Driving Cleaner Performance

Westport Fuel Systems

H_2 HPDI Webinar:
Vienna Motor Symposium, Advancing the Research on H_2 HPDI
June 6, 2023

Agenda

1

Welcome and housekeeping items

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

2

Application of Westport's H_2 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 H_2-ICE

Regulation

Positive momentum in the recognition of H_2-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 H_2-ICE builds on Diesel engines.

Supply Chain

Leverages existing supplier, powertrain and vehicle production supply base.

Scania / TRATON:

A view on the H_2 economy and the outlook for H_2 ICEs

SCANIA

Scania: Why H_2 ICE?

- How does TRATON prepare – in a capital efficient way – for a possible scenario where our future customers demand an H_2 energy converter?
- This possible risk diversification/mitigation must be carried out at low cost, in order not to jeopardize TRATON's main route to CO_2 neutral road transports of heavy goods, i.e. the BEV
- **This is where the H_2 Internal Combustion Engine fits in**
- H_2 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.
- **H_2 ICE is therefore a capital-efficient way to use H_2**
- H_2 ICE will consequently not cannibalize the resources allocated to BEV. Simultaneously it will make TRATON prepared for a possible future scenario where H_2 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, CH_4 and H_2 engines will therefore be important in the future

- **Only one engine platform is needed to be able to handle all fuels i.e. diesel, H_2 and CH_4**
  - 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 H_2 society
  - Will it happen?
- Risky to invest in only one of the two available renewable energy carriers, i.e. electricity and hydrogen
  - Must meet CO_2 emission reductions. 45% 2030, 65% 2035 and 90% 2040
- **H_2 ICE is a cost-effective way to acquire an H_2 energy converter**
- HPDI provides the opportunity to
  - High Torque and Power Density
  - Very good efficiency, both WtT and TtW, in relation to competitive H_2 Technologies
  - Extreme Commonality for Diesel, H_2 and CH_4 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 H_2 HPDI™ Fuel System to a Demonstration Truck

Westport Fuel Systems

Westport – An Overview of the Vienna Paper

SCANIA

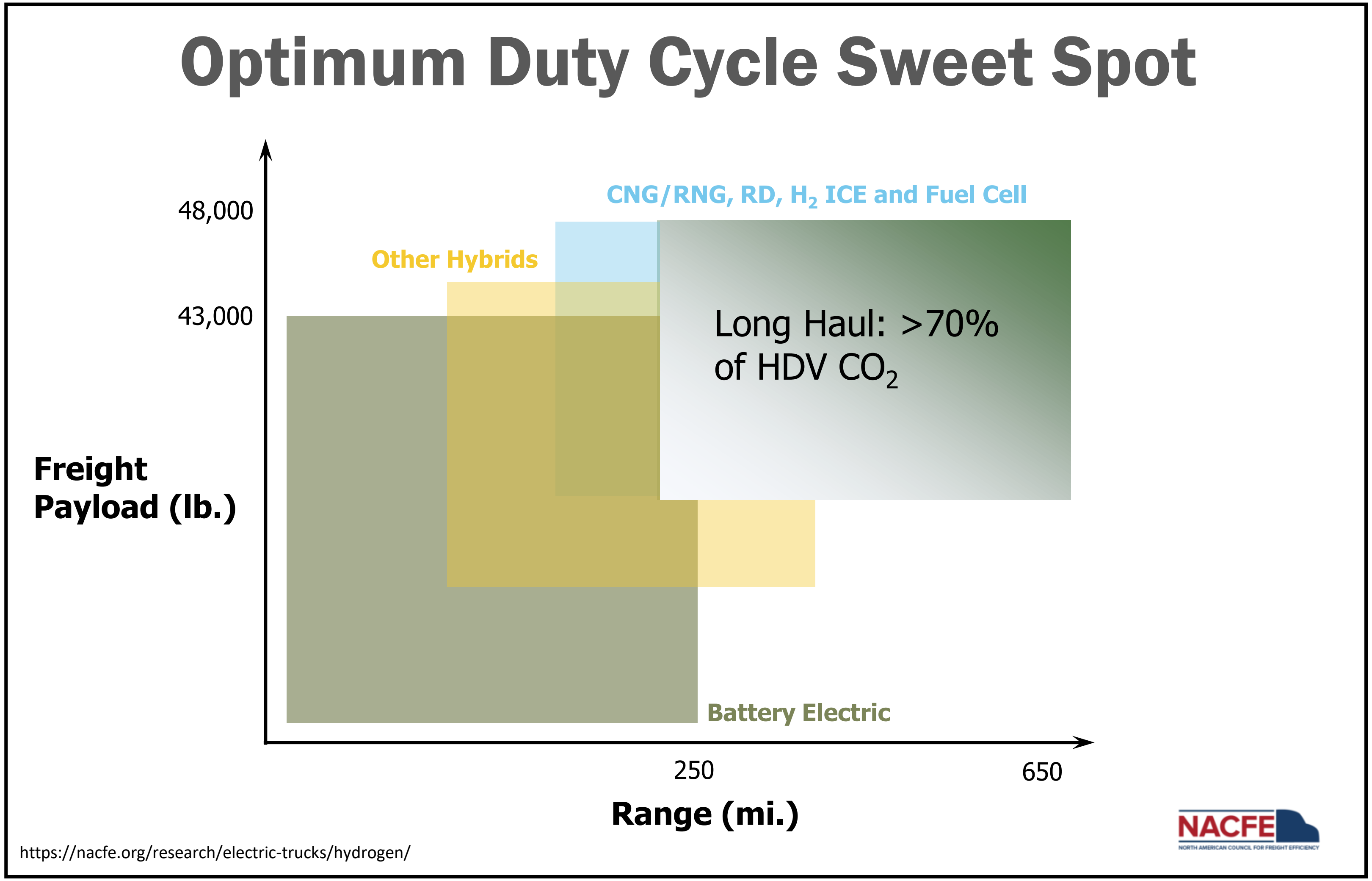
GHG Reduction: The Role for H_2 ICEs

Multiple solutions for decarbonizing transportation:

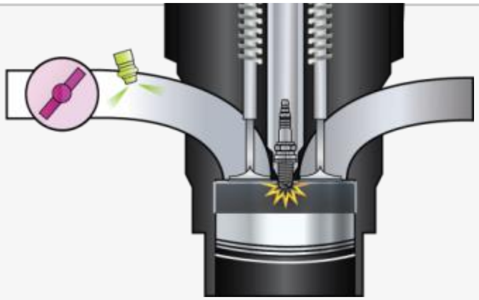
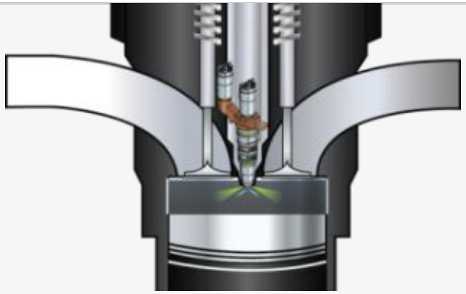
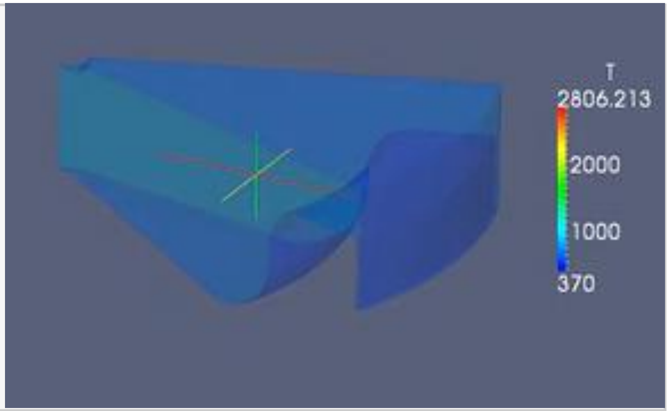
- BEVs
- FCEVs
- H_2 ICEs
- Hybrids

NACFE Study:

- BEVs & hybrids - short haul
- FCEVs & H_2 ICEs - long haul

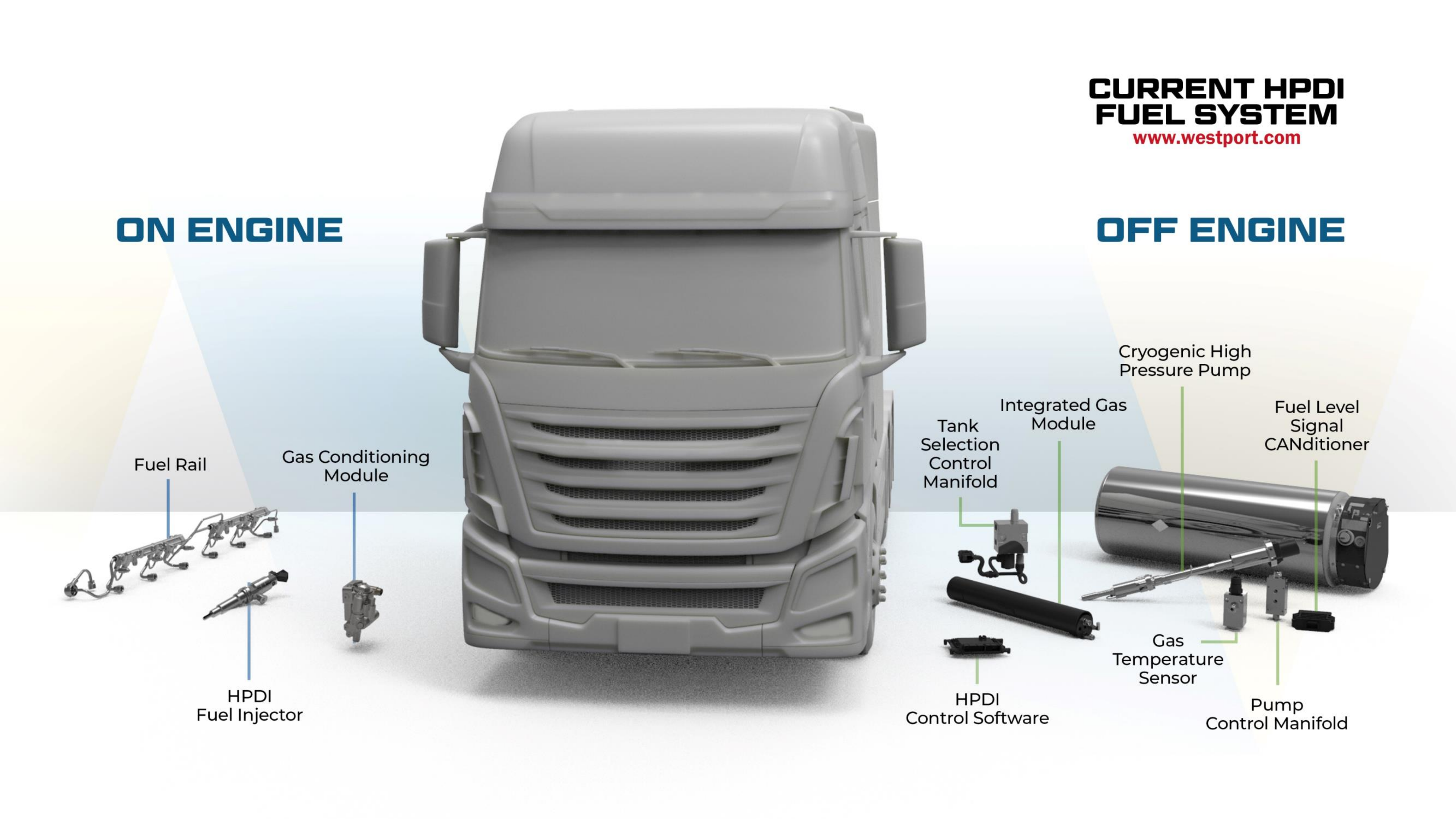


NG / H_2 ICE Technologies

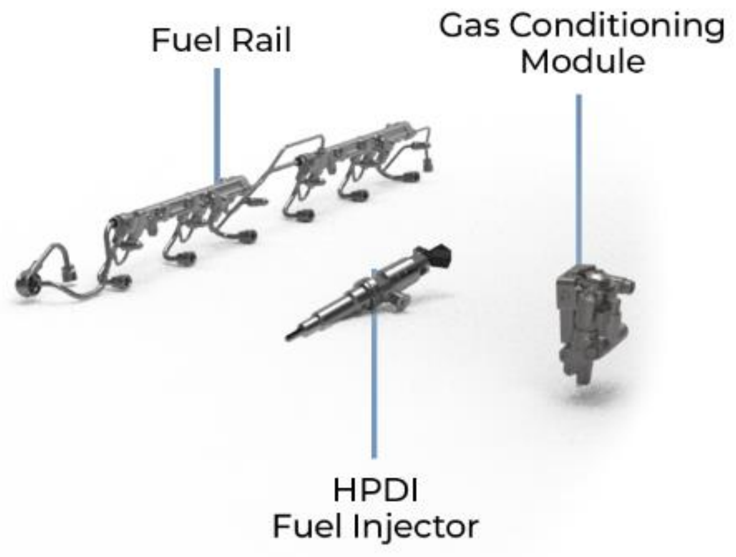
	 **Spark Ignited**	  **Compression Ignition**
How it works	• Fuel & air pre-mixed at low pressure • Dedicated natural gas (100%) • Ignition from spark plug • Reduced compression ratio to avoid knock • Simple 3-way catalyst • Otto cycle (Stoichiometric) • **Power / torque / efficiency typically lower than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

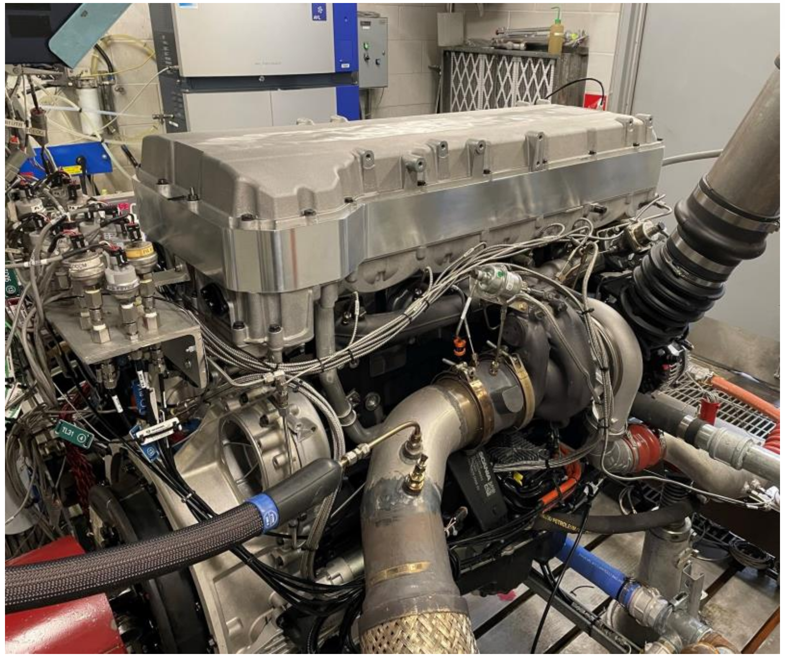
- Westport's **HPDI™** fuel system was conceptualized ~30 years ago with the goal of creating a more efficient natural gas engine.
- The "heart" of the system is a **unique fuel injector** which features a small pilot injection and a larger primary injection of the main fuel – initially natural gas.
- 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
Fuel Rail
Gas Conditioning Module
HPDI Fuel Injector
Tank Selection Control Manifold
Integrated Gas Module
Cryogenic High Pressure Pump
Fuel Level Signal CANditioner
Gas Temperature Sensor
HPDI Control Software
Pump Control Manifold

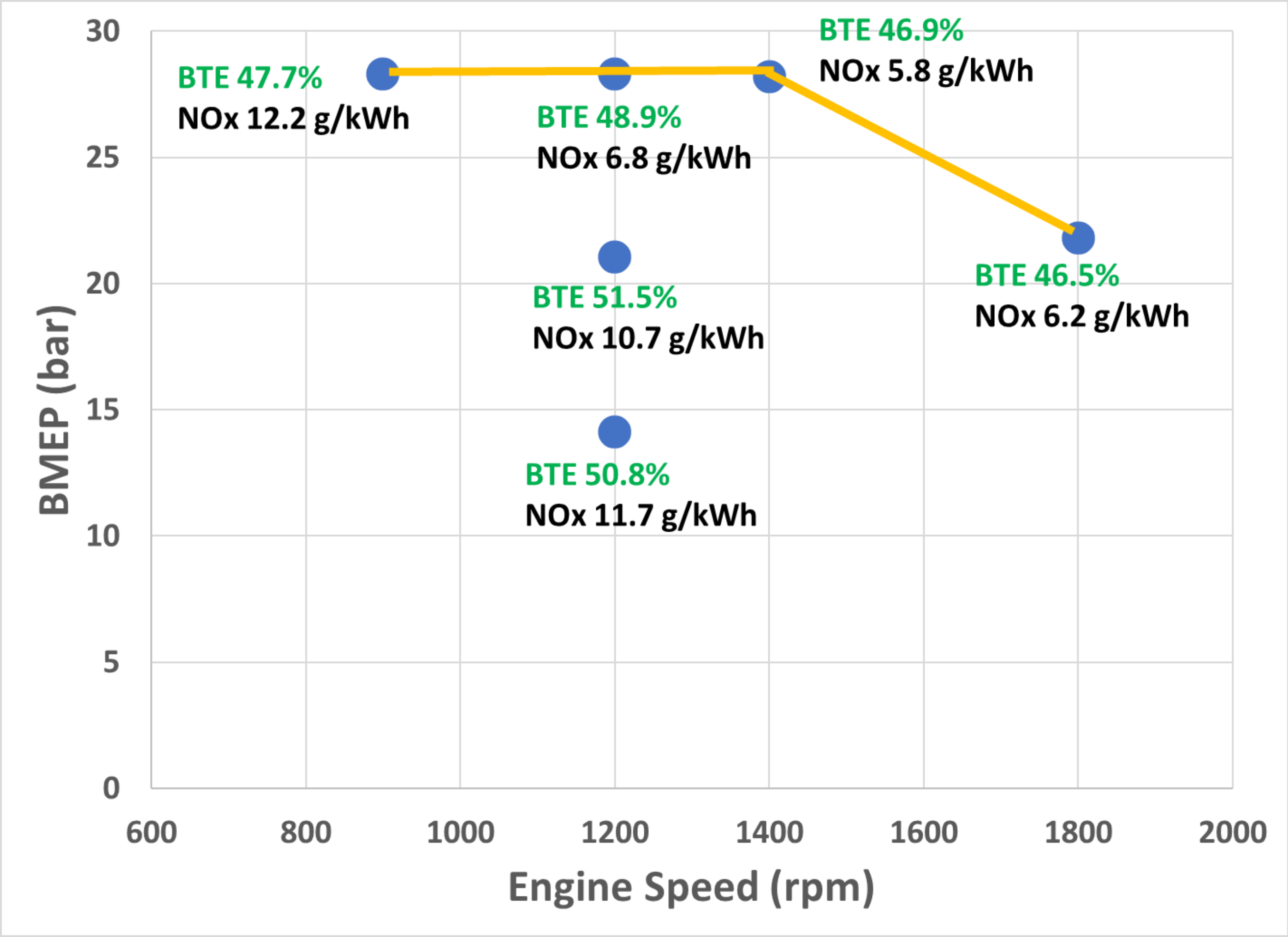
H_2 HPDI Combustion Overview



- 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.

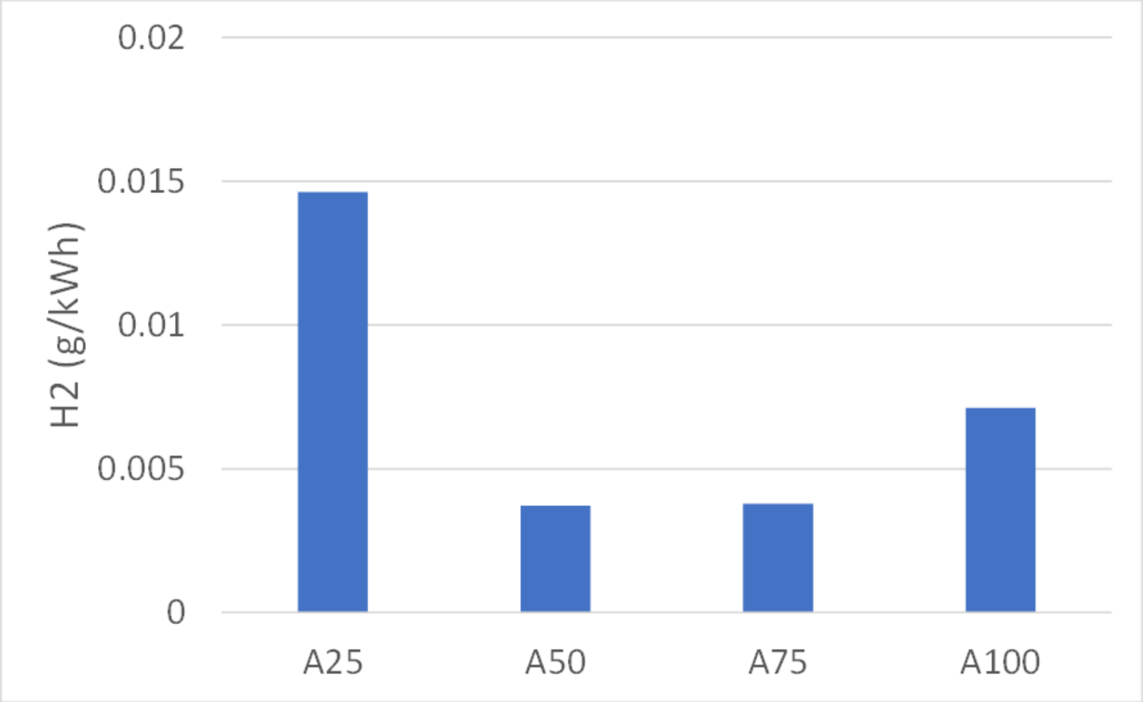


H_2 Combustion on Scania CBE1 Engine

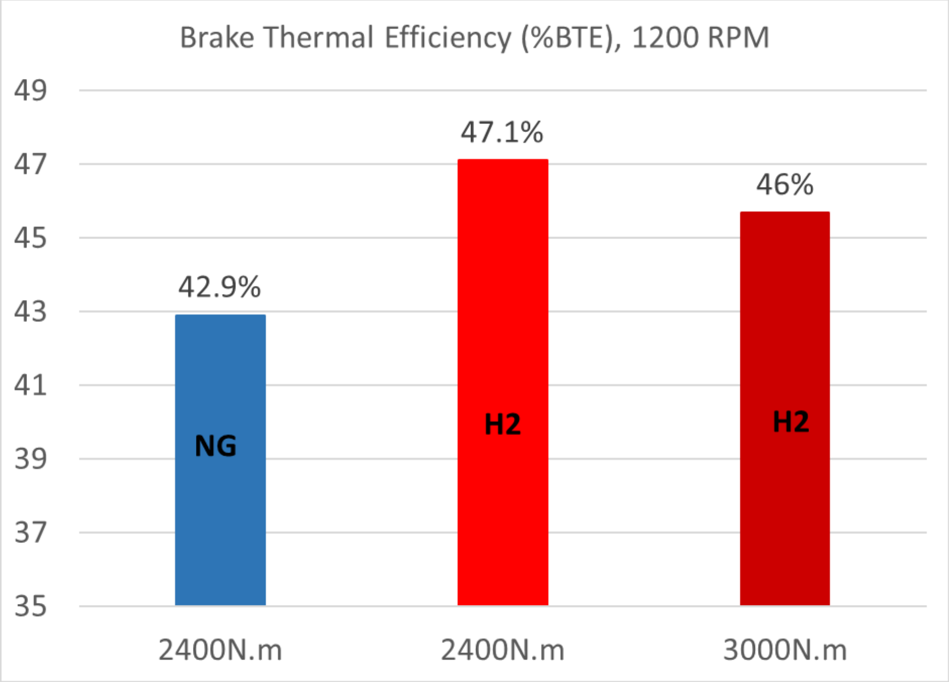


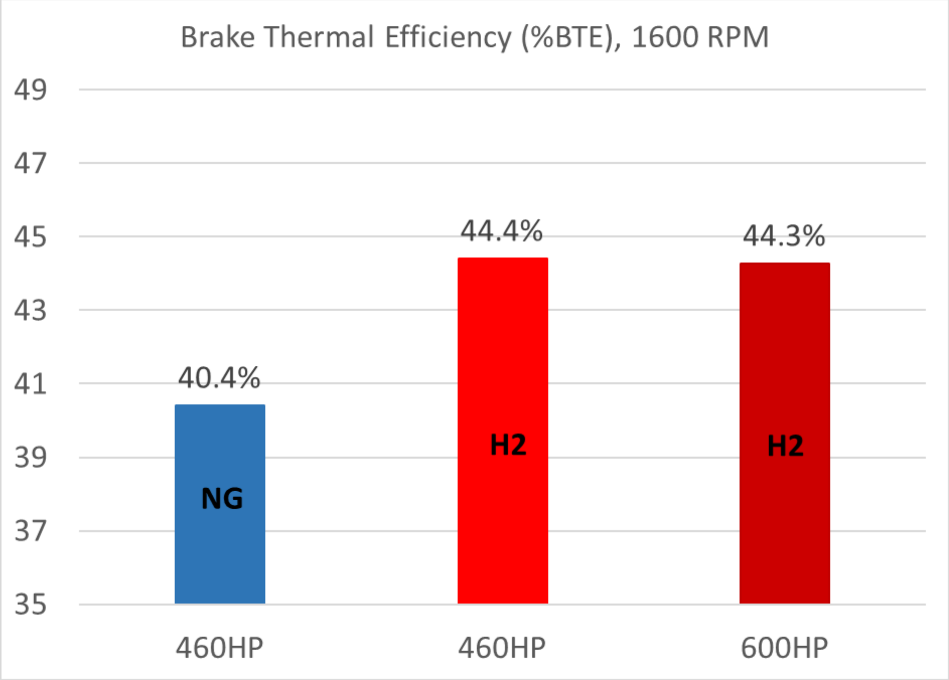
- BTE on torque curve of ~47-49%
- **Peak BTE at 51.5%**
- Engine-out NOx levels calibrated to ~6-12 g/kW.h to reflect EATs strategy
- Note: EGR can be used to reduce NOx further to ~3g/kW.hr
- Pilot quantities as low as 2-3mg have been tested, equating to **near-zero CO_2 emissions**

H_2 HPDI



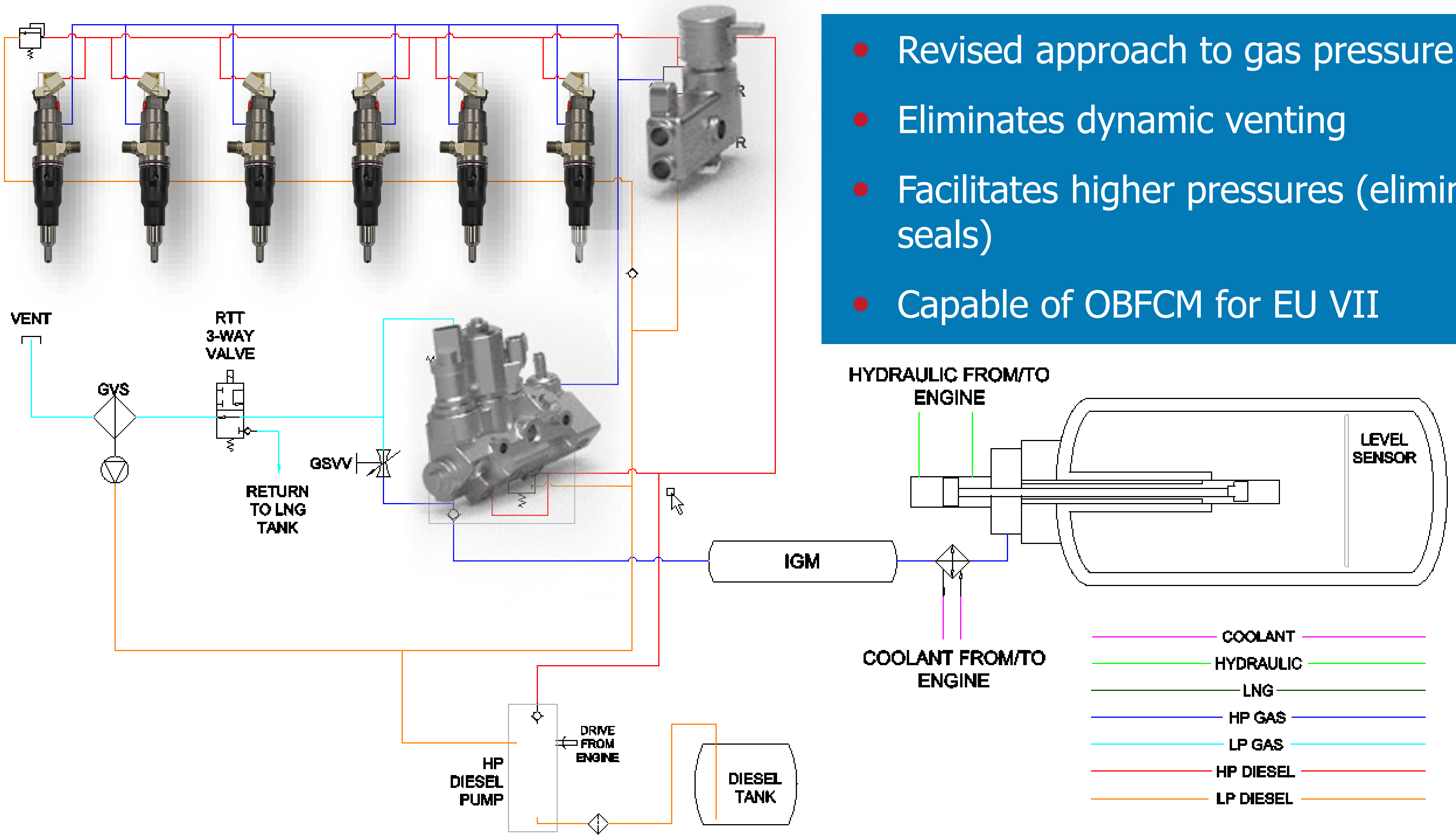
- No measurable slip infers a low risk of H_2 interaction with combustion chamber
- Capable of exceeding base engine power and torque






ON ENGINE
OFF ENGINE
H2
Gas Rail Inlet Injector
& Gas Rail Vent Valve
Fuel Rail
HPDI
Fuel Injector
Diesel Rail Pressure Regulator &
Diesel Minimum Pressure Regulator
LNG
HPDI
Control Software
Integrated Gas Module
NEXT GENERATION
HPDI FUEL SYSTEM
www.westport.com

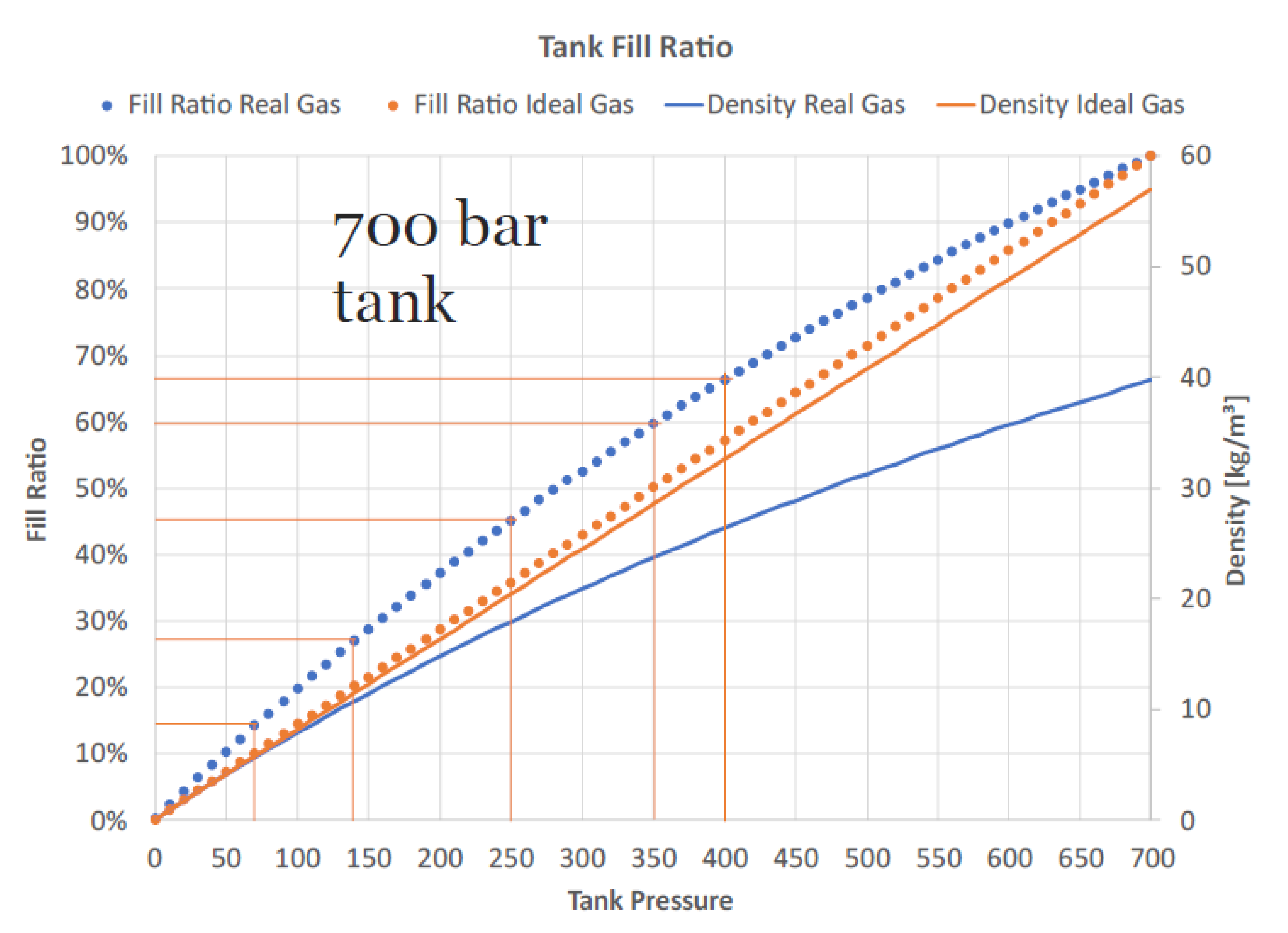
Next Generation Fuel System Architecture (LNG Shown)



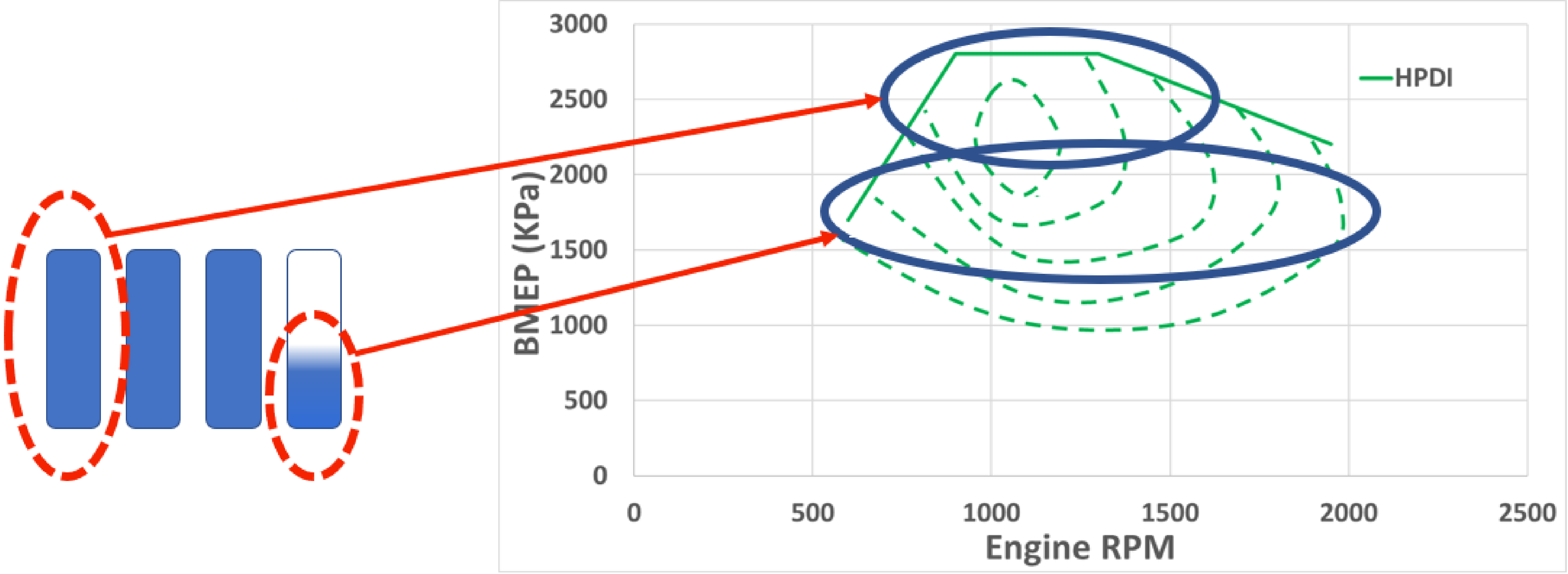
- Revised approach to gas pressure control
- Eliminates dynamic venting
- Facilitates higher pressures (eliminates non-metallic seals)
- Capable of OBFCM for EU VII

H_2 Fuel System Off Engine Approach

- Target for onboard fuel is 80kg – equates to ~2050-litres of storage
  - Note: H_2 does not follow ideal gas law at higher pressures: 40% over-estimate for ideal gas calculation
- Range without compressor is less than 600km



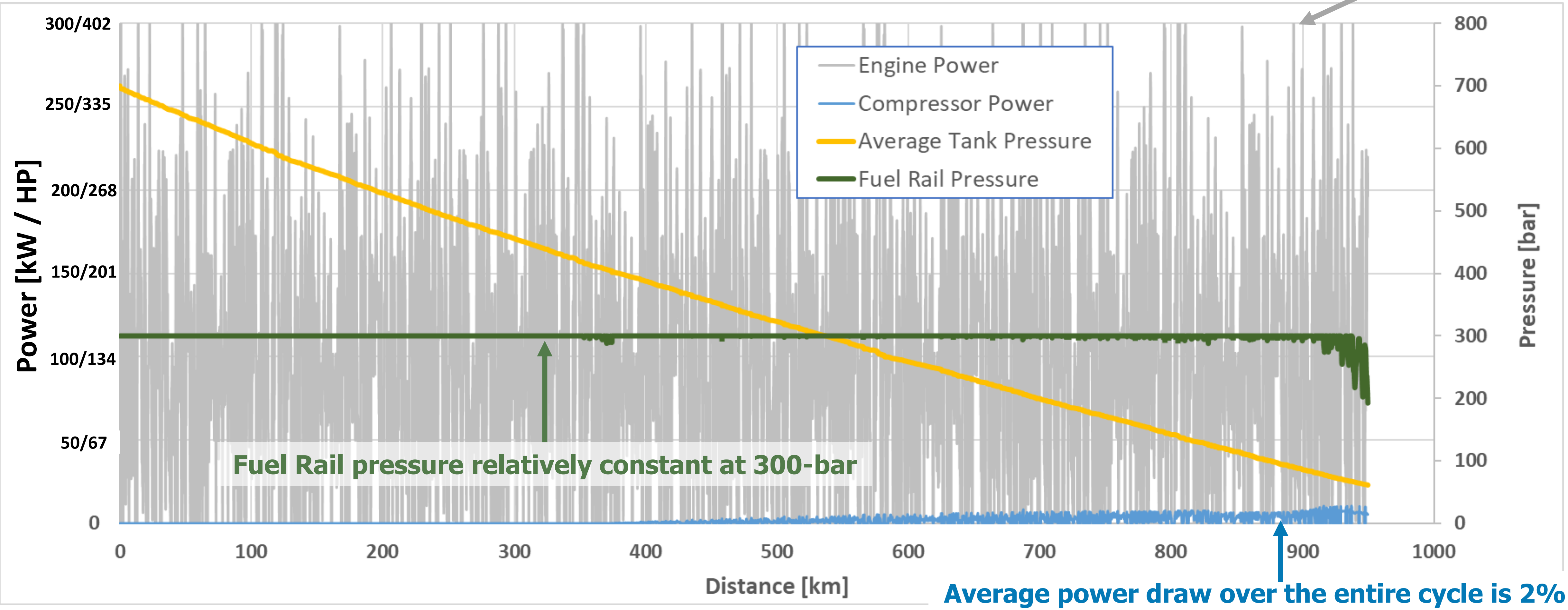
H_2 Smart Tank System



- 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)

Full power available throughout operating range



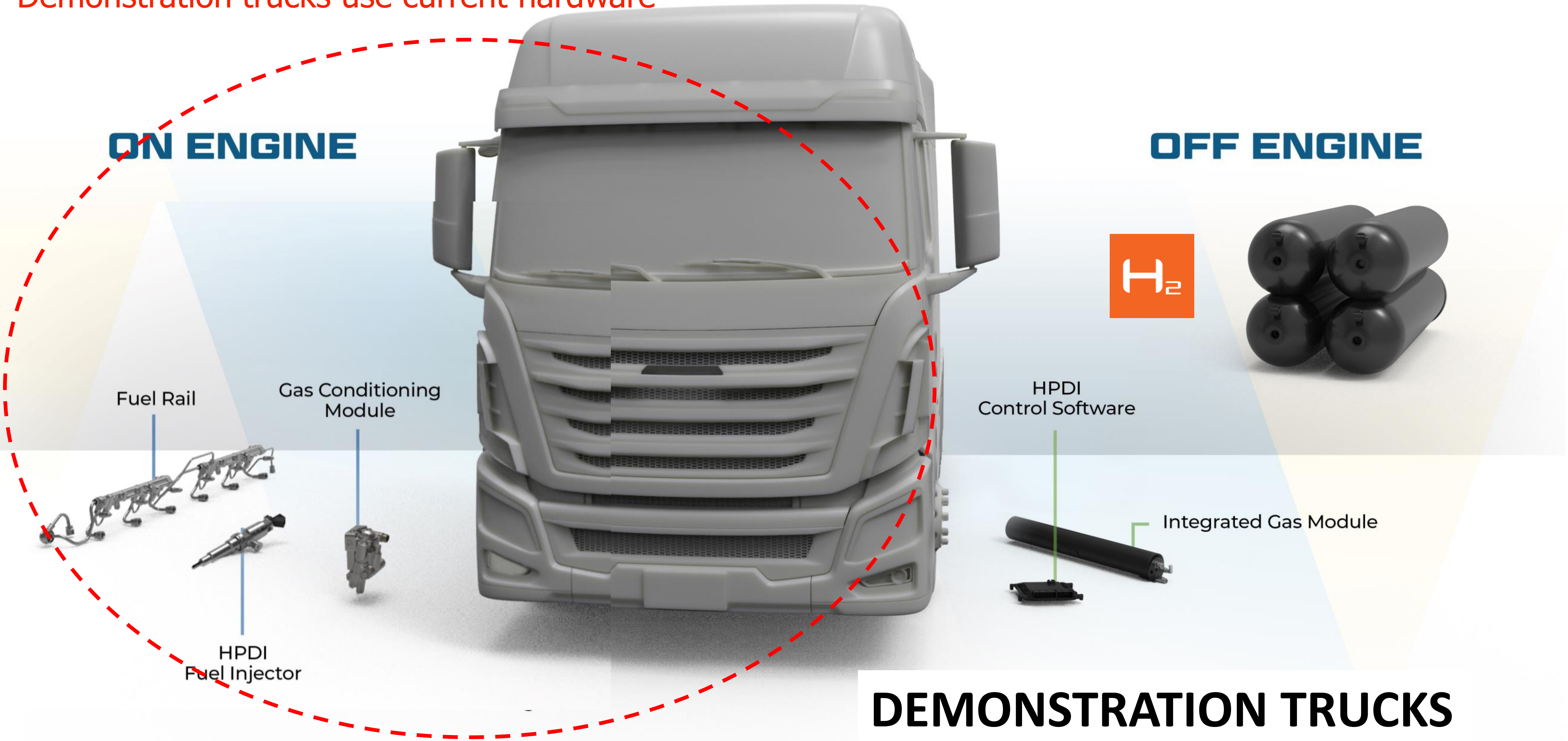
Average power draw over the entire cycle is 2%

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



DEMONSTRATION TRUCKS

H2
Hydrogen
Station
Changing the way
HPDi
Hydrogen
Mobility
HPDi
Westport

H_2 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

H_2 Demonstration Trucks

- Westport has built two H_2 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 H_2 HPDI fuel system is growing from OEMs, with **multiple development projects** recently announced and underway.
- The SCANIA CBE1 engine equipped with Westport's H_2 HPDI fuel system reached a **peak BTE of 51.5%.**
- H_2 HPDI fuel system equipped engines have demonstrated **near-zero CO_2** 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 H_2 storage and a small compressor.
- Demonstration vehicles with H_2 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 CO_2 in long-haul trucking and other high-load, long-haul applications.

H_2 HPDI

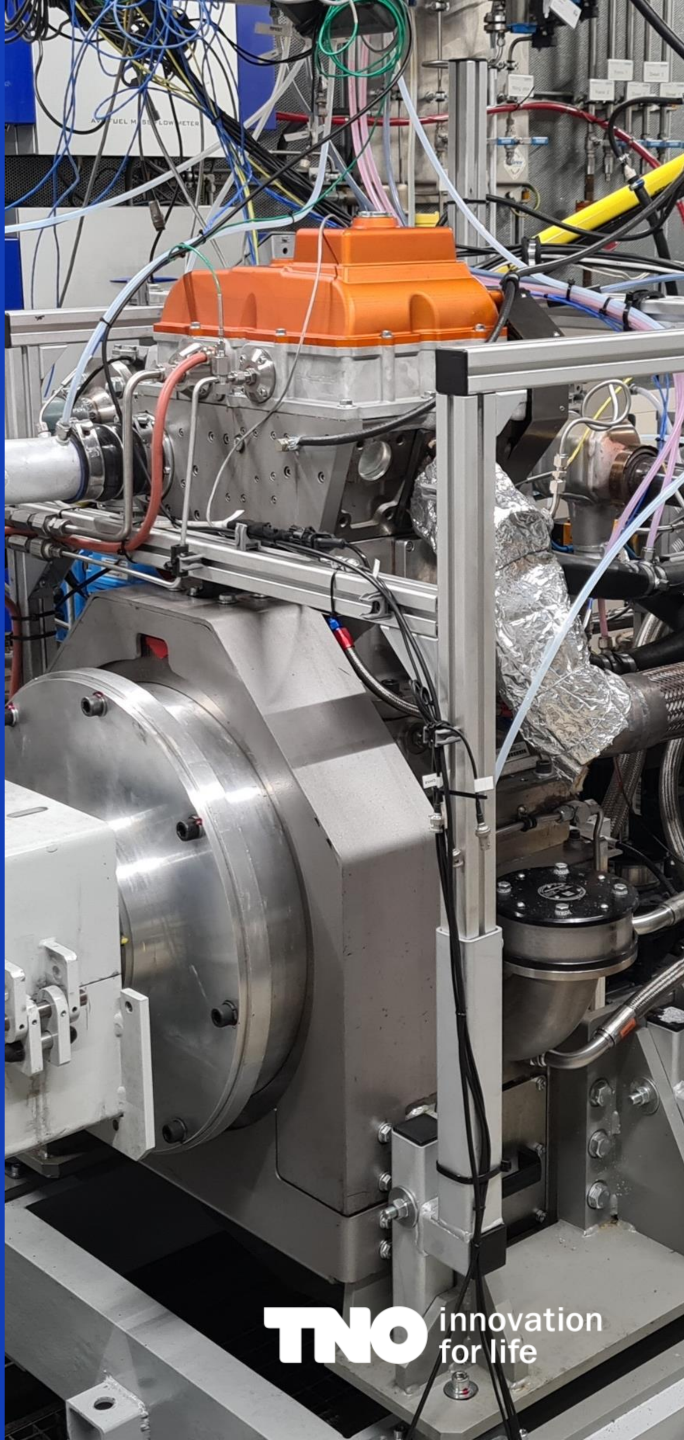
- 20% more power, 15% more torque
- **Near zero CO_2 emissions**
- **Lower cost CO_2 abatement than fuel cell vehicles**
- Preserve existing engine manufacturing

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^{TM})

Power Density, Efficiency and Emissions

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



Positioning of TNO paper

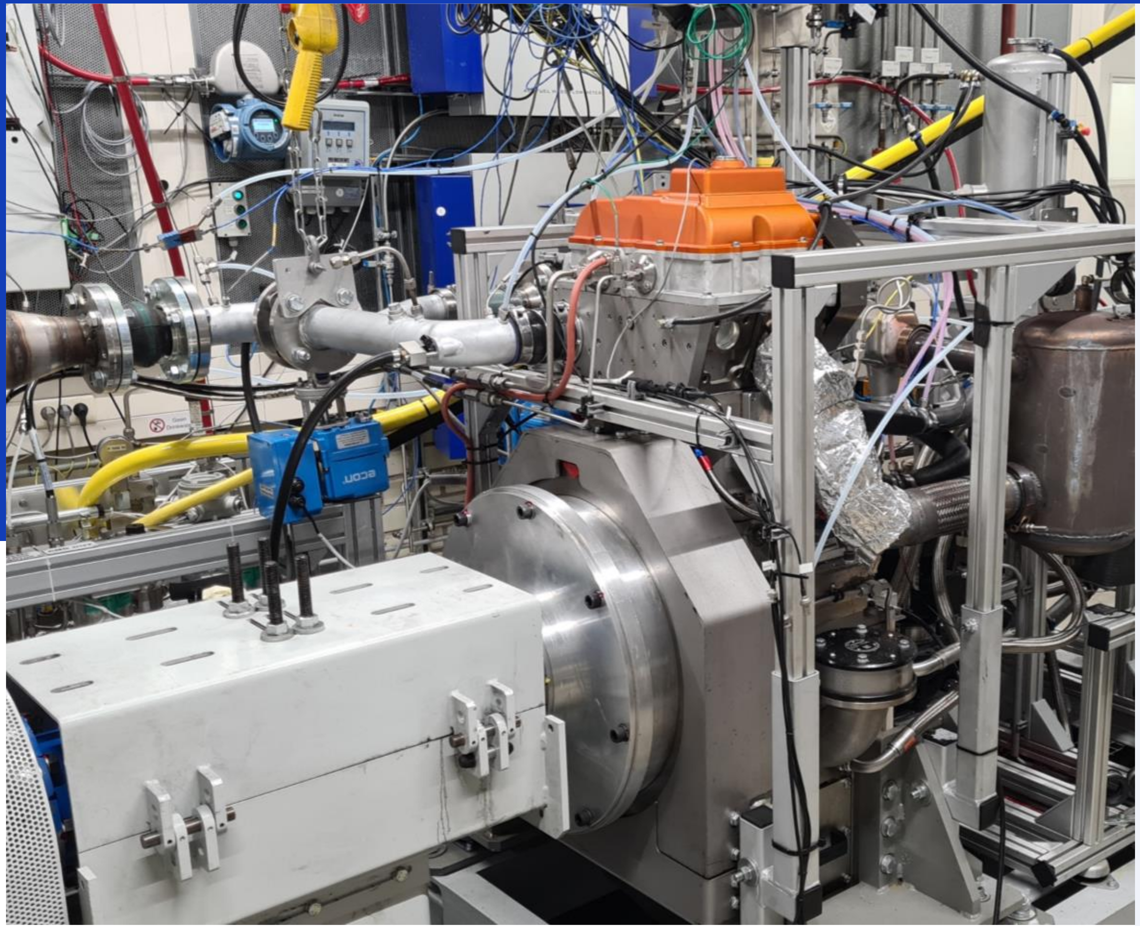
- Paper targets to present a fair comparison between two different combustion concepts for H2-ICE
  - Lean burn Spark Ignited (SI) concept with port fuel hydrogen injection (PFI)
  - Westport Fuel Systems HPDI concept (HPDI™)

- 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

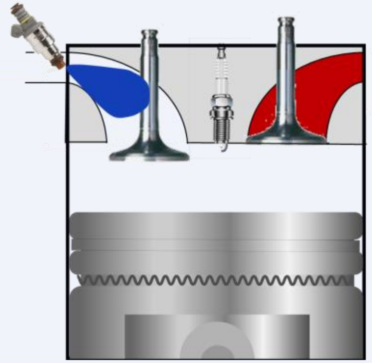
Agenda



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

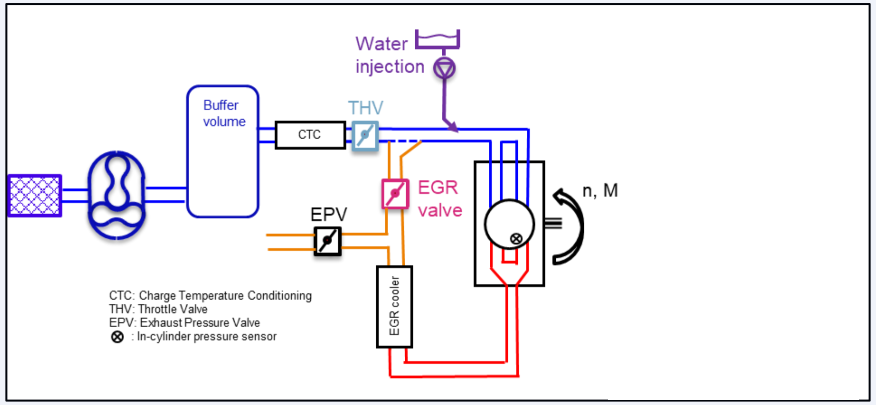
PFI SI and HPDI on same base 1-cylinder engine

PFI SI



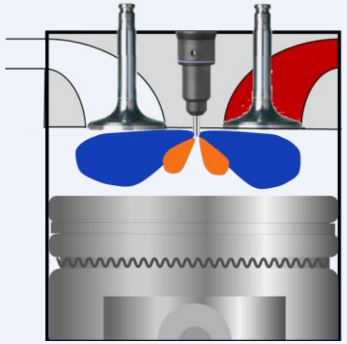
Fuel	hydrogen
Combustion mode	Premixed, flame propagation
fuel injection system	Port Fuel Injection into intake runners, pressure max.10 bar
H2 Ignition	Spark Ignited
Piston, Compression Ratio (CR)	CR 10 – 12.5 

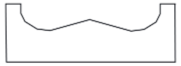
Single-cylinder research setup



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 ^{o}C] Port Water injection

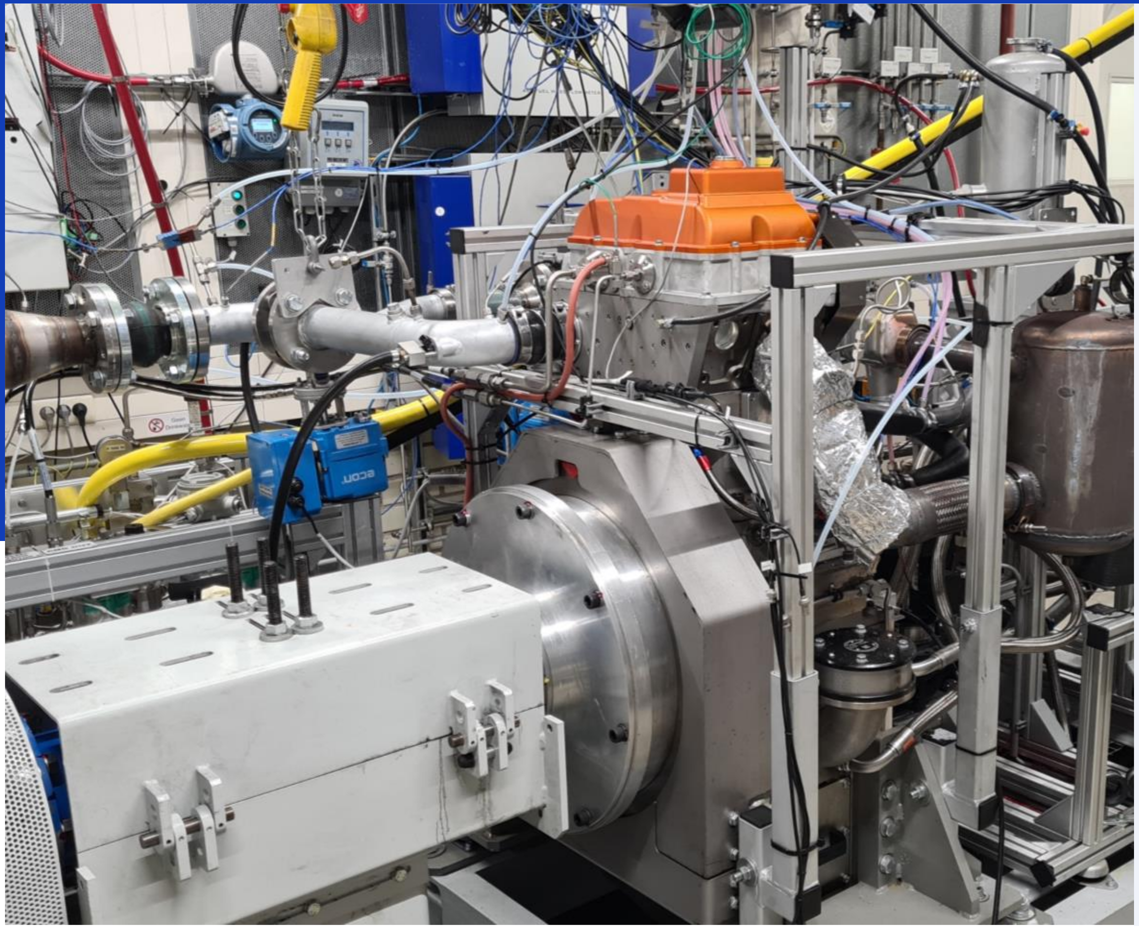
HPDI



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
- Comparison PFI SI and HPDI
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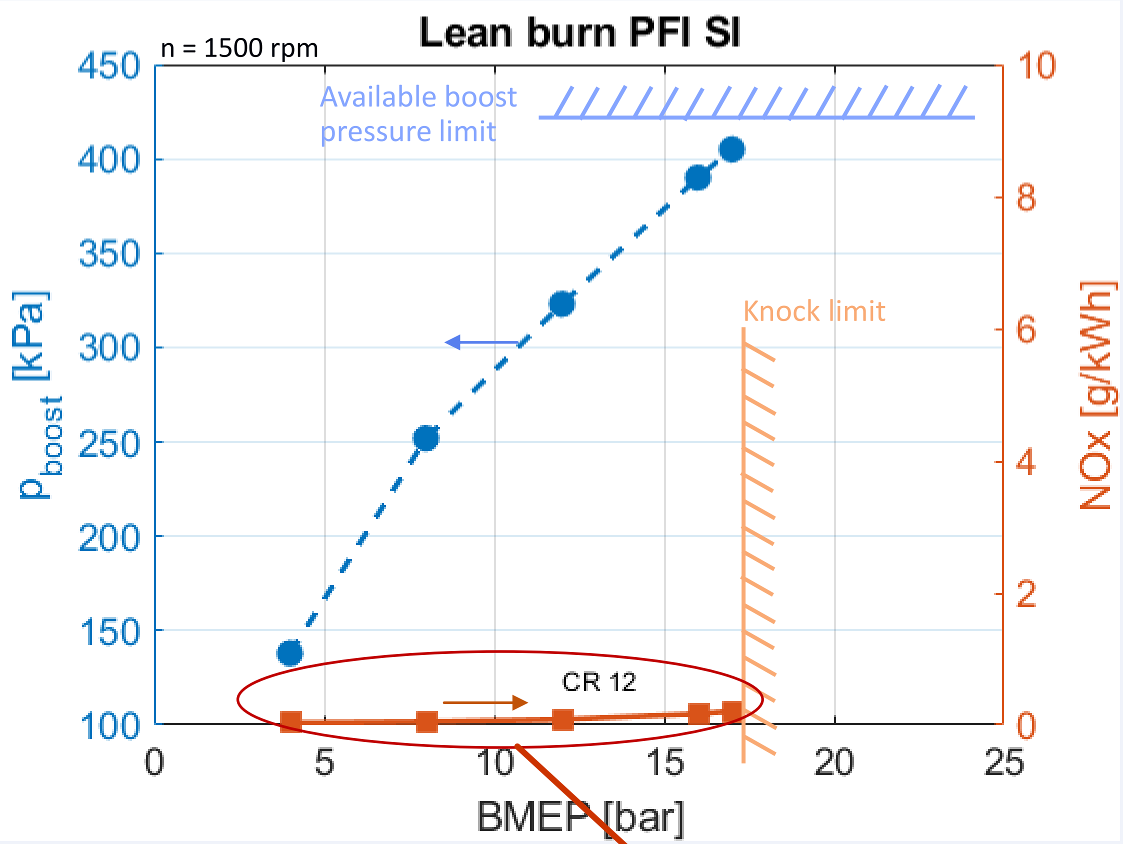
Low NOx load range limited by available boost pressure and occurrence of knock

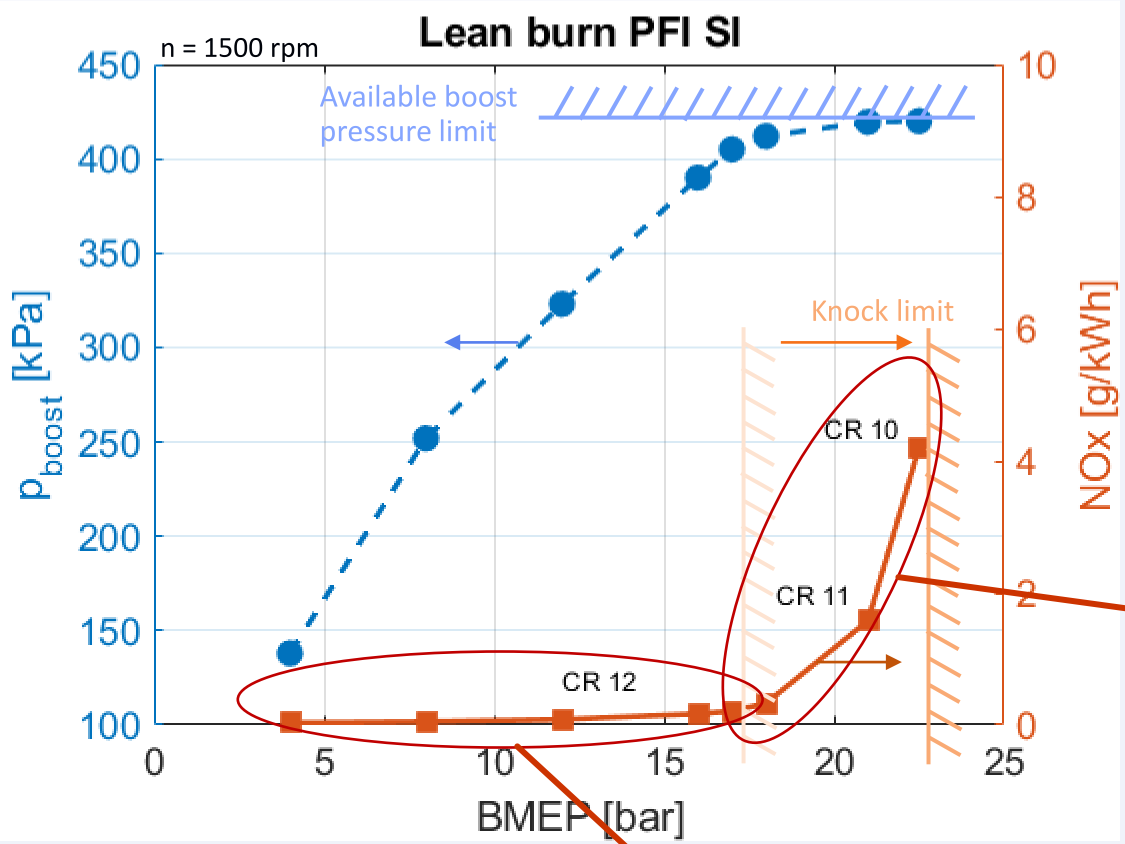
PFI SI: Low NOx potential



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

X. Seykens, E. Doosje, C. Bekdemir, P. van Gompel, "The hydrogen ICE for heavy-duty applications: Towards Ultra-low NOx Emissions", 43rd International Vienna Motor Symposium, 2022

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)

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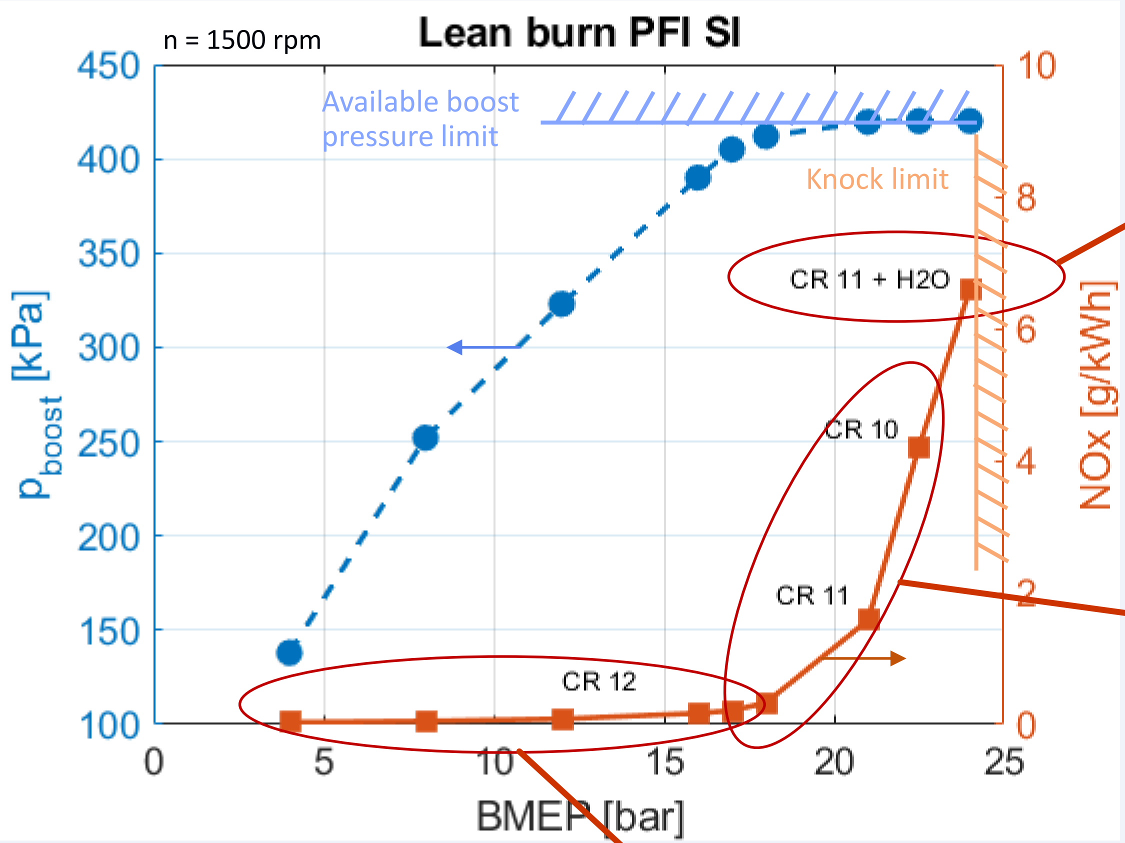
At fixed swept volume, high load feasible for PFI SI at the expense of increased system complexity

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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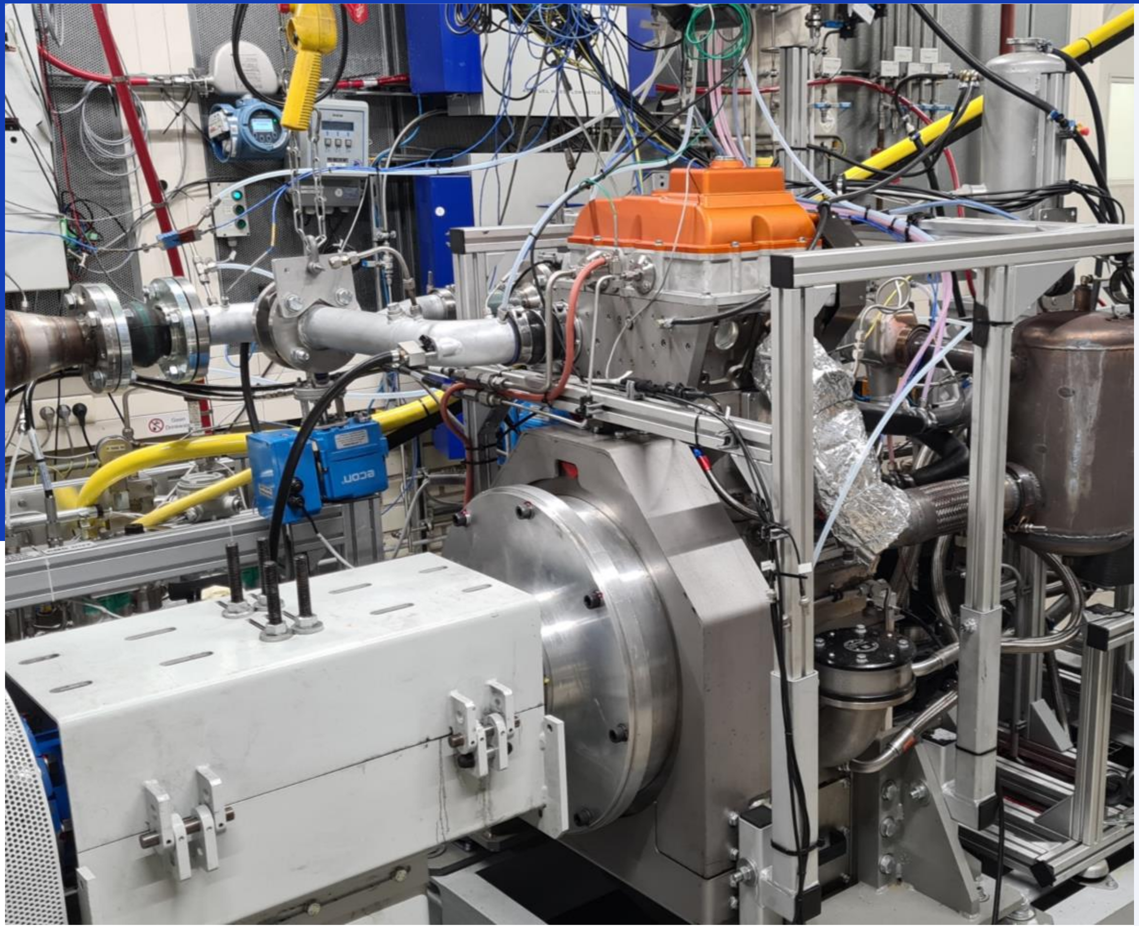


- Single-cylinder setup & H2-ICE concepts: PFI SI and HPDI™
- PFI SI results overview
- **HPDI™ results overview**
- Comparison PFI SI and HPDI
- Summarizing conclusions

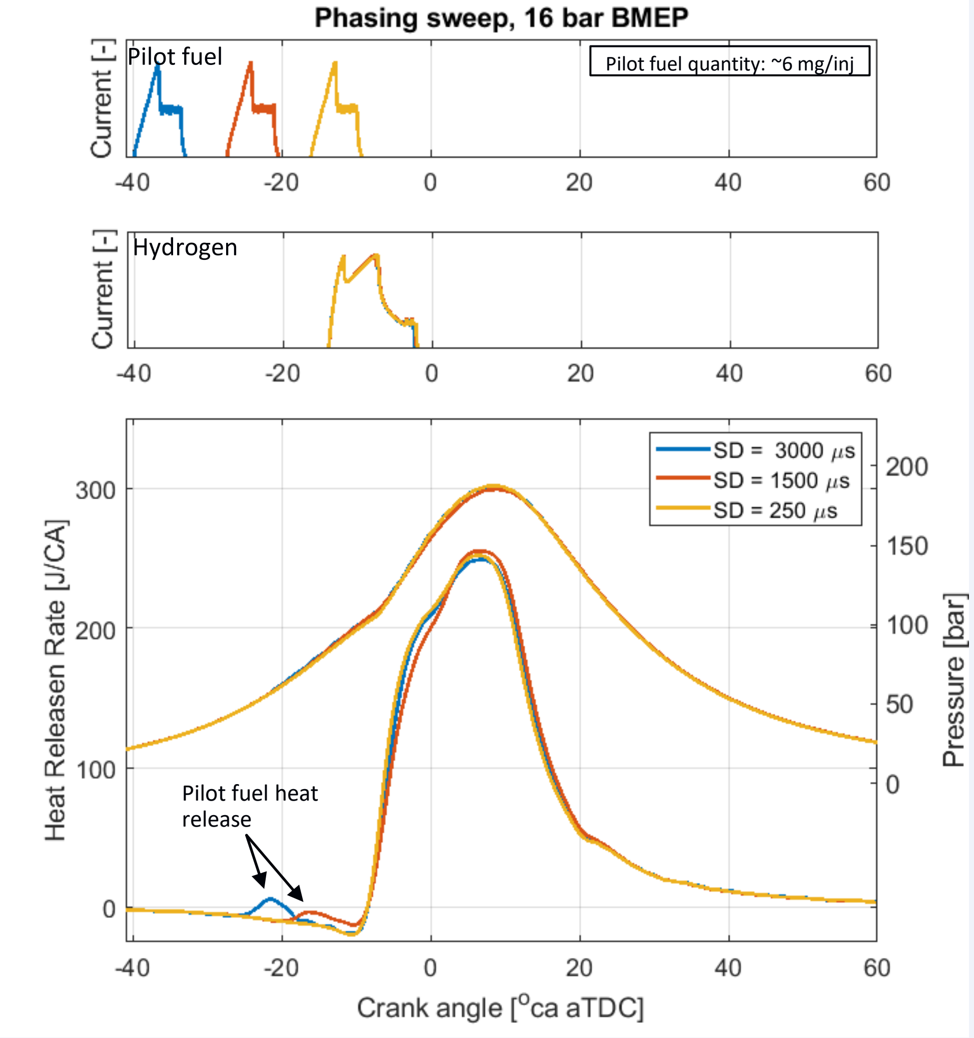
HPDI single-cylinder measurements

- **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

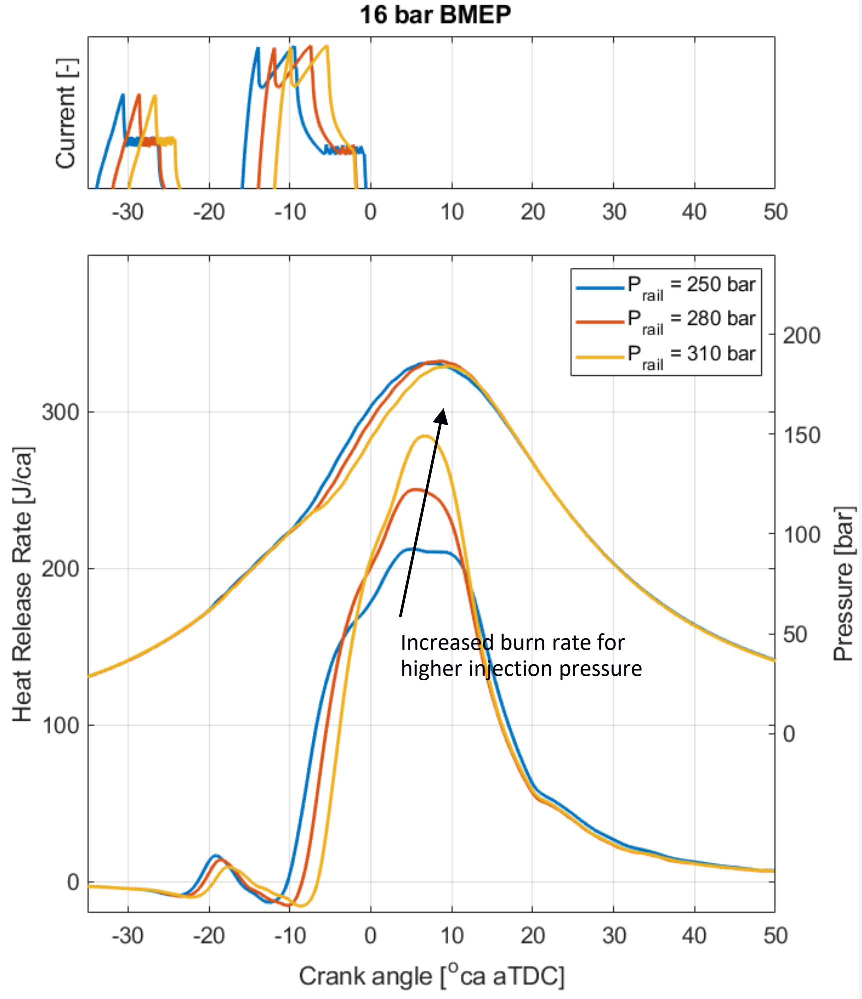


*SD = Time between Start current pilot and start current main

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

Injection pressure variation: fixed combustion phasing

Injection pressure variation



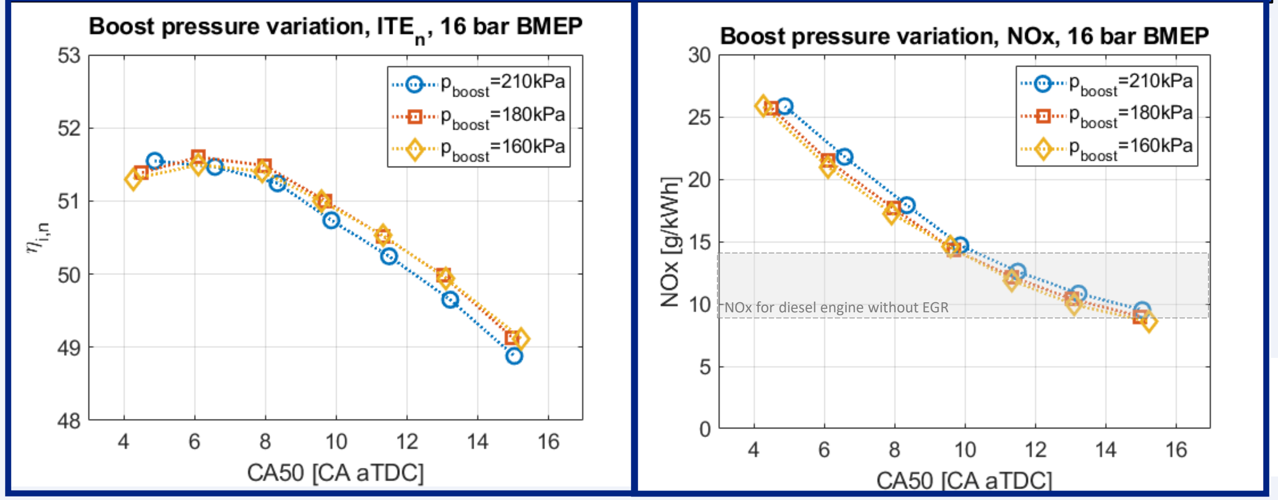
- Net indicated efficiency and NOx emissions close to identical for different injection pressures at same combustion phasing

- **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
$P_{cyl,max}$ [bar]	185.7	186.7	184.2

Variation of main injection timing at different λ

λ variation by boost pressure variation



- Efficiency and NOx 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 NOx levels within diesel engine range.

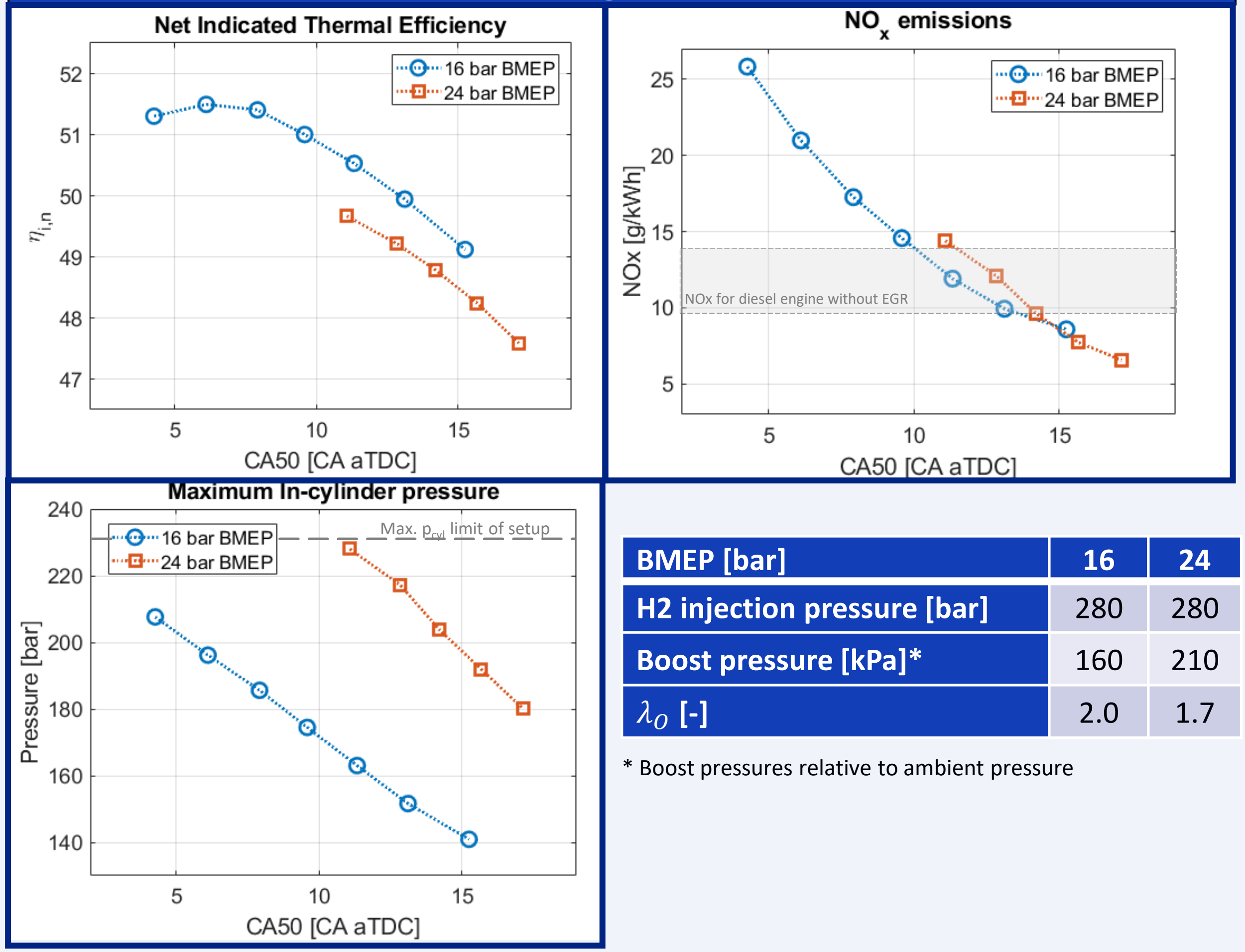
Overview of results for fixed CA50 (~8 ca aTDC):

Boost pressure [kPa]*	160	180	210
λ_O [-]	2.0	2.2	2.6
CA50 [CA aTDC]	7.9	8.0	8.4
NOx [g/kWh]	17.3	17.6	17.9
ITEn [%]	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

Load range increase

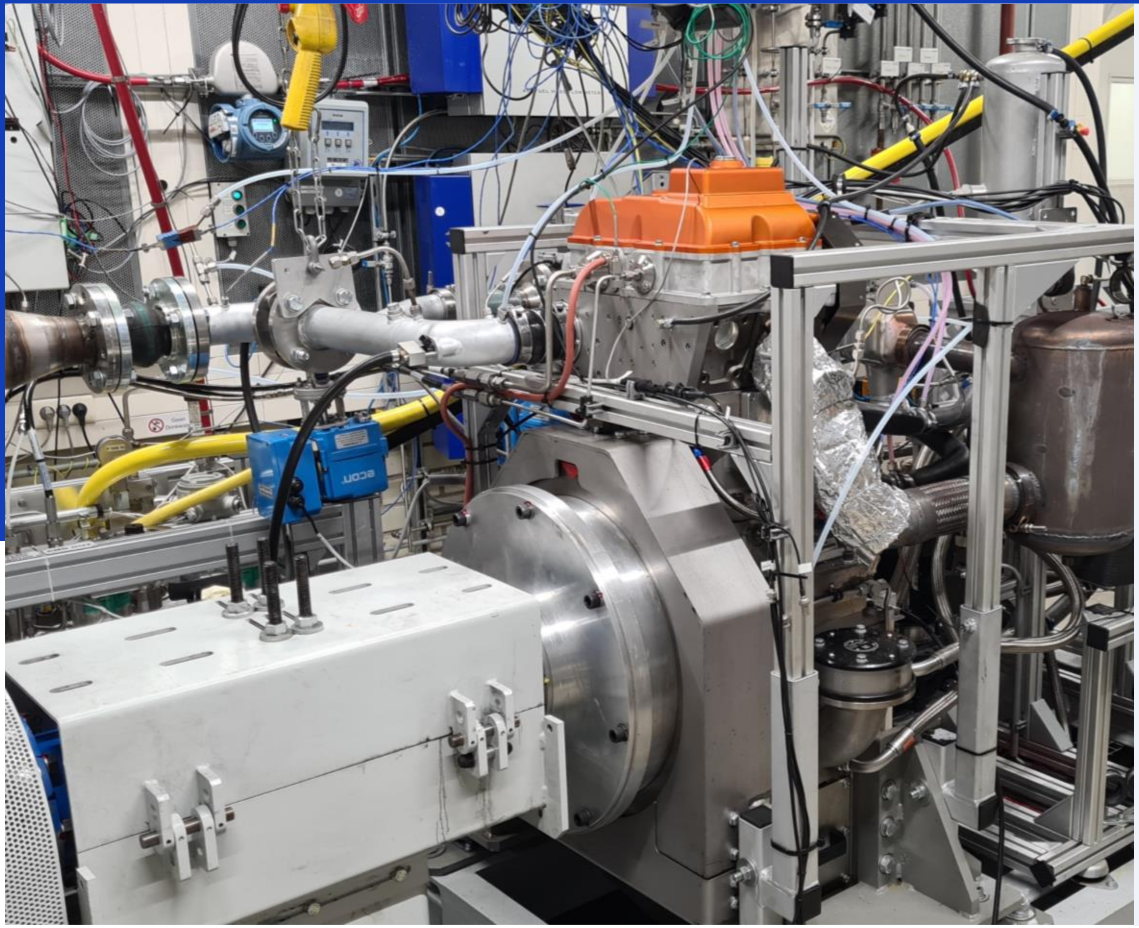


BMEP [bar]	16	24
H2 injection pressure [bar]	280	280
Boost pressure [kPa]*	160	210
λ_O [-]	2.0	1.7

* Boost pressures relative to ambient pressure

- 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 NOx (similar to diesel)
  - $p_{cyl,max}$ setup constraint
- At 24 bar BMEP & diesel-like NOx level the observed efficiency is competitive to diesel engine efficiency
- Developments in aftertreatment technology support realizing full efficiency potential

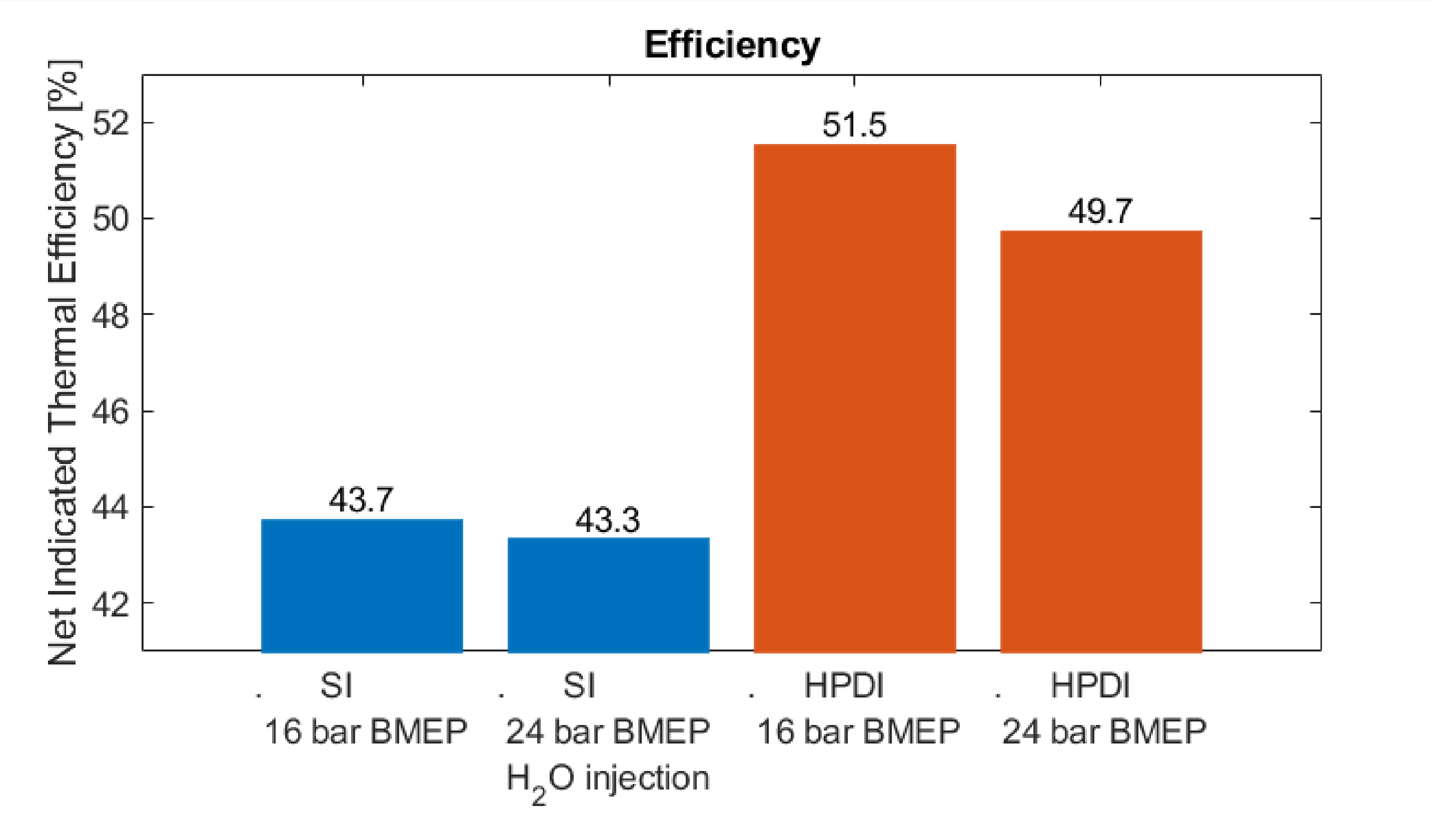
Agenda



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

Comparison PFI SI & HPDI™

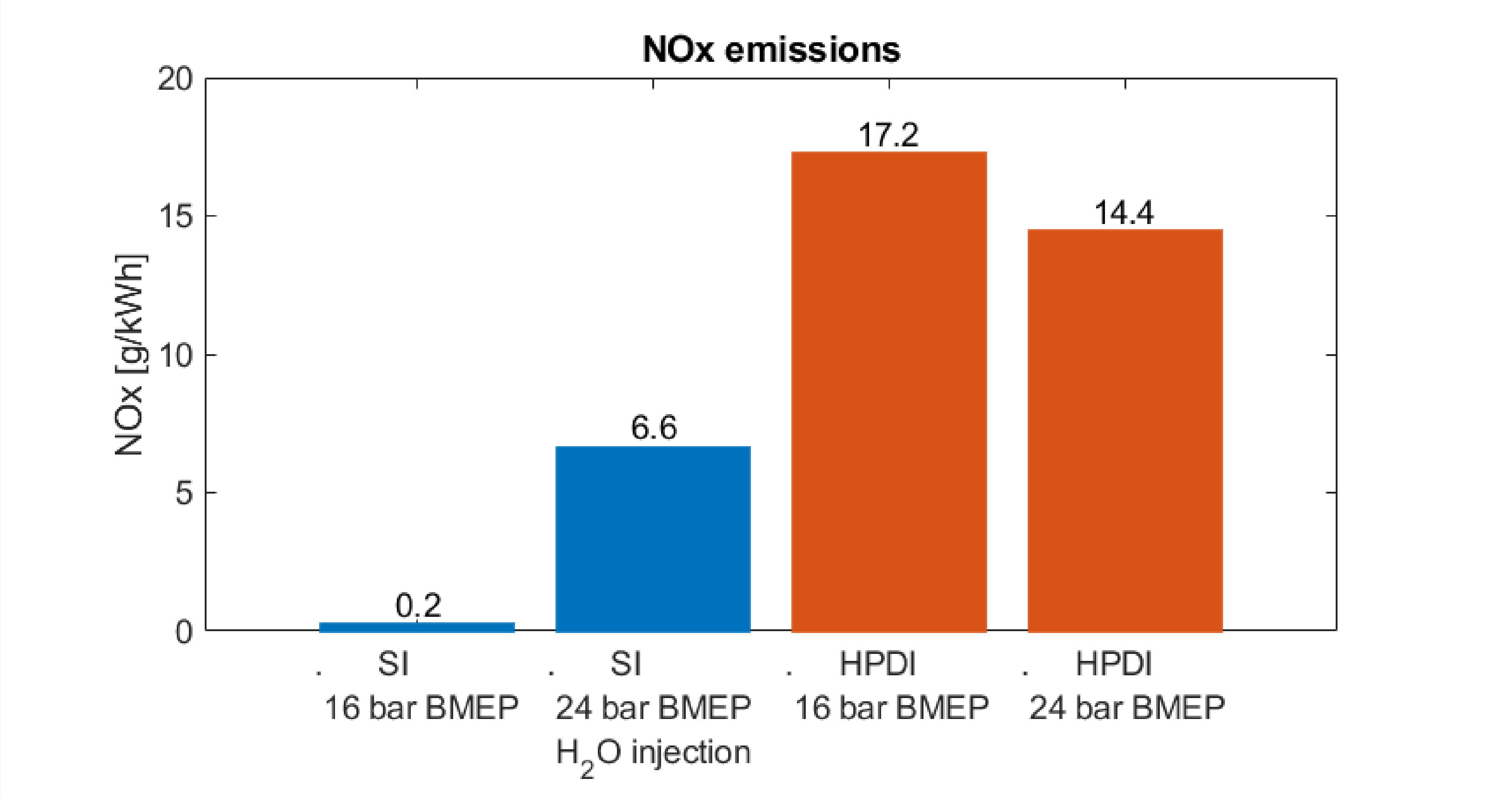
1500 rpm



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

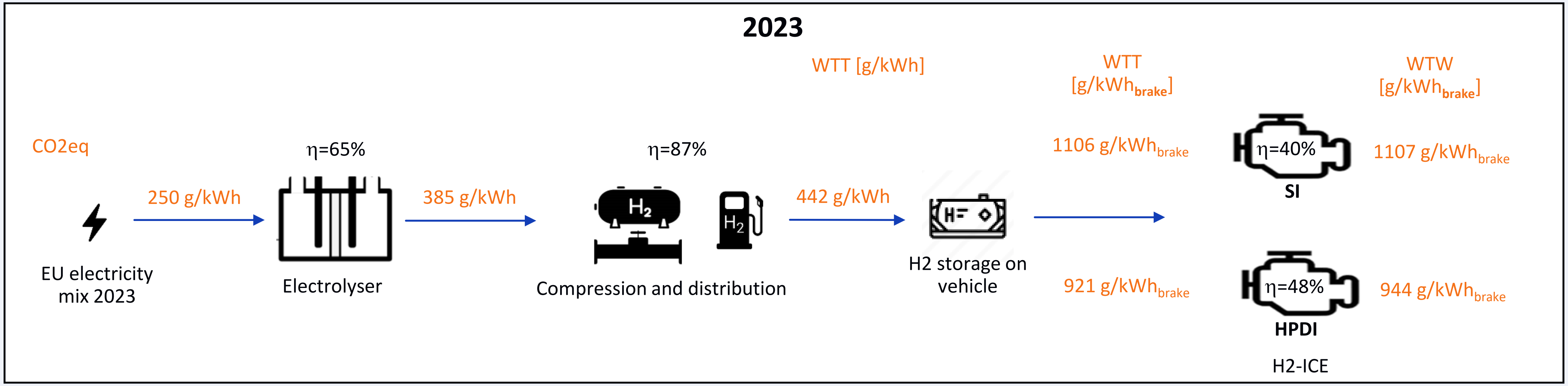
Comparison PFI SI & HPDI™

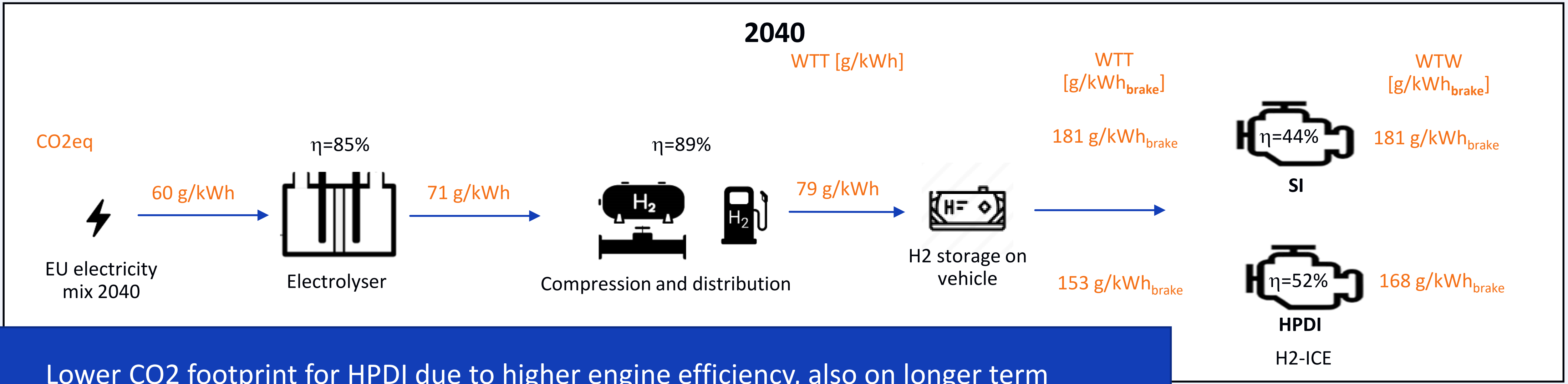
1500 rpm



- 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)

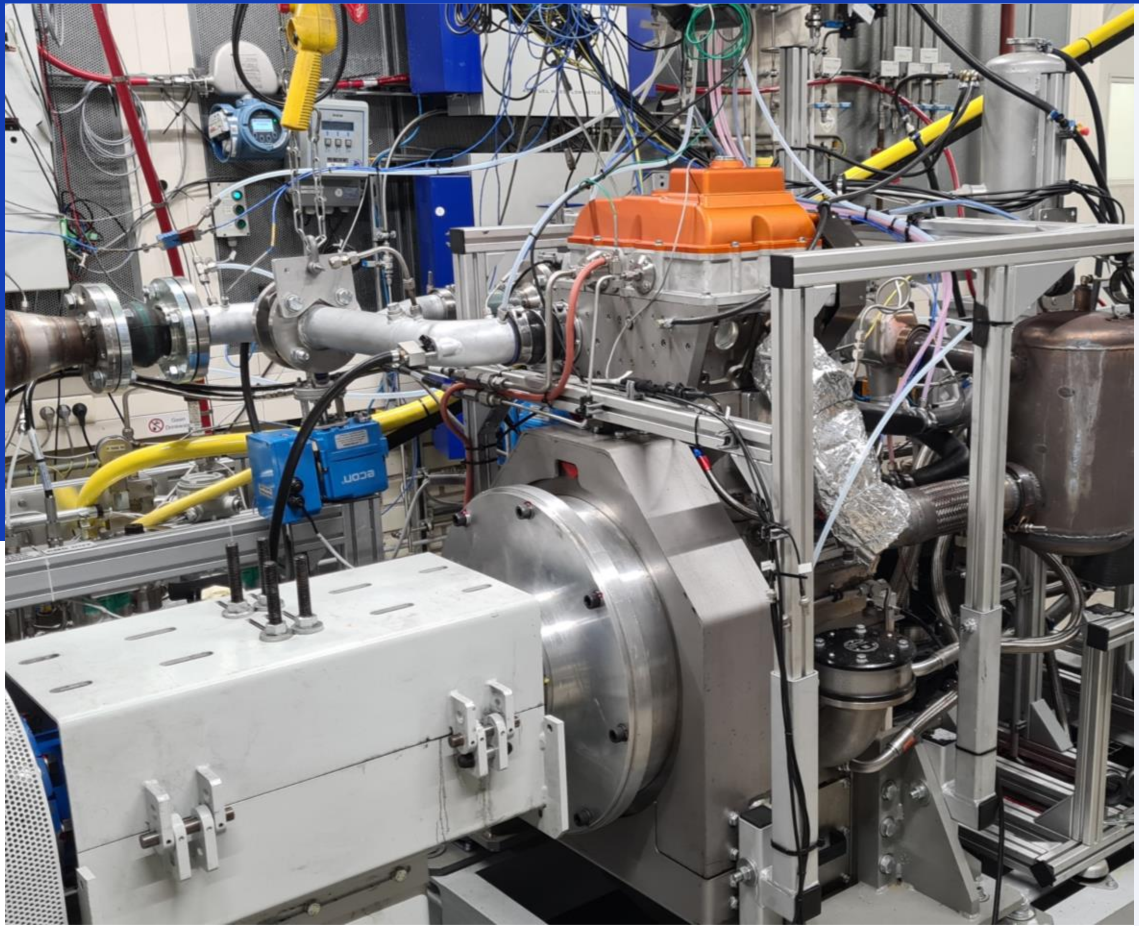
WTT and WTW CO2 footprint for PFI SI and HPDI





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

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**

Summarizing conclusions

- PFI SI and HPDI ™ 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 NOx results in 6 – 7 %-point higher efficiency than PFI SI.
- Engine-out NOx:
  - PFI SI: low NOx potential for medium to high load;
  - HPDI: conventional CI engine-like NOx 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.
- CO_2 footprint
  - Considering EU electricity mix, HPDI has lower WTT and WTW CO_2 footprint than PFI SI engine, also on longer term

Thank you for your attention

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Q&A


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Thank You

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