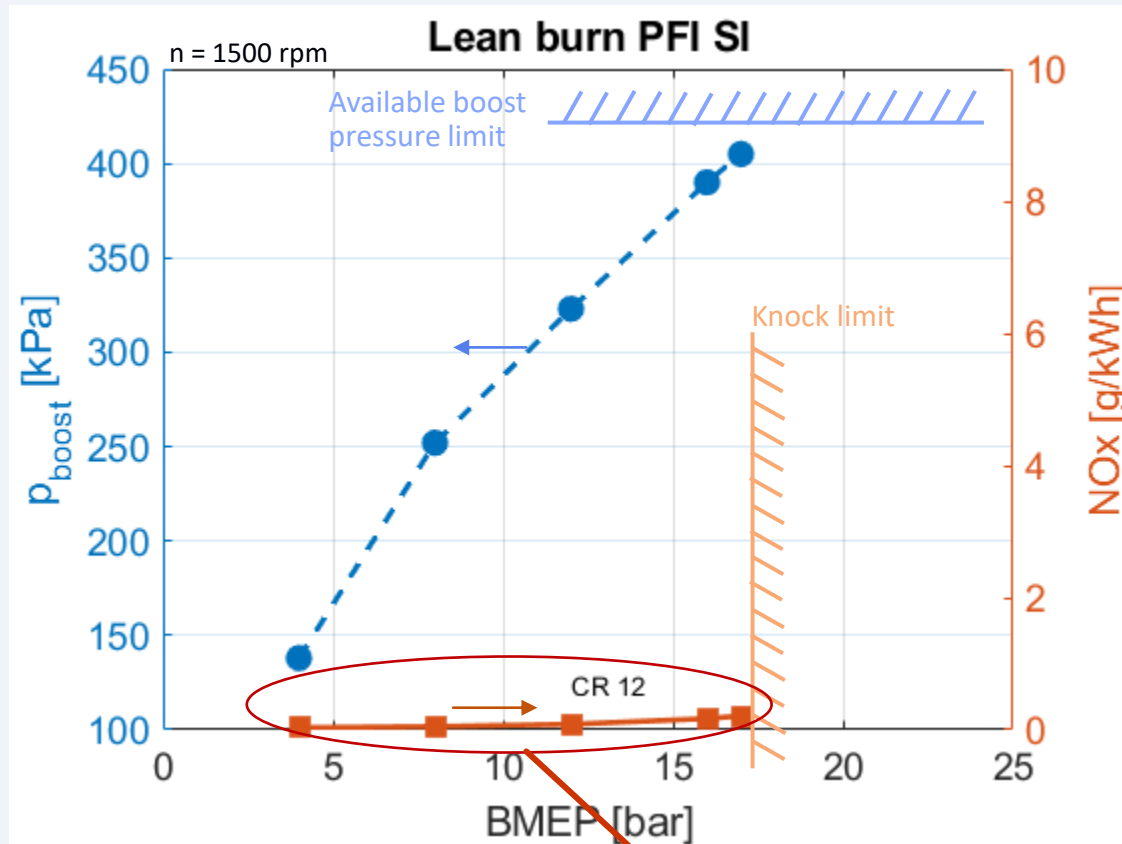
- All measurements performed at an engine speed of 1500 rpm (typical for fixed speed power generation applications)
- All measurements without EGR

Agenda



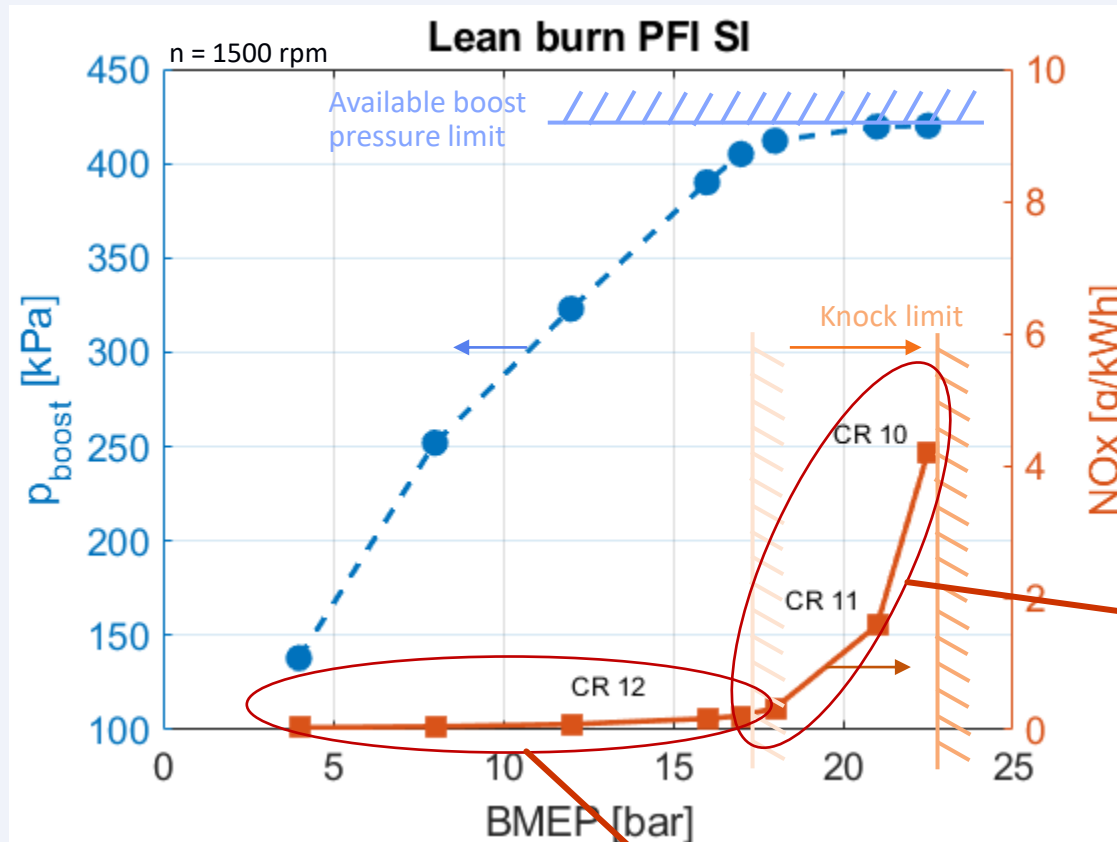
- Single-cylinder setup & H₂-ICE concepts: PFI SI and HPDI™
- **PFI SI results overview**
- HPDI™ results overview
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PFI SI: Low NOx potential



(Ultra-)low NOx (NOx < 0.2 g/kWh) potential demonstrated up to load of 17 bar BMEP (knock limit & boost pressure limit)

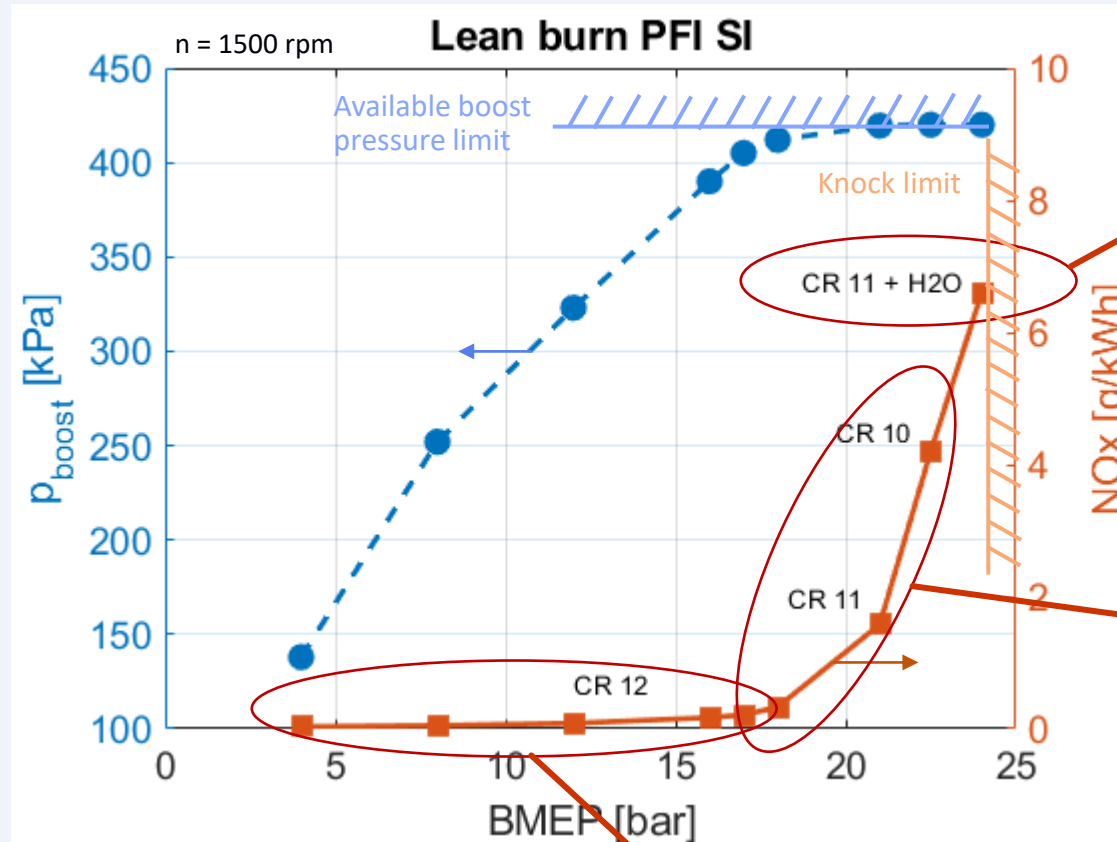
PFI SI: reduction CR for load range extension



Reducing the compression ratio is effective for increasing power density (21 bar BMEP), but comes at the cost of higher engine-out NOx and reduced efficiency

(Ultra-)low NOx (NOx < 0.2 g/kWh) potential demonstrated up to load of 17 bar BMEP (knock limit & boost pressure limit)

Power density increase: CR reduction & water injection

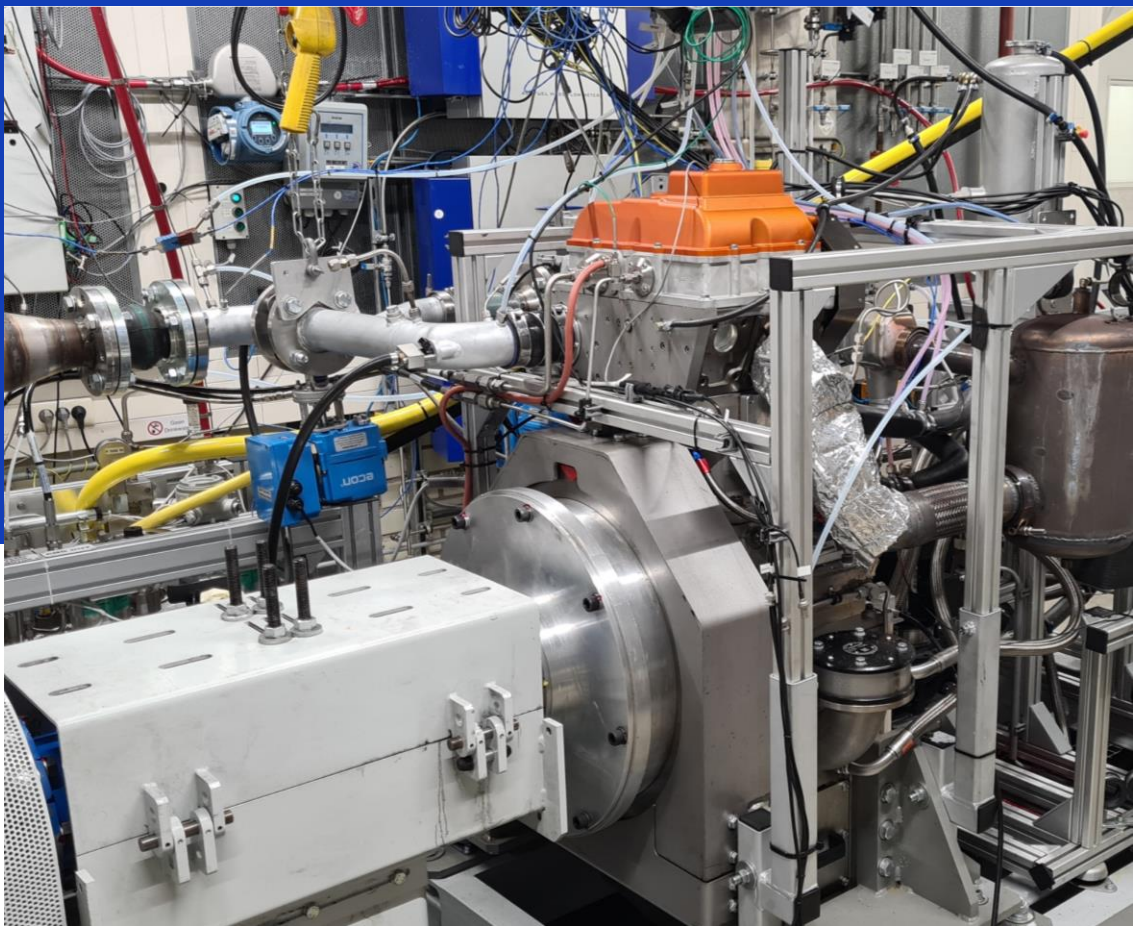


Injection of water into the intake manifold reduces combustion temperatures resulting in lower knock tendency enabling higher power density (24 bar BMEP), but at the expense of higher engine-out NOx

Reducing the compression ratio is effective for increasing power density (21 bar BMEP), but comes at the cost of higher engine-out NOx and reduced efficiency

(Ultra-)low NOx (NOx < 0.2 g/kWh) potential demonstrated up to load of 17 bar BMEP (knock limit & boost pressure limit)

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HPDI single-cylinder measurements

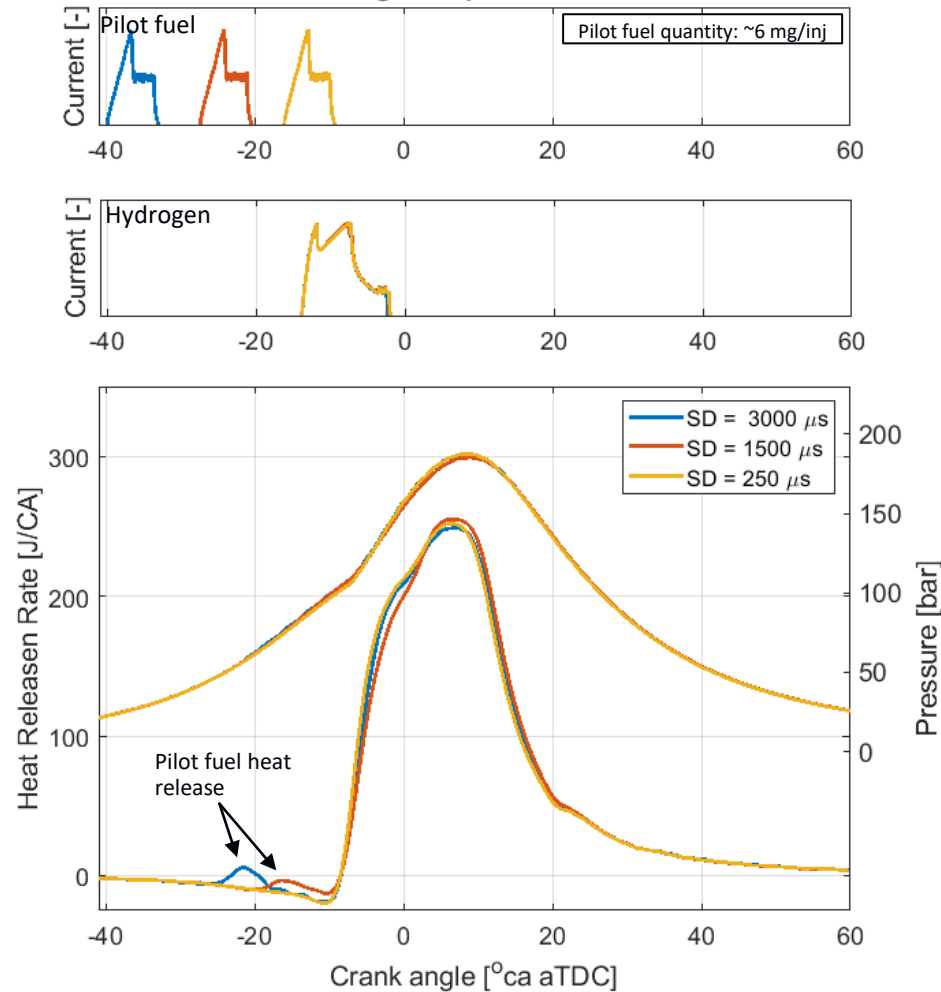
- **Identify** HPDI combustion characteristics and **quantity efficiency, power density** and **engine-out NOx**:
 - Variation of pilot fuel injection timing relative to main hydrogen injection (“separation duration”)
 - Variation of fuel injection pressure
 - Variation in intake manifold pressure (boost pressure), i.e. air-excess ratio λ
 - Variation in hydrogen injection timing

And compare these KPI's with lean burn PFI SI results

Pilot-Main Separation Duration (SD*) variation

Pilot fuel injection timing variation

Phasing sweep, 16 bar BMEP

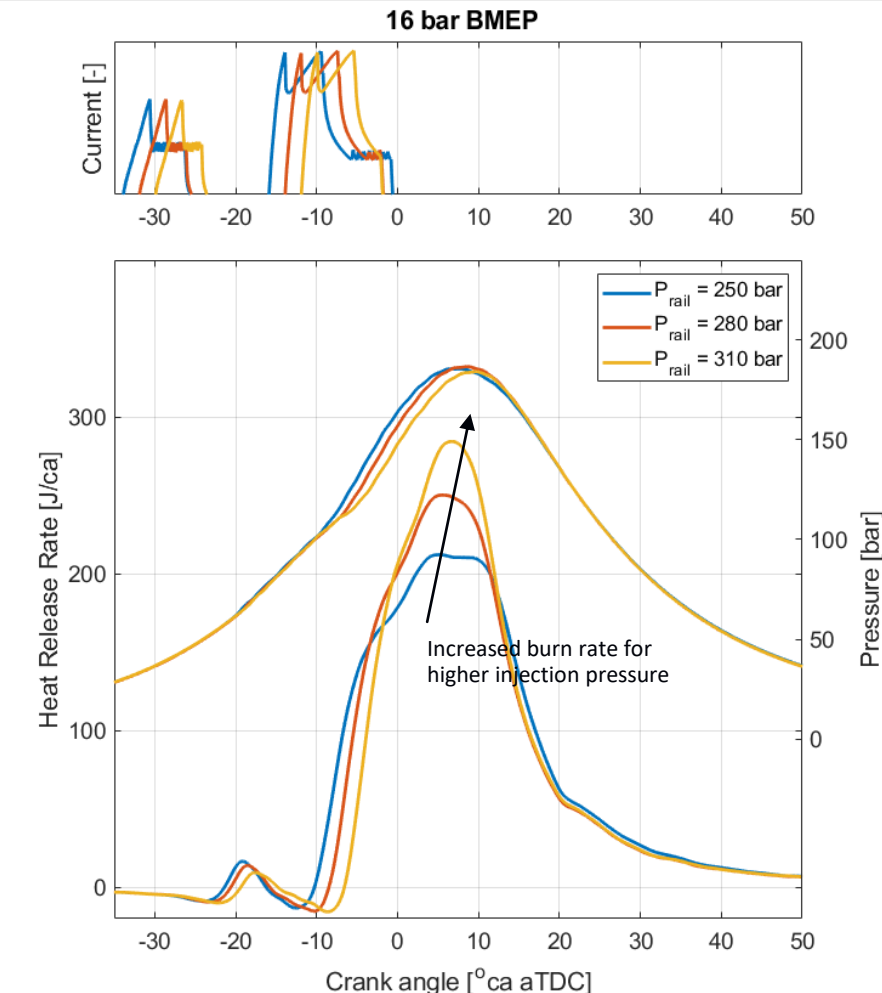


- Hydrogen combustion not significantly affected by pilot fuel injection timing
- Efficiency determined by hydrogen injection timing
- Potential for reducing pilot fuel quantity

*SD = Time between Start current pilot and start current main

Injection pressure variation: fixed combustion phasing

Injection pressure variation

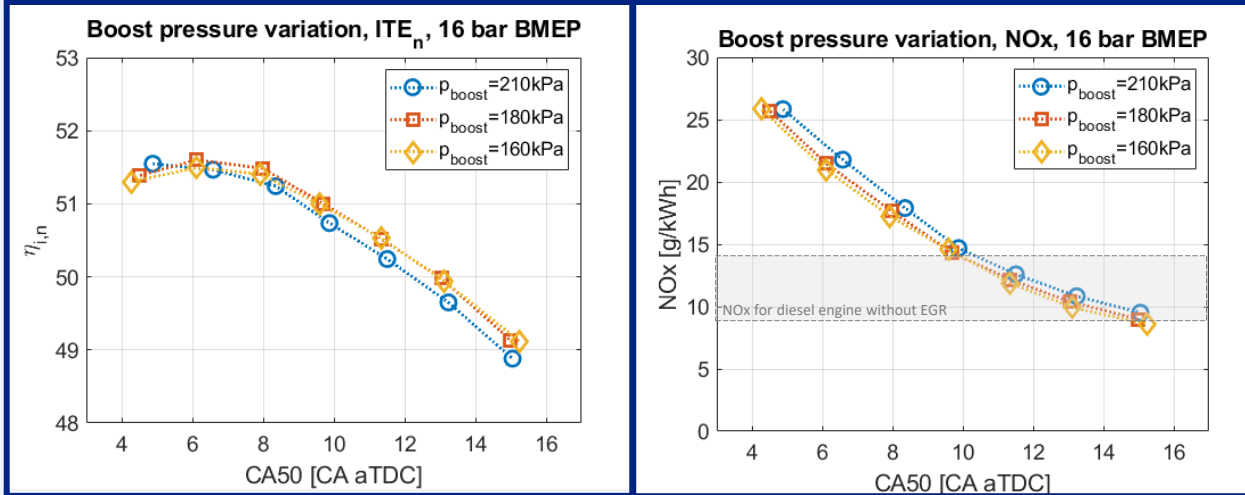


- Net indicated efficiency and NOx emissions close to identical for different injection pressures at same combustion phasing
- **Potential for reducing injection pressure** without loss in efficiency and with limited impact on engine-out NOx emissions.

Injection pressure [bar]	250	280	310
CA50 [CA aTDC]	8.2	7.9	8.3
ITEn [%]	51.3	51.4	51.3
NOx [g/kWh]	16.7	17.2	15.9
$P_{\text{cyl,max}}$ [bar]	185.7	186.7	184.2

Variation of main injection timing at different λ

λ variation by boost pressure variation



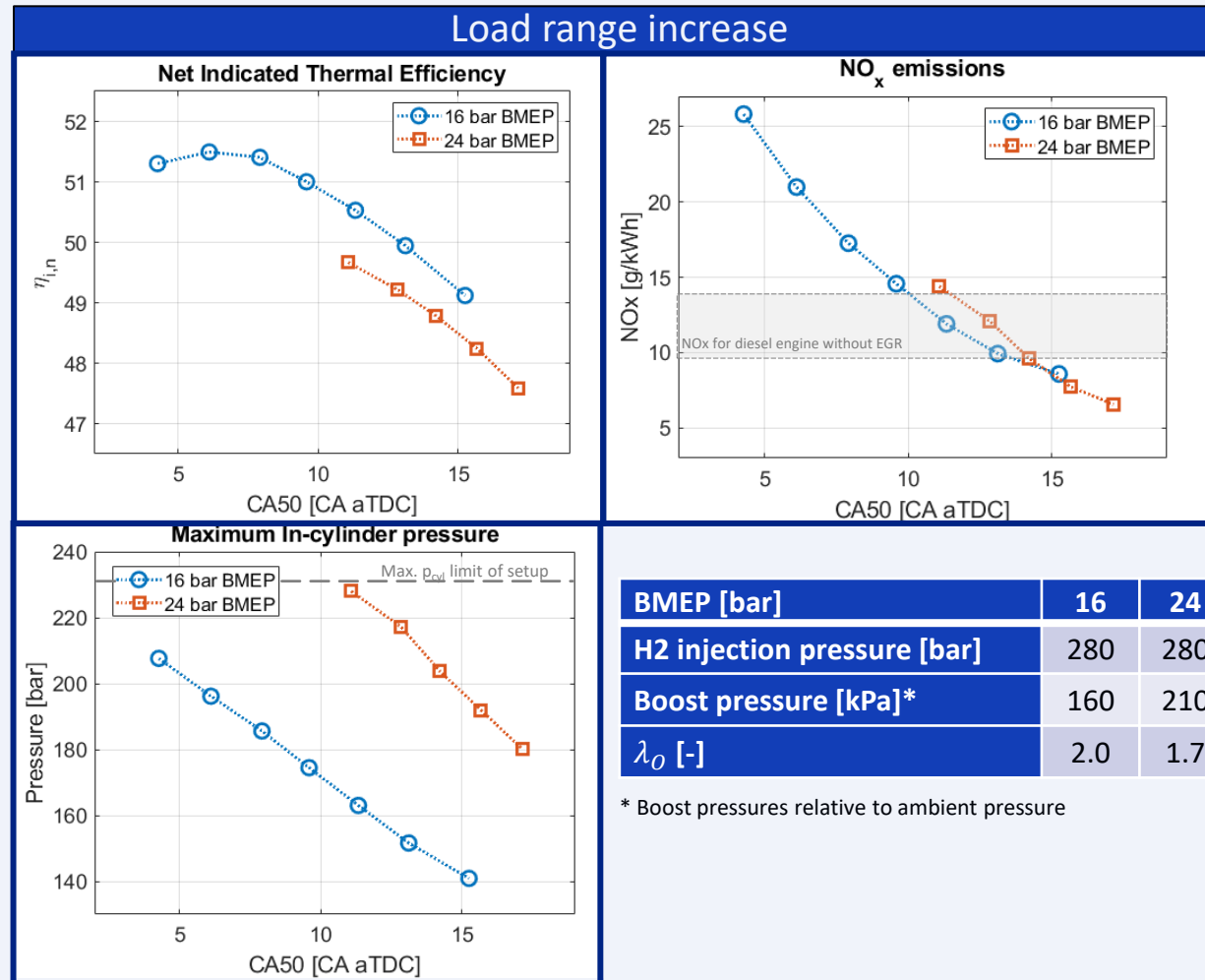
- Efficiency and NO_x mainly determined by H₂ injection timing. Little impact of λ . Potential for reduction of boost pressure.
- Max. efficiency > 51.5%
- High efficiency (> 50%) at engine-out NO_x levels within diesel engine range.

Overview of results for fixed CA50 (~8 ca aTDC):

Boost pressure [kPa]*	160	180	210
λ_o [-]	2.0	2.2	2.6
CA50 [CA aTDC]	7.9	8.0	8.4
NO _x [g/kWh]	17.3	17.6	17.9
ITE _n [%]	51.4	51.5	51.2
P _{cyl,max} [bar]	186.7	193.6	203.3
T exhaust gas [°C]	447	420	385

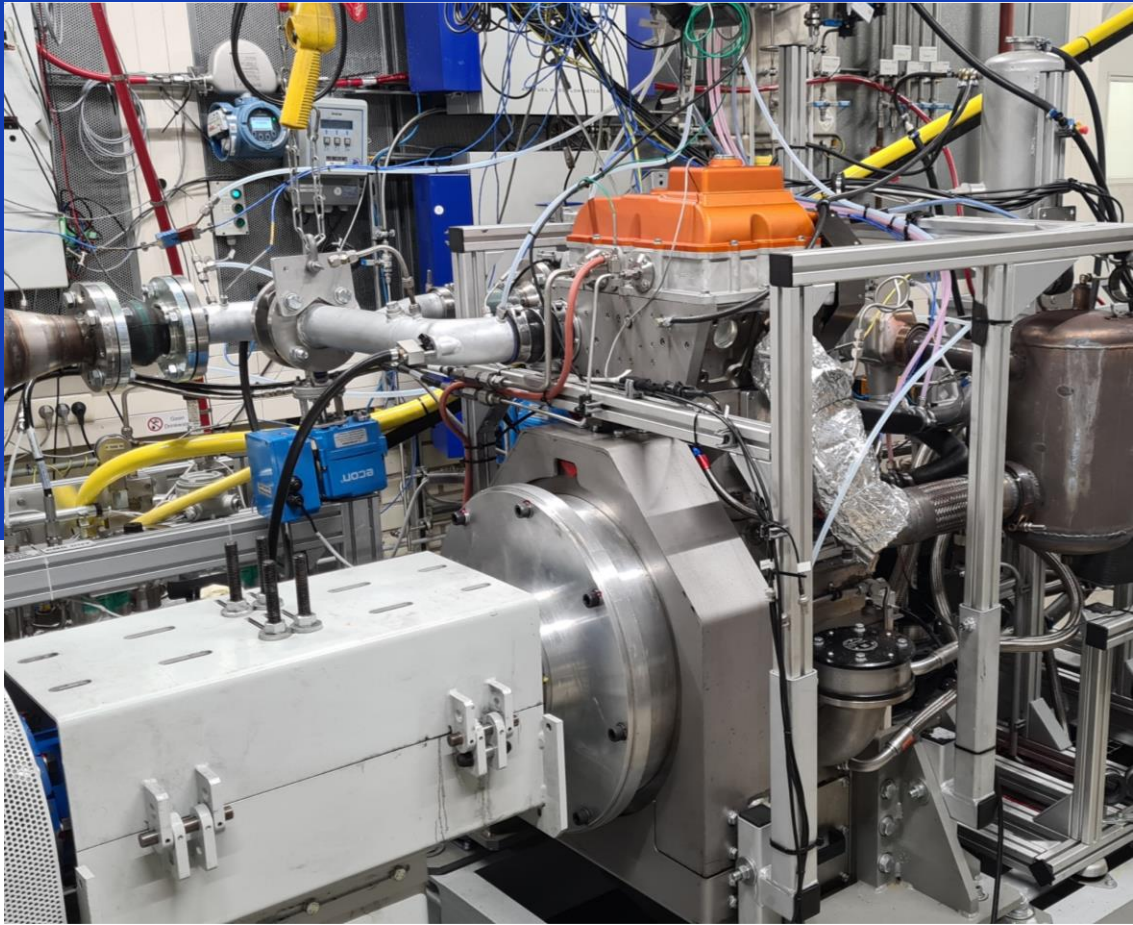
* Boost pressures relative to ambient pressure

Injection timing variation at 16 bar & 24 bar BMEP



- 24 bar BMEP realized by use of conventional boost pressure level, i.e. conventional turbocharger requirements
- At 24 bar BMEP, realization of full efficiency potential limited by:
 - acceptable engine-out NO_x (similar to diesel)
 - $p_{cyl,max}$ setup constraint
- At 24 bar BMEP & diesel-like NO_x level the observed efficiency is competitive to diesel engine efficiency
- Developments in aftertreatment technology support realizing full efficiency potential

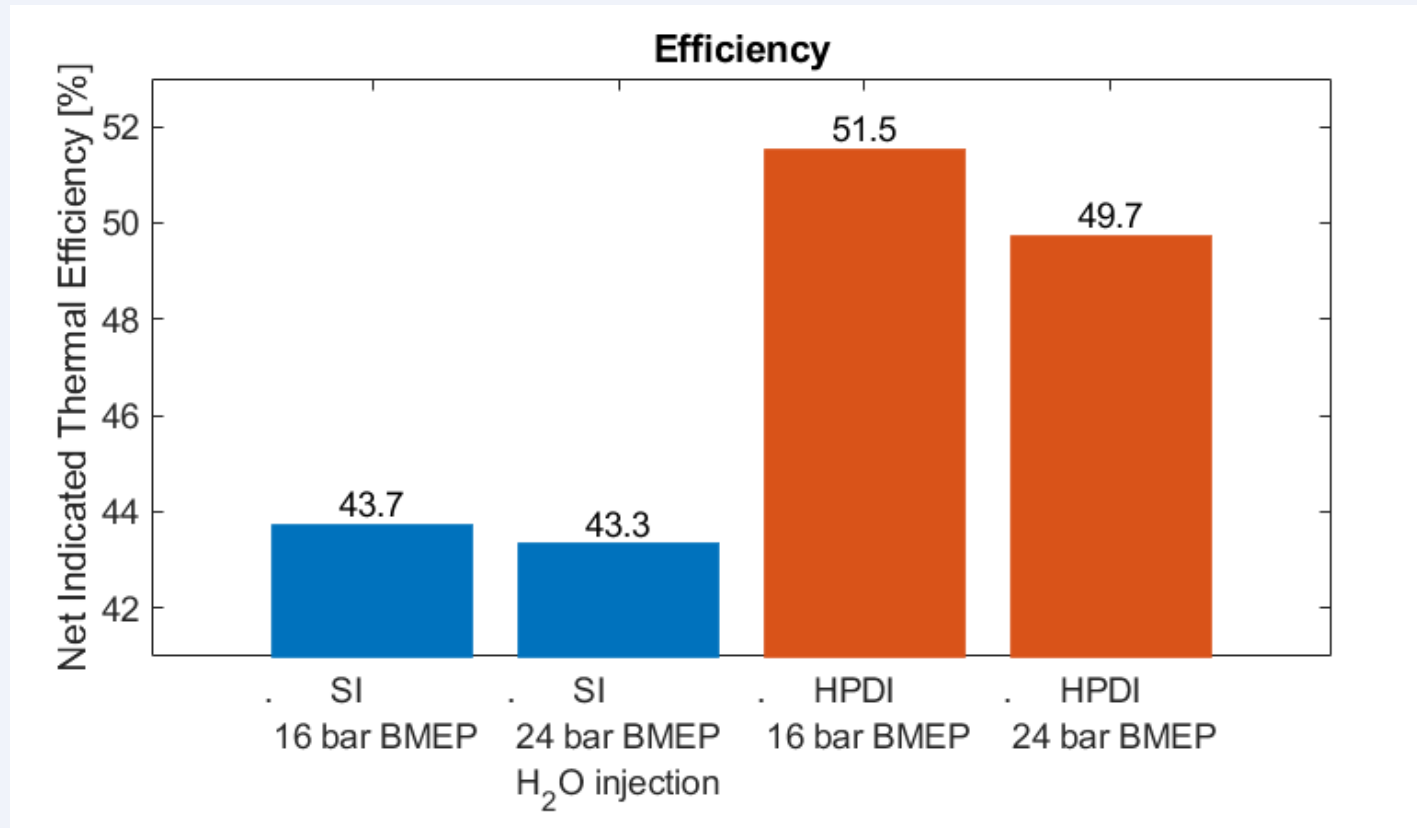
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Comparison PFI SI & HPDI™

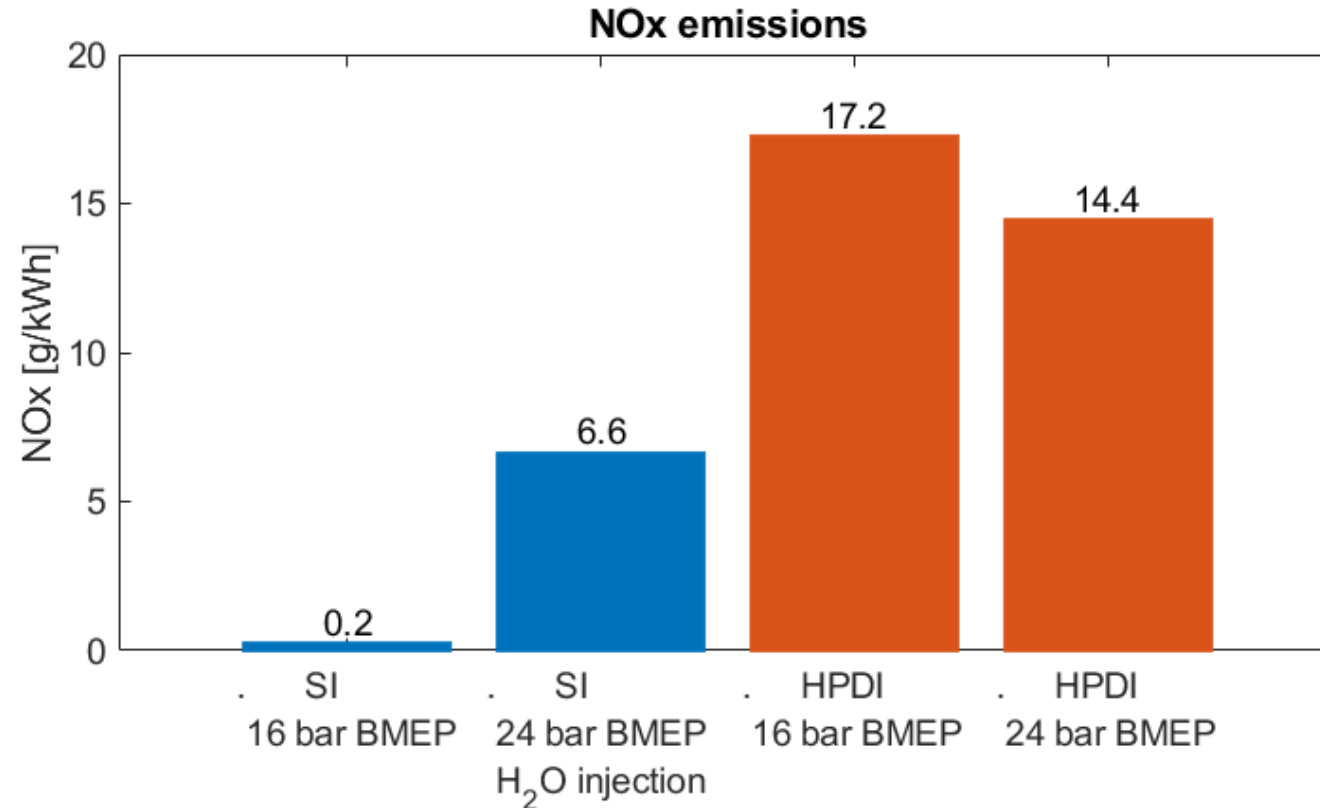
1500 rpm



- When targeting max. efficiency, the efficiency for HPDI is 7 – 8 %-point higher efficiency than PFI SI
- HPDI with diesel-like engine-out NO_x, has 6 – 7 %-point higher efficiency than PFI SI.

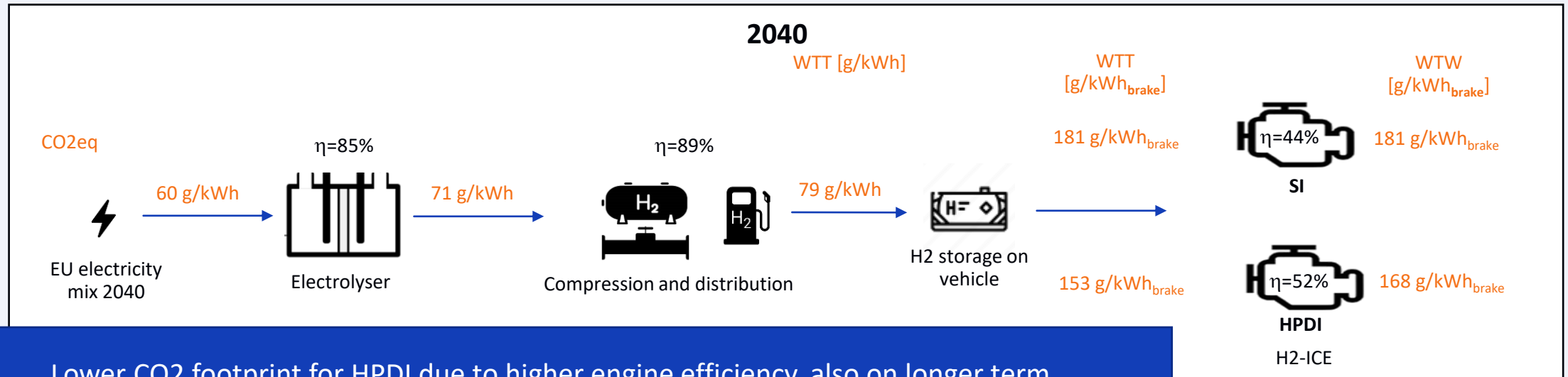
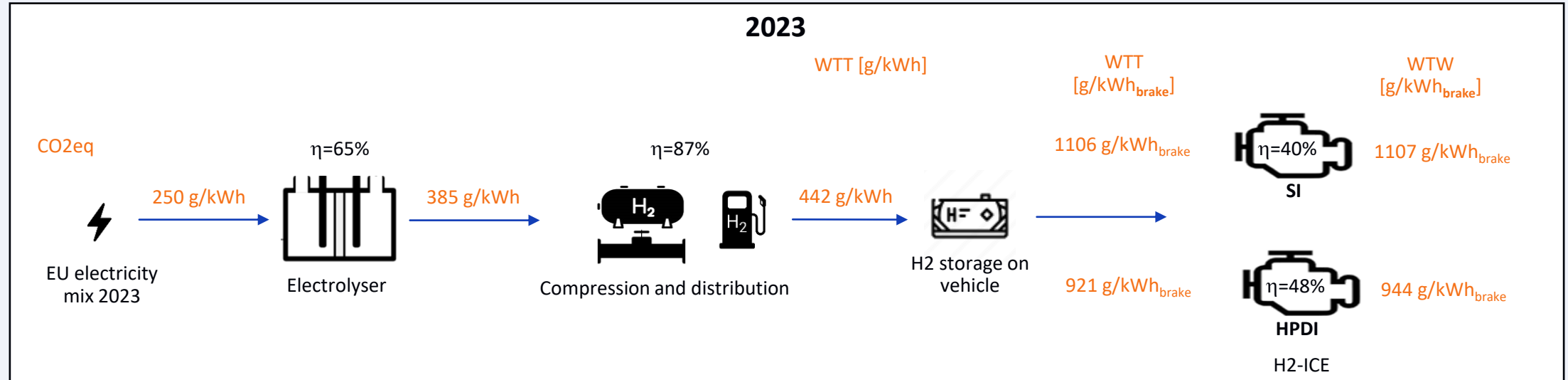
Comparison PFI SI & HPDI™

1500 rpm



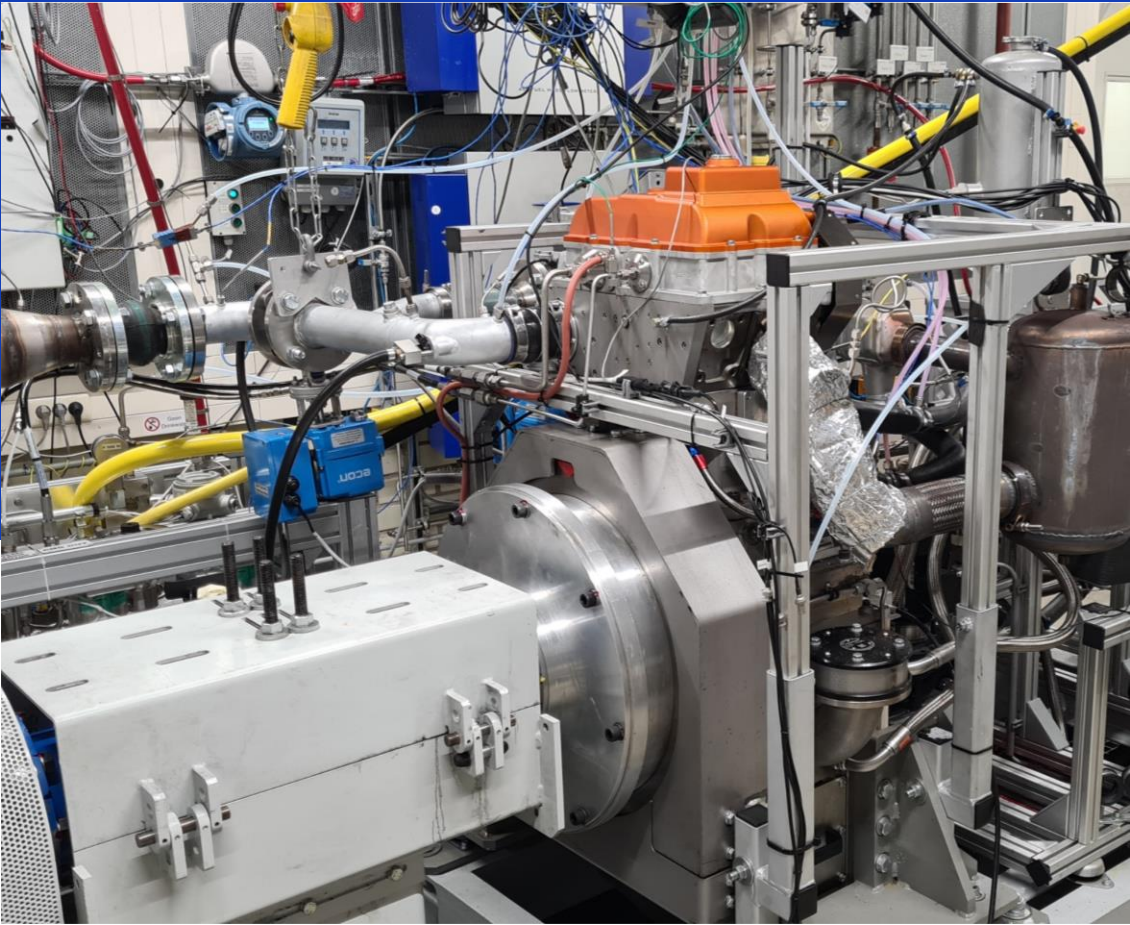
- PFI SI: (Ultra-) low NOx potential of PFI SI for medium to medium/high load.
- HPDI: High engine-out NOx when targeting maximum efficiency; Diesel-like NOx realized at the expense of slightly reduced efficiency (but still within diesel-range)

WTT and WTW CO2 footprint for PFI SI and HPDI



Lower CO2 footprint for HPDI due to higher engine efficiency, also on longer term

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Summarizing conclusions

- PFI SI and HPDI TM combustion concept evaluated on same base single-cylinder research setup
- Efficiency:
 - HPDI has ~7 – 8 %-point higher efficiency potential than PFI SI. Using retarded combustion phasing for acceptable NO_x results in 6 – 7 %-point higher efficiency than PFI SI.
- Engine-out NO_x:
 - PFI SI: low NO_x potential for medium to high load;
 - HPDI: conventional CI engine-like NO_x and efficiency for retarded combustion phasing
- Power density:
 - PFI SI: 24 bar BMEP realized with high boost and water injection (additional system complexity)
 - HPDI: 24 bar BMEP possible with use conventional charging and with base CI engine piston; Potential for higher power density when the allowable max. in-cylinder pressure of the setup is increased.
- CO₂ footprint
 - Considering EU electricity mix, HPDI has lower WTT and WTW CO₂ footprint than PFI SI engine, also on longer term



Thank you for your attention

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for life

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Q&A



Thank You

