H_2 HPDI: A Gamechanger in the H_2 Society

September 2022

Westport Fuel Systems

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- Introduction of WFS
- Introduction of HPDI technology
- Hydrogen society, case study
- H_2 HPDI technology update

We’re Changing the Way the World Moves

Delivering advanced, proprietary, market-ready alternative-fuel systems for today’s combustion-powered vehicles that lower fuel costs and cut carbon emissions without sacrificing performance.

Tier 1
Transportation supplier with diverse business units

Manufacturing
7 global locations

Accessing
Full suite of renewable and alternative fuels

Sales in 70
countries, strong global footprint

>100
Global distributors worldwide

>1,400 Patents & Applications
Robust patent portfolio

We design, engineer, and manufacture clean fuel systems and components that address the challenges of climate change and meet stricter carbon emissions regulations.

HPDI HPDI 2.0™ is a High-Performance, Low-Emissions Fuel System Solution for Today's Combustion-Powered Heavy-Duty Trucks

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.

HPDI: LNG

- Same torque, efficiency, and reliability as diesel engines
- **20% CO_2 reduction tailpipe**
- **100% CO_2 reduction with bio-LNG**
- No change to vehicle or engine architecture

H_2 HPDI

- 20% more power, 15% more torque
- **Near Zero CO_2 emissions**
- **Lowest cost to CO_2 compliance**
- Preserve existing engine manufacturing

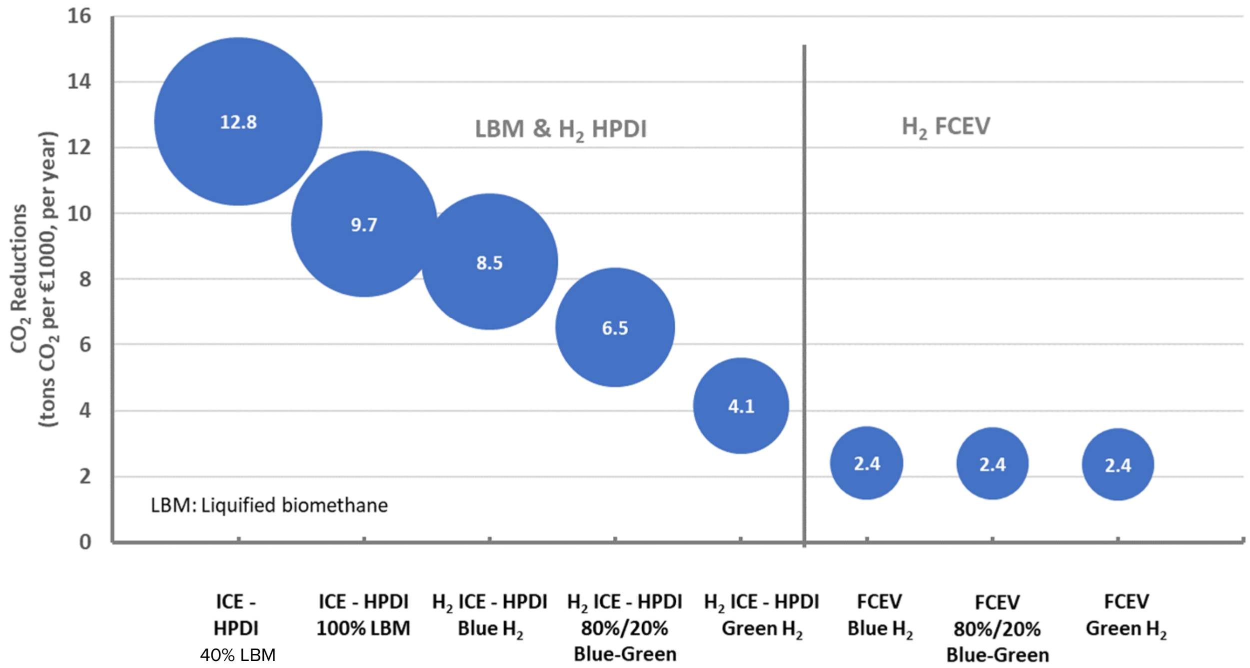
Hydrogen HPDI offers compelling TCO for high load applications

- Growing interest in H_2 HPDI from OEMs
- H_2 HPDI offers a pathway to green hydrogen
- Scania development project underway
- Additional development underway with Tupy and AVL

H_2 HPDI – Path to Zero Carbon

HPDI solutions are more cost effective than fuel cells for CO_2 abatement

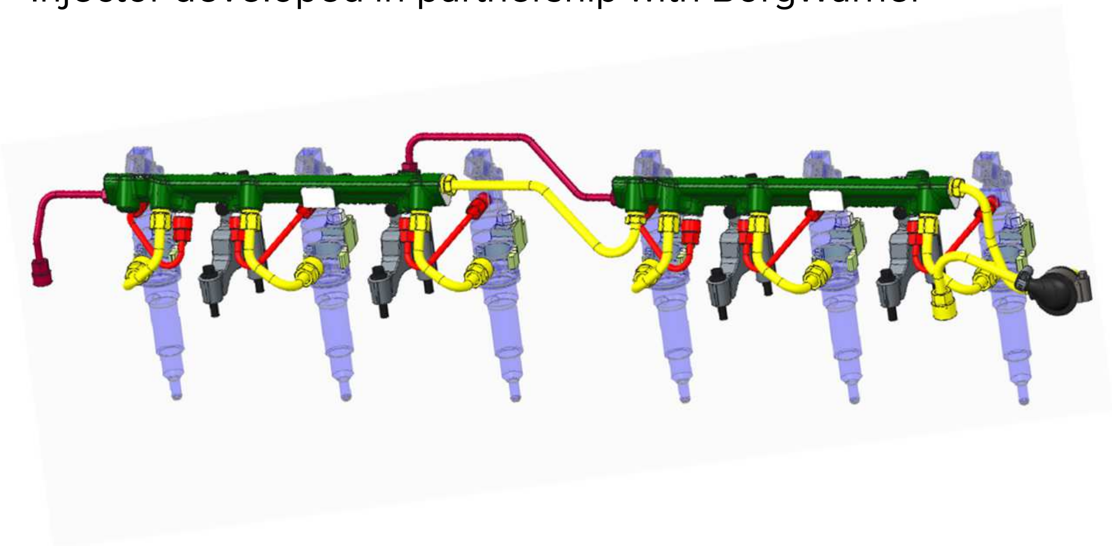
Tons CO_2 reduced per €1,000 invested. WTW CO_2 – includes fuel source and manufacturing emissions



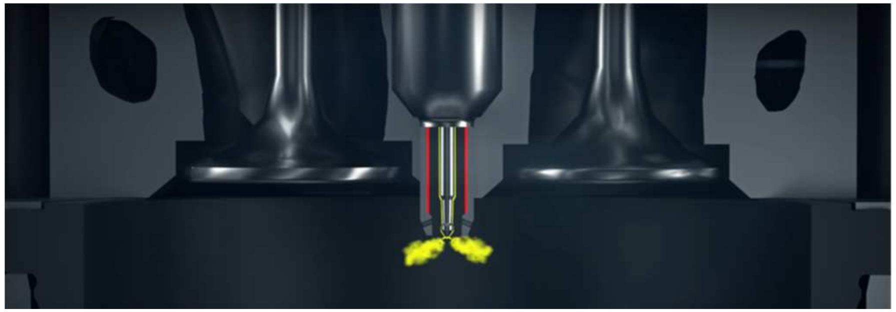
Source: AVL/Westport TCO study, 2021

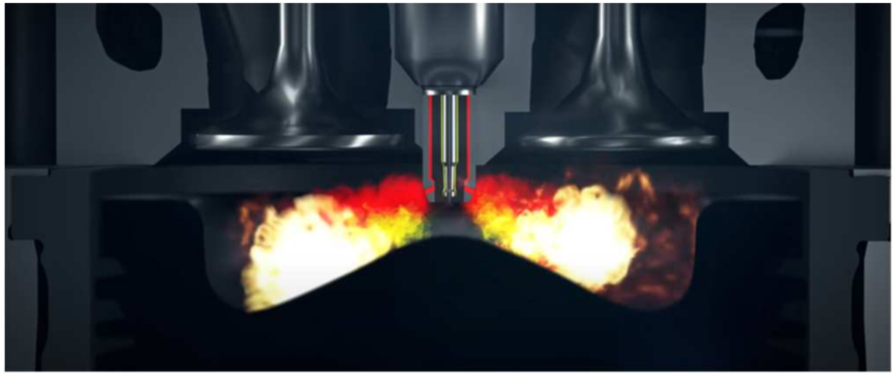
Injector and Rails

- Fits in a wide range of HD engines
- Improved reliability and durability
- Reduced cost
- Injector and rail designed for 500 bar capability
- Certified to R110
- Injector developed in partnership with BorgWarner

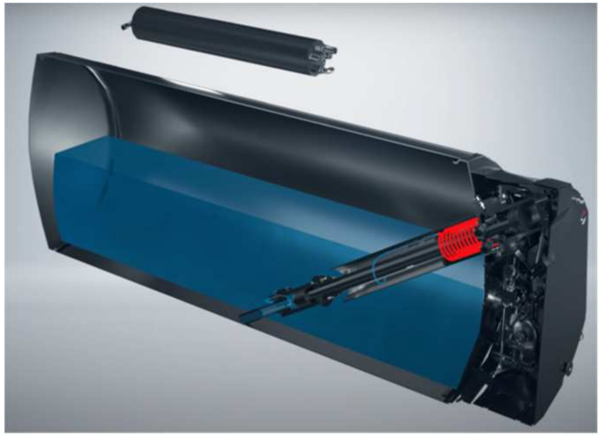


HPDI LNG & H_2

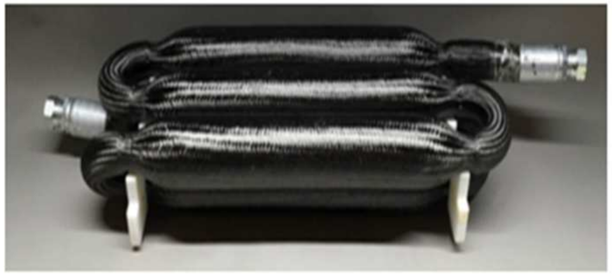




https://www.youtube.com/watch?v=KNGzgzmFIV0

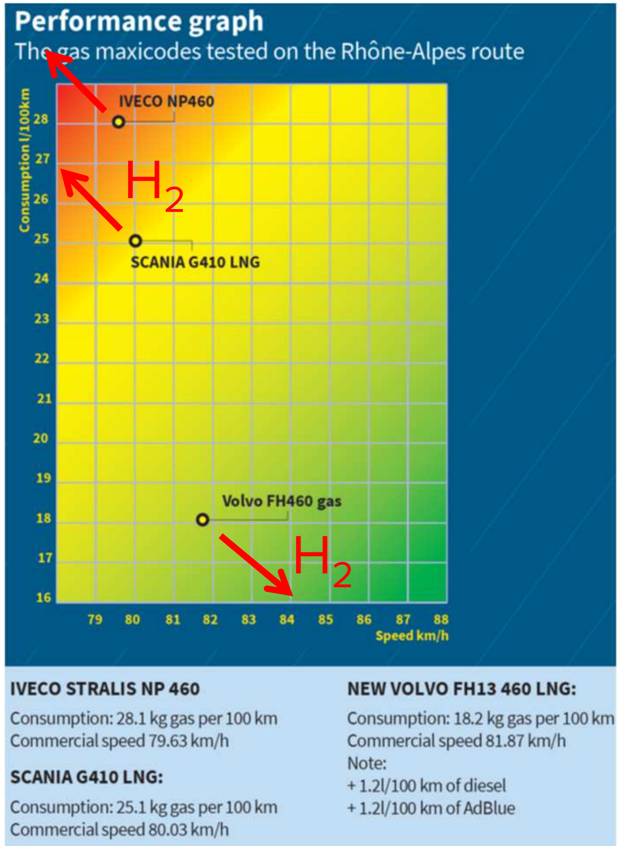


Liquid LNG / H_2 Storage



Compressed H_2 Storage

Fuel Consumption Comparision HPDI vs. SI LNG



- Three brands were compared in a defined route by magazine "FrenchRoutes" in April 2022. HPDI has by far the lowest fuel consumption and, in the same time, the highest commercial speed during the mission

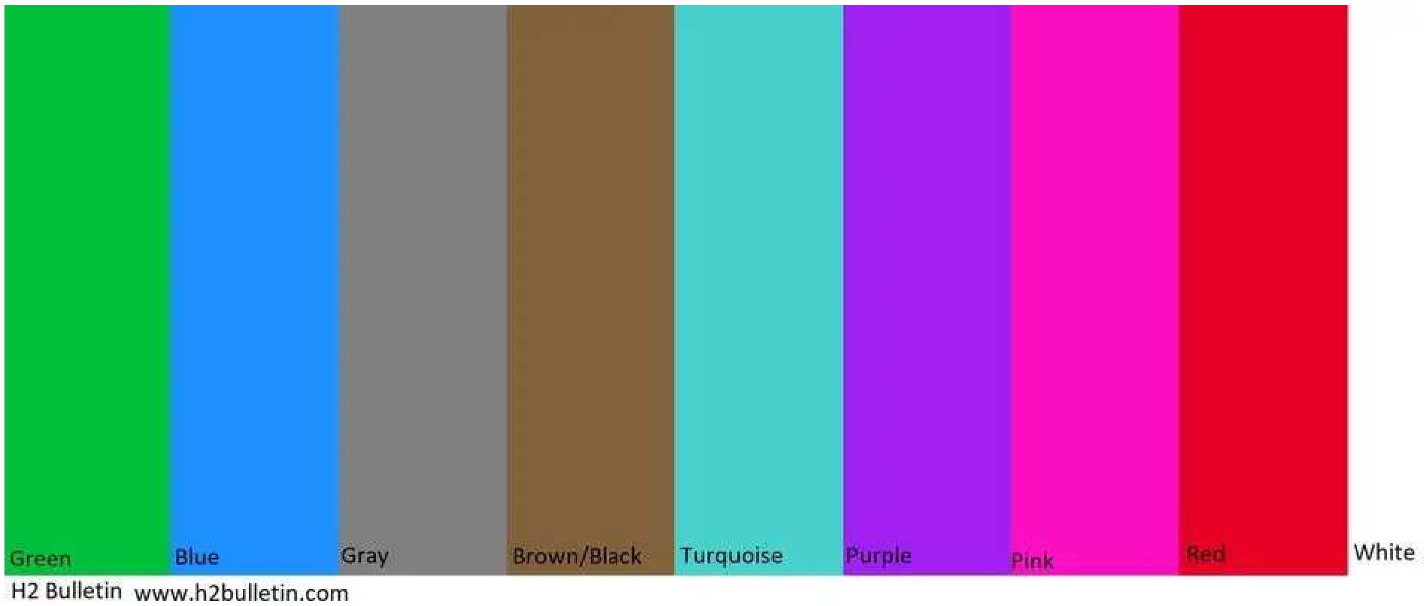
- When operating on Hydrogen (H_2), the HPDI system will:
  - Achieve higher efficiency than a fuel cell vehicle
  - Perform better than a fuel cell vehicle

  At a fraction of the cost of a fuel cell vehicle

Hydrogen Society

Hydrogen colours codes

Hydrogen itself is a colourless gas but there are around nine colour codes to identify hydrogen. The colours codes of hydrogen refer to the source or the process used to make hydrogen. These codes are: green, blue, gray, brown or black, turquoise, purple, pink, red, and white.



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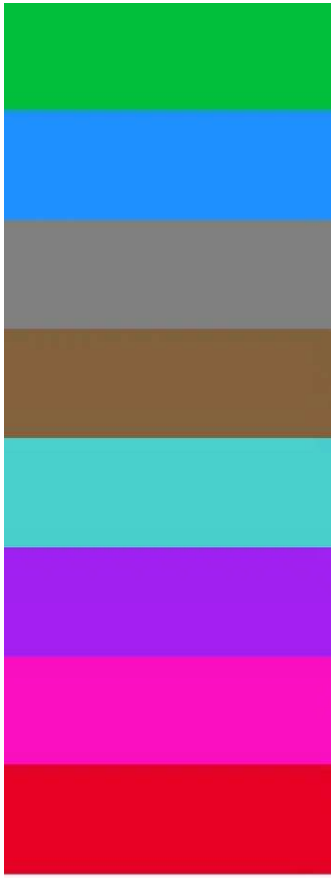


Green hydrogen is produced through water electrolysis process by employing renewable electricity. The reason it is called green is that there is no CO_2 emission during the production process. Water electrolysis is a process which uses electricity to decompose water into hydrogen gas and oxygen.

Blue hydrogen is sourced from fossil fuel. However, the CO_2 is captured and stored underground (carbon sequestration). Companies are also trying to utilise the captured carbon called carbon capture, storage and utilisation (CCSU). Utilisation is not essential to qualify for blue hydrogen. As no CO_2 is emitted, so the blue hydrogen production process is categorised as carbon neutral.

Gray hydrogen is produced from fossil fuel and commonly uses steam methane reforming (SMR) method. During this process, CO_2 is produced and eventually released to the atmosphere.

Black or brown hydrogen is produced from coal. The black and brown colours refer to the type bituminous (black) and lignite (brown) coal. The gasification of coal is a method used to produce hydrogen. However, it is a very polluting process, and CO_2 and carbon monoxide are produced as by-products and released to the atmosphere.

Turquoise hydrogen can be extracted by using the thermal splitting of methane via methane pyrolysis. The process, though at the experimental stage, removes the carbon in a solid form instead of CO_2 gas.

Purple hydrogen is made though using nuclear power and heat through combined chemo thermal electrolysis splitting of water.

Pink hydrogen is generated through electrolysis of water by using electricity from a nuclear power plant.

Red hydrogen is produced through the high-temperature catalytic splitting of water using nuclear power thermal as an energy source.

White hydrogen refers to naturally occurring hydrogen.

Hydrogen Society, Sweden Case Study

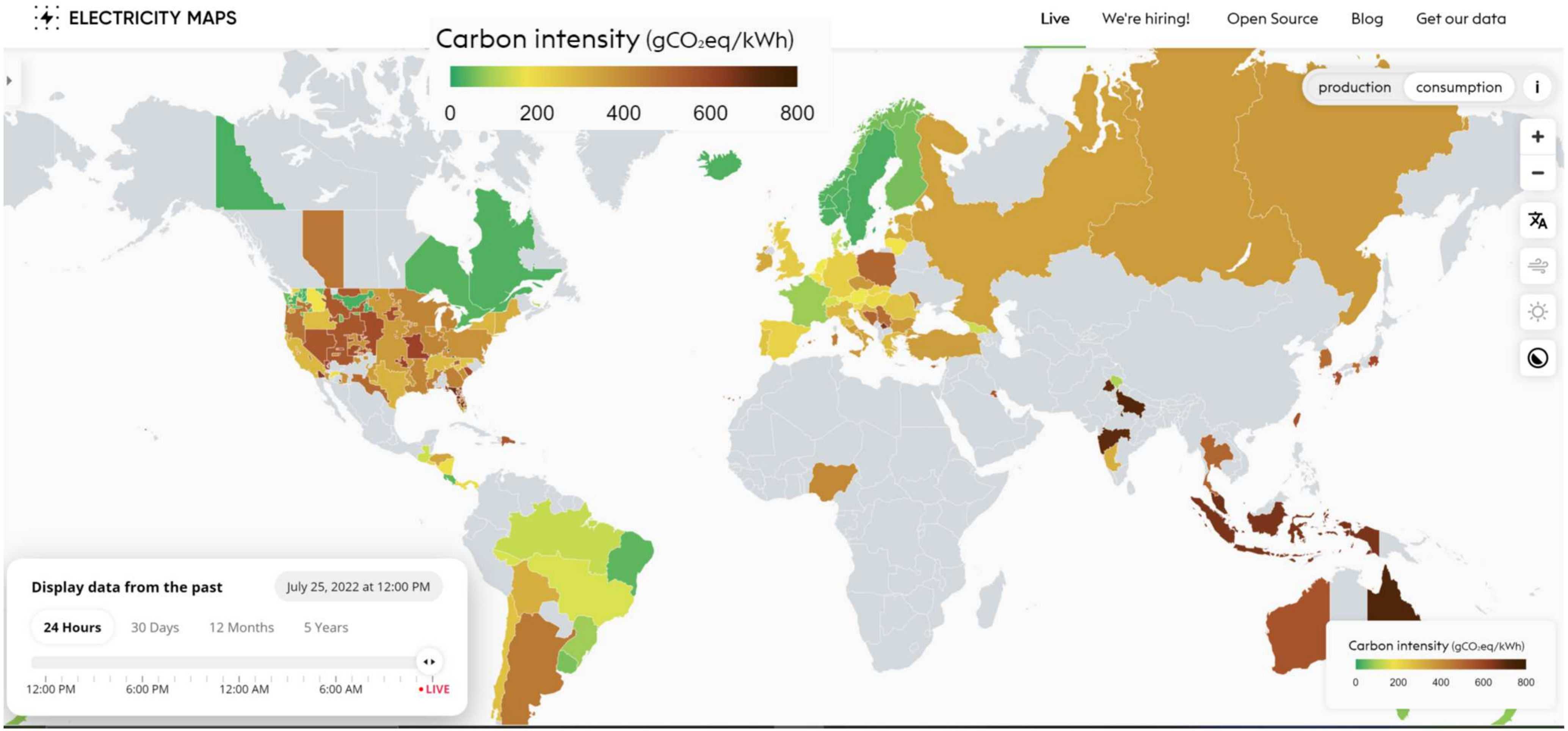
- Sweden emits 46 million tons CO_2 in 2020
- 8 million tons CO_2 originate from steel production
- Sweden produces 90% of the iron ore in EU
- Coal is used for the reduction of iron oxide => CO_2
- If H_2 is used instead in the process => H_2O

Hydrogen Society, Sweden Case Study

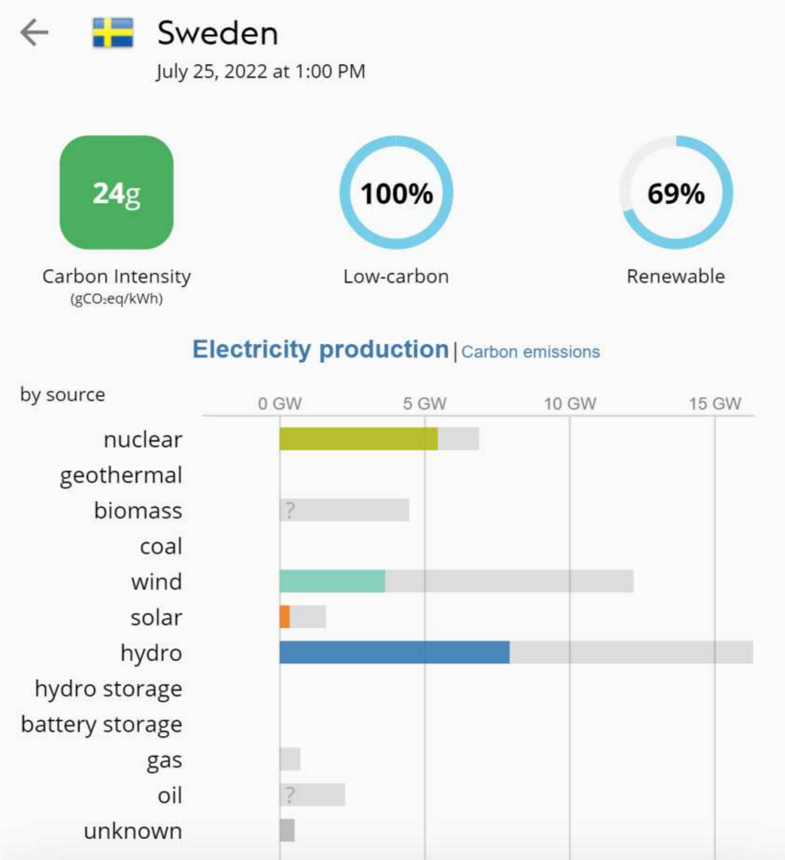
- Currently Sweden is producing 160 TWh and consuming 150 TWh of electricity. E.i 10 TWh overcapacity of electricity.
- Sweden has started several H_2 demanding initiatives
  - Hybrit, LKAB, Green Steel, Ovako, Scania, AB Volvo
- The H_2 production will need 55 TWh of electricity
- In 2019, Sweden used 83 TWh for road transportation, that will be partly electrified

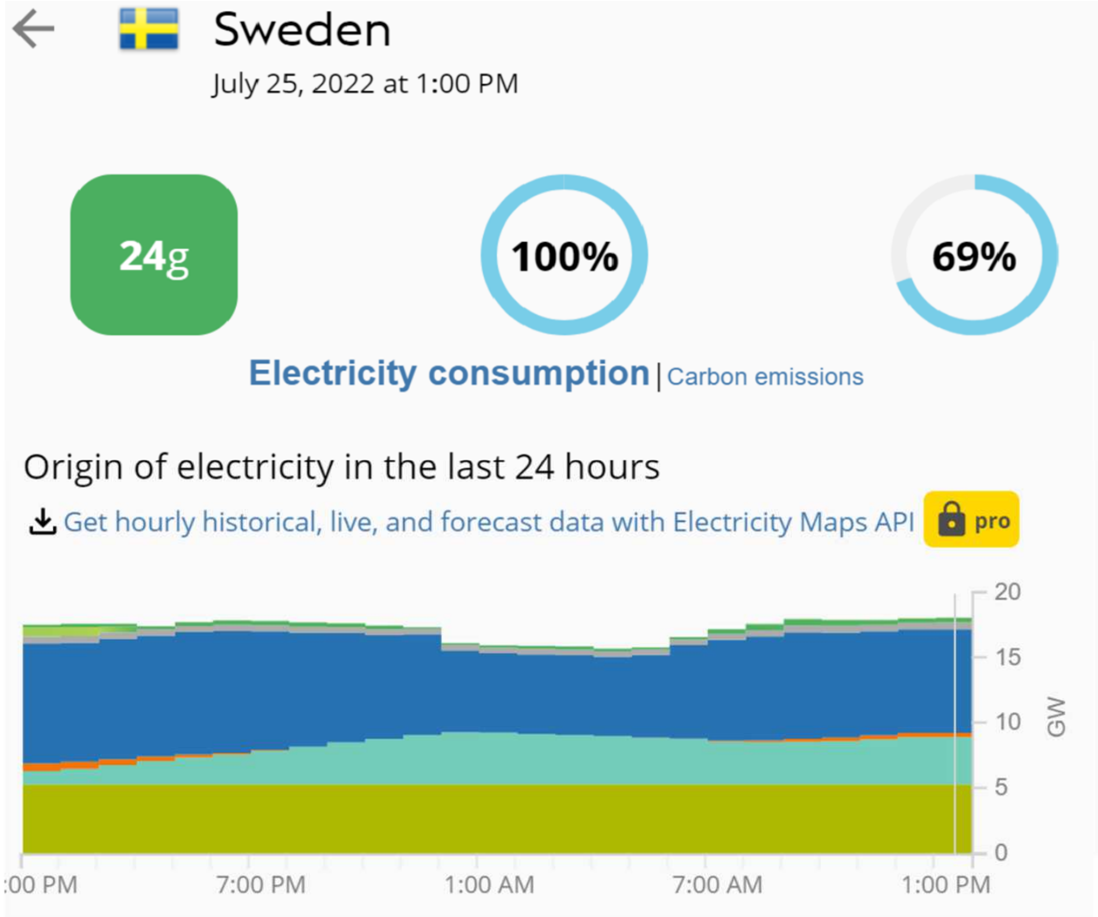
Shortage of electricity is foreseen.

Electricity Map

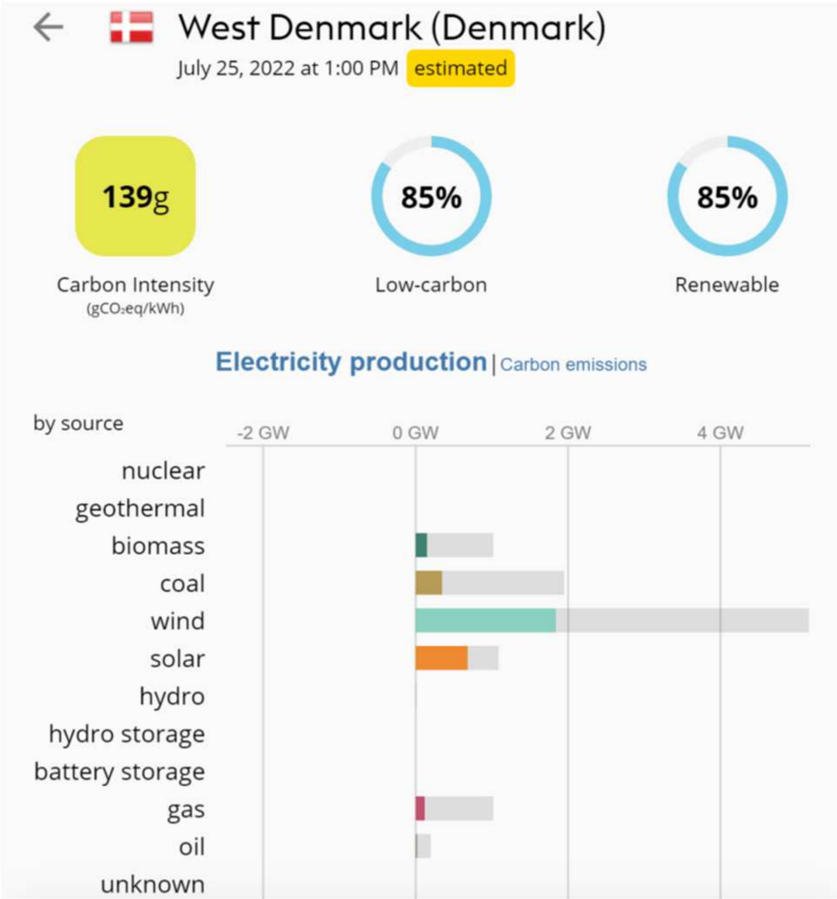


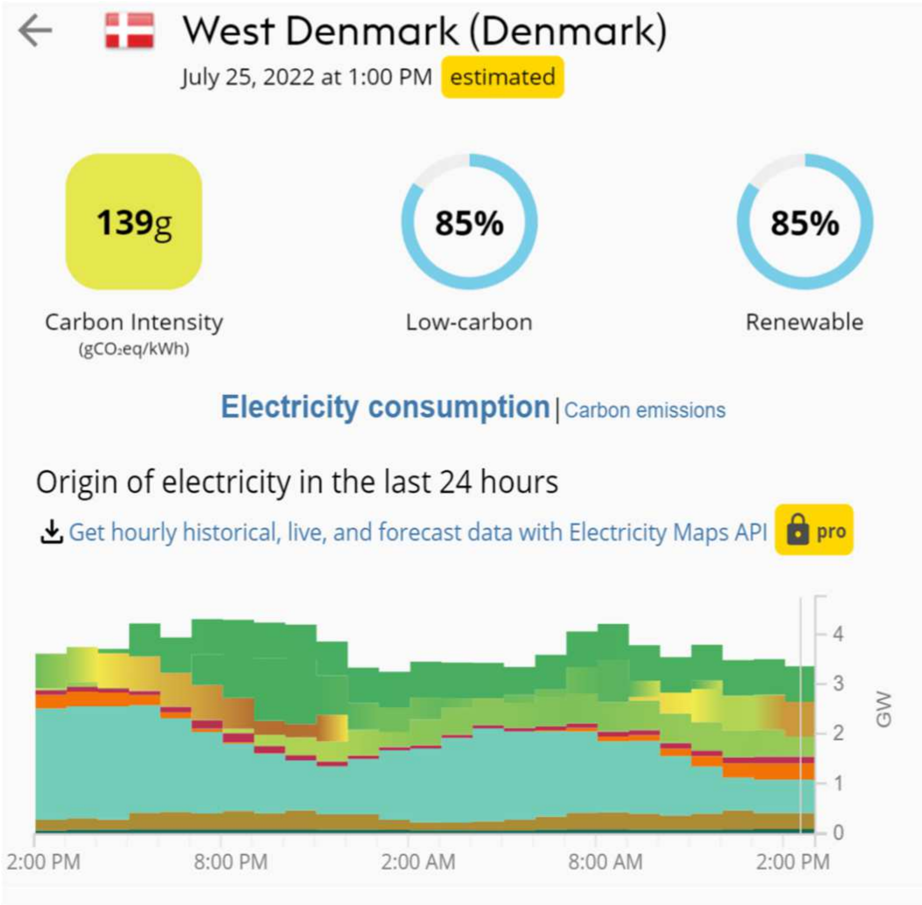
Green Electricity Production



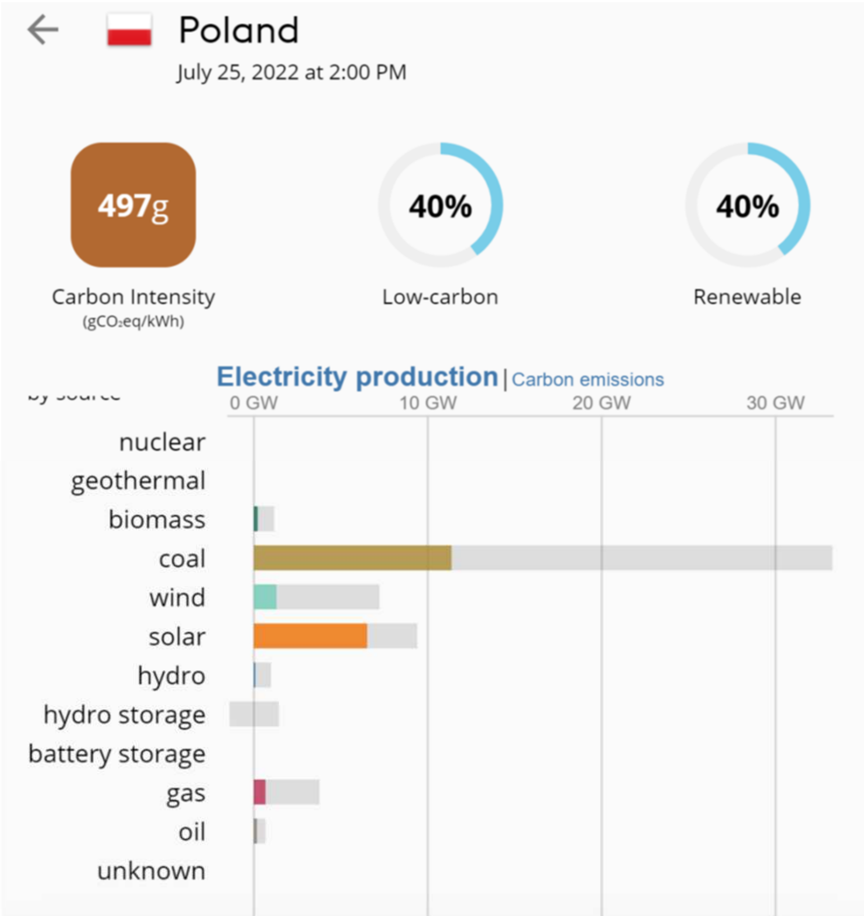


Green Electricity Production





Green Electricity Production



As a comparison, a good diesel engine has typically 585 gCO$_2$/kWh.

A 75% efficiency of a BEV gives 497/0.75 = 663 gCO$_2$/kWh in Poland.

Heavy Duty BEV vs. H_2 Vehicle

Energy efficiency

Battery Electric Vehicle

100 kWh Electricity	Charging 90% efficiency	90 kWh available

Fuel Cell Vehicle

100 kWh Electricity	Electrolysis 20% loss	Compression 7% loss	Fuel Cell Operation 50% efficiency	37 kWh available

Heavy Duty BEV vs. H_2 Vehicle

Cost

0,3 - 0,8 €/kWh
Very expensive electricity at fast charging stations

Battery Electric Vehicle

100 kWh Electricity → Charging 90% efficiency → 90 kWh available

0,33 – 0,88 €/kWh

0 - 0,1 €/kWh

Very cheap electricity captured when there is low or no demand

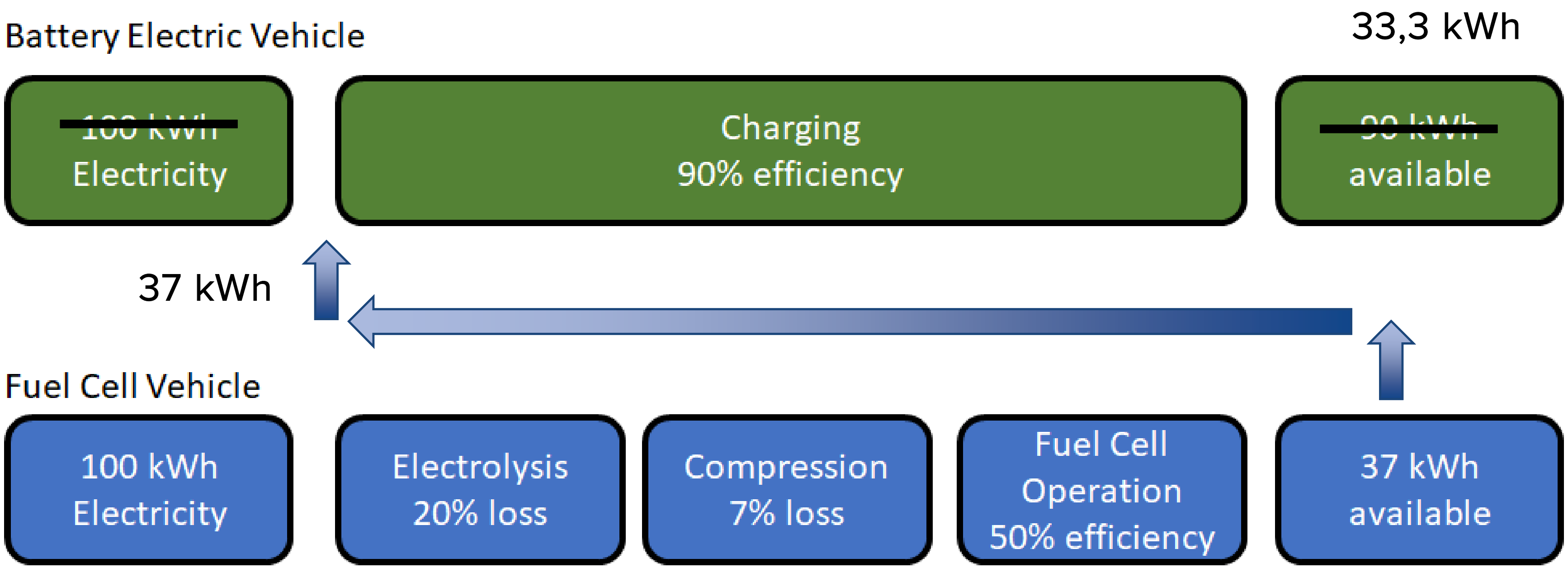
Fuel Cell Vehicle

100 kWh Electricity → Electrolysis 20% loss → Compression 7% loss → Fuel Cell Operation 50% efficiency → 37 kWh available

0 - 0,27 €/kWh

BEV vs. H_2 Vehicle in Hydrogen Society

Electricity energy storage in H2



Is H_2 internal combustion engine ruled out due to low efficiency?
No, not after the breakthrough with H_2 HPDI.

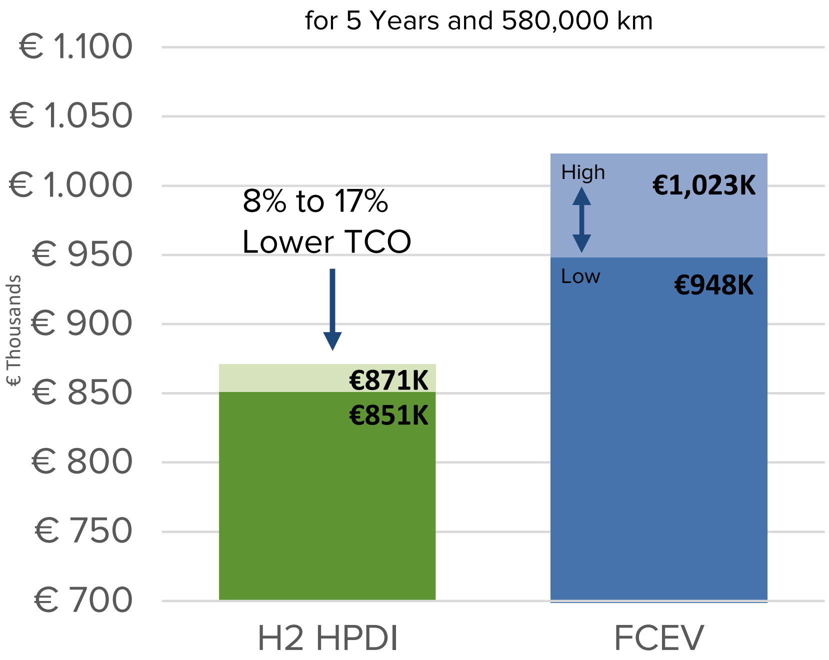
H_2 HPDI the Gamechanger

- Biggest challenge for H_2 as a fuel in HD vehicles is range due to the low energy density of the fuel. This is valid both for compressed (700 bar) and LH2.
  - 90kg H_2 => 900 km range
- H_2 HPDI offers higher efficiency than corresponding diesel engine, 5-8% higher efficiency
- H_2 HPDI offers the most efficient solution for an HD combustion engine. At high load it is even more efficient than a fuel cell on vehicle level.
- With the introduction of H_2 HPDI, HPDI is no longer a methane "bridge" technology and will be competitive with FCEV near and long term
- HPDI requires minimal changes to the base engine. Only fuel system is replaced. Existing production lines can be used and value creation kept within the OEM company.
- Potential to utilize same injector hardware for both LNG and H_2
- Ignition initiator fluid (pilot) can be significantly reduced. Westport is aiming for a Zero CO_2 engine

TCO Analysis of H_2 HPDI

H_2 HPDI: Pathway to Near-Zero Emissions

Total Cost of Ownership (TCO)



Source: AVL / Westport TCO study, 2021

Benefits vs. Fuel Cell

For the Truck Customer

- Lower upfront acquisition costs
- Proven truck design and durability
- Familiar truck operation

For the OEM

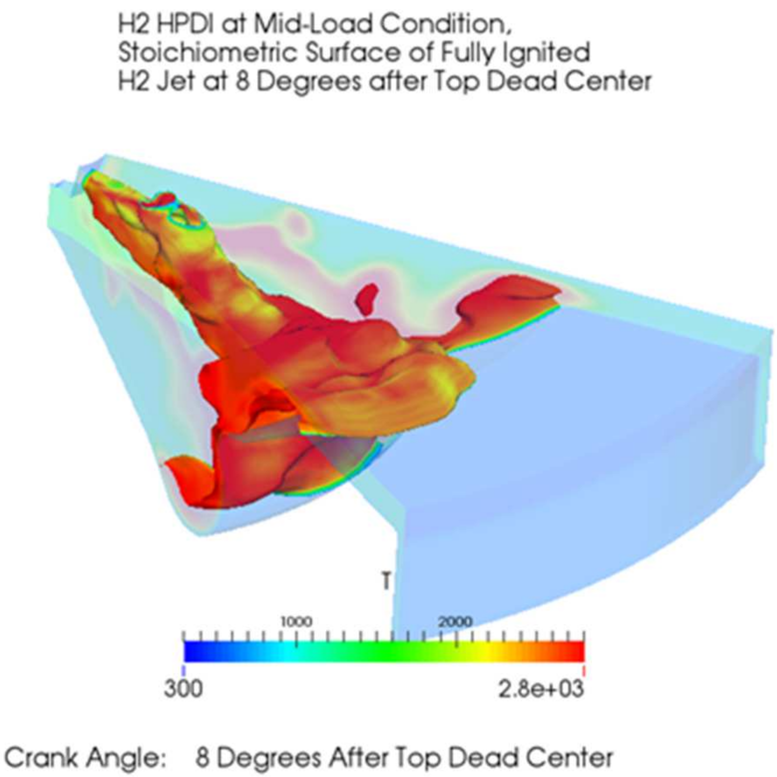
- Low product development cost
- Preserve current manufacturing, supply chain, and service infrastructure
- Avoid manufacturing investments for fuel cells, batteries, and motors

For the Environment

- Renewable, zero carbon fuel
- Lower investment path to reduce CO_2 in heavy-duty, long-haul trucking

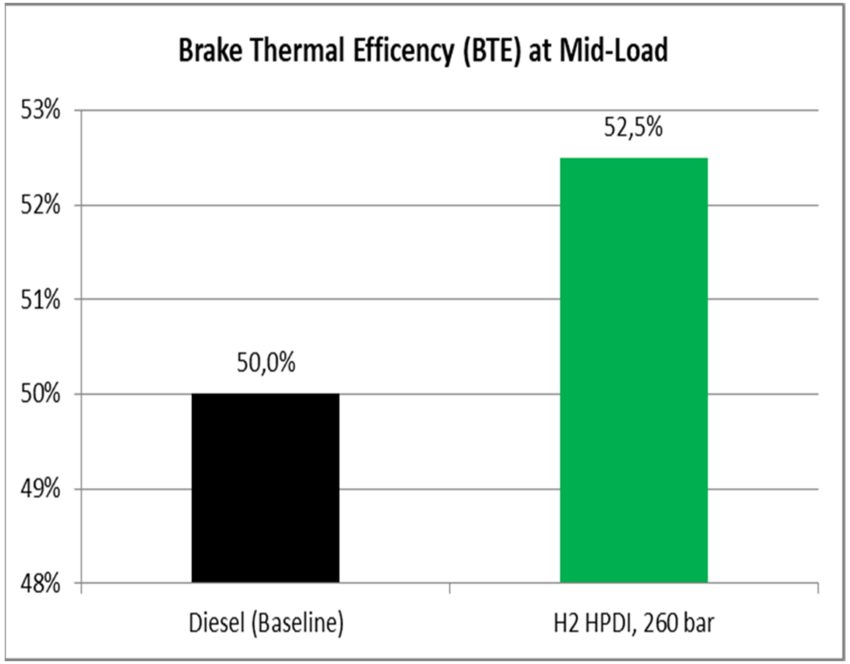
Evaluation & Simulation of H_2 Combustion

H_2 HPDI Investigation on a State-of-the-Art HD Diesel Engine



- Westport Fuel Systems carried out a simulation study on a heavy-duty diesel engine utilizing the WFS in-house state-of-the-art engine combustion CFD solver
- The model predictions have been validated against experimental engine test data over a wide range of operating conditions on multiple engine platforms for pilot-ignited gaseous fuel combustion over the last 15+ years including H_2
- Figure 1 shows the CFD visualization of the fully ignited hydrogen jet as the HPDI combustion is unfolding in the engine cylinder at mid-load condition (50% load at 1200 RPM). The CFD tool has been critical in investigating and optimizing HPDI combustion for H_2 fuel.

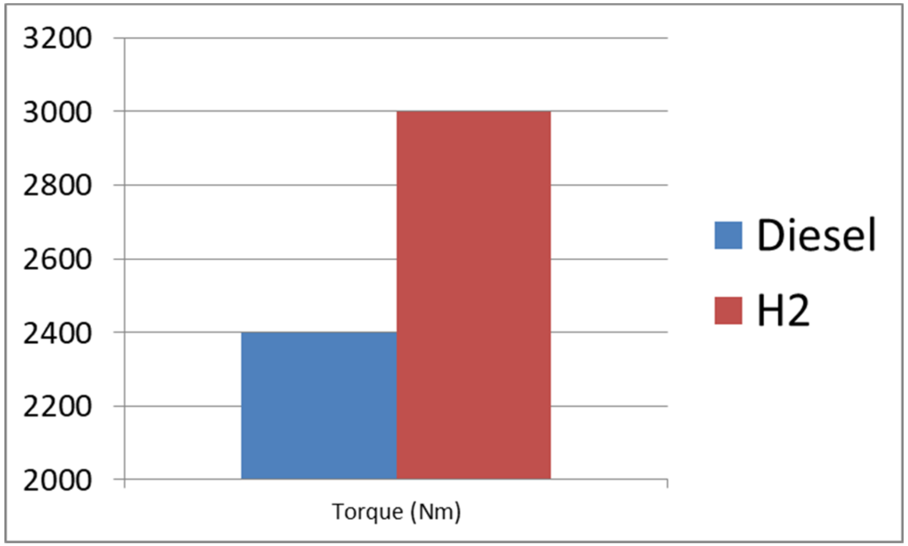
H_2 HPDI Investigation on a State-of-the-Art HD Diesel Engine



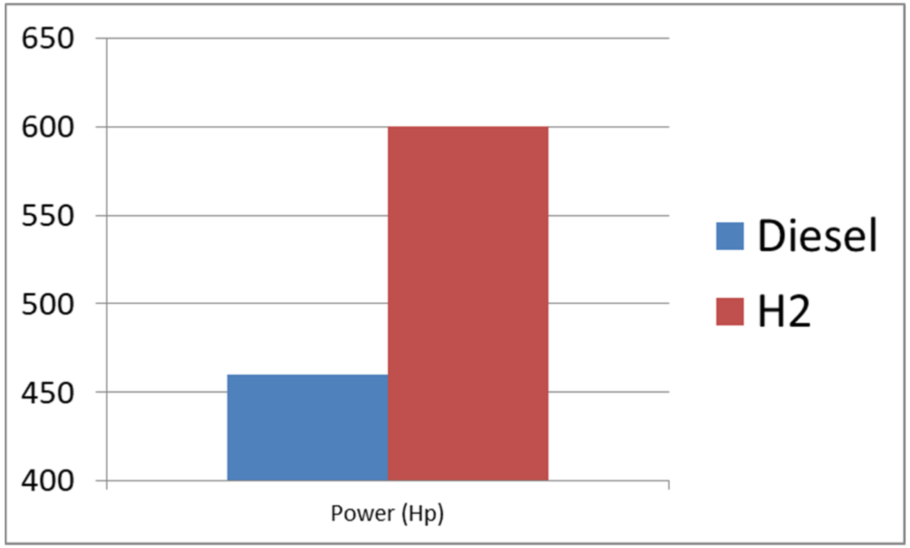
- CFD simulation shows comparison between diesel and hydrogen (H_2) HPDI. Baseline simulation is made on a diesel combustion system designed to achieve 50% BTE. As seen from Figure 2, the H_2 HPDI at mid-load (50% load) condition demonstrates a brake thermal efficiency (BTE) of 52.5% with 260 bar gas injection pressure.
- Similarly, at peak torque condition (not shown in the figure), the H_2 HPDI brake thermal efficiency (BTE) was 50.1% with 290 bar gas injection pressure. Increasing the fuel injection pressure for H_2 HPDI to 440 bar, peak torque BTE was 51.4%.

H_2 HPDI Initial Testing of Performance Potential

Torque



Power



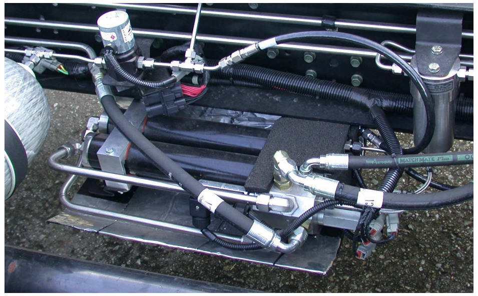
Torque and power comparison of 13-liter engine with diesel and with H_2 HPDI
(engine limitations like PCP, exhaust temp, and boost pressure kept below limit)

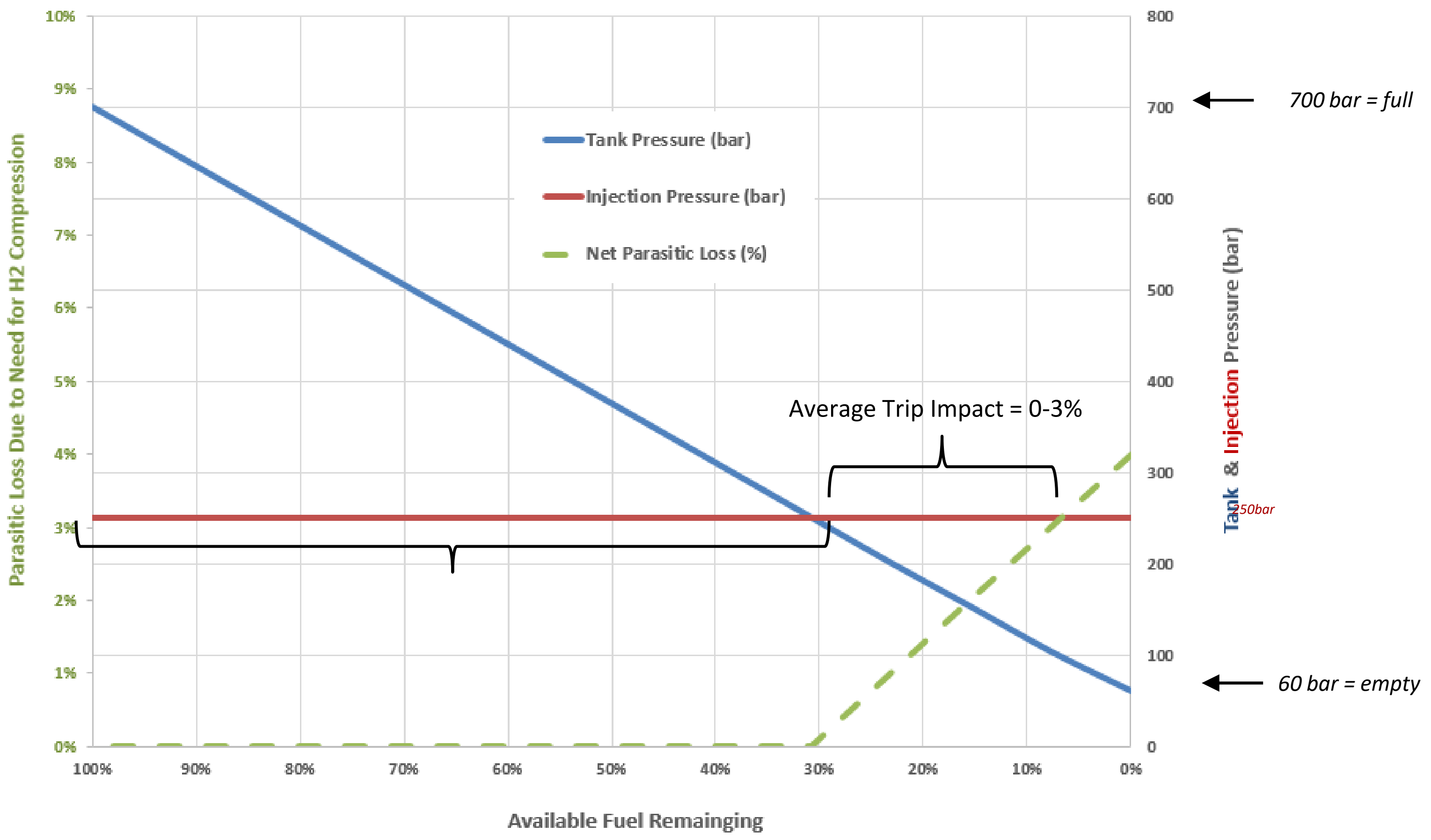
What Makes WFS and H_2 HPDI Uniquely Positioned

- H_2 HPDI can leverage the same on-engine fuel system components we sell today
- H_2 HPDI can leverage the same off-engine storage system as FCEVs, plus a booster compressor
  - WFS supplies H_2 tank vales, regulators, PRVs for FCEVs today
  - WFS has a booster compressor at TRL 3-4
- Hydrogen market is moving toward 700 bar for automotive applications, and this benefits H_2 HPDI significantly
  - Injection pressure will be <300 bar so booster compressor only needed for 30-40% of the trip

Example of Booster Compressor During Drive Cycle

- Compressor only runs when needed tank pressure < injection pressure
- Hydraulic drive will be same as for HPDI 2.0 LNG product





Prototype H_2 HPDI Trucks are Already Running on the Road

The world's first compression ignition HD H_2 Truck

Back-Up Material

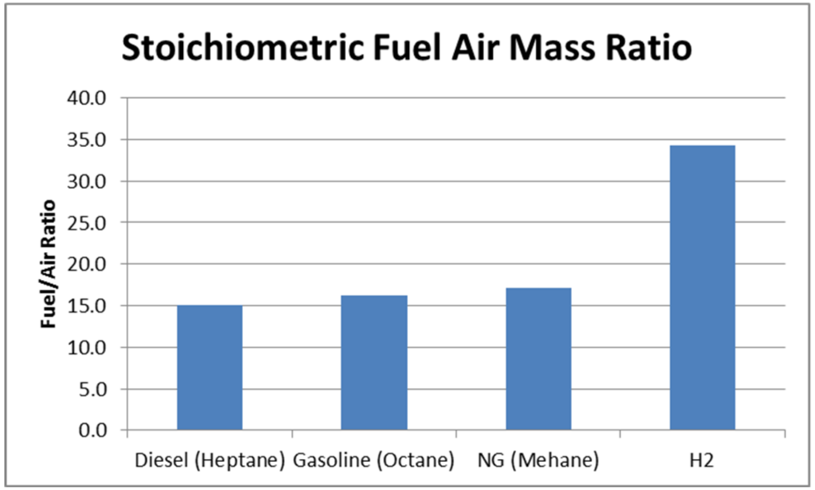
H_2 HPDI Conclusions and Statements

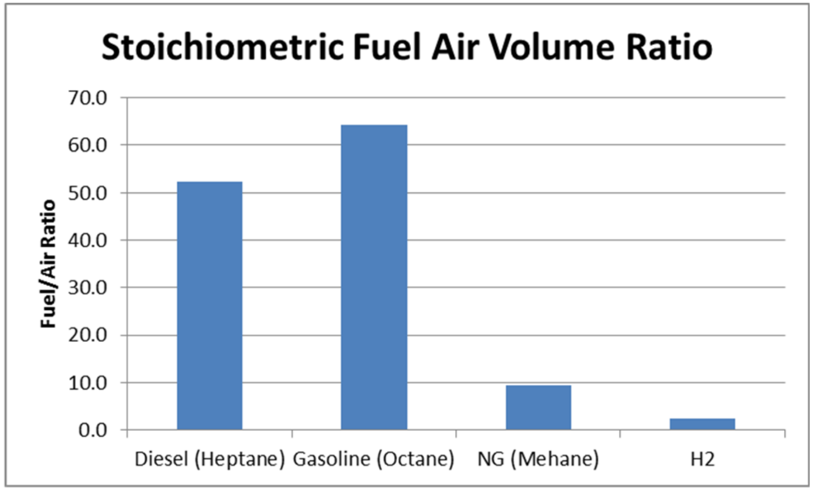
The fact that H_2 HPDI solves at lot of issues operating a combustion engine with H_2 while delivering excellent performance and efficiency makes it a promising path forward and enables a short time to market.

- H_2 HPDI offers the most efficient solution for an HD combustion engine. At high load, it is even more efficient than a fuel cell
- With the introduction of H_2 HPDI, HPDI is no longer a methane “bridge” technology and will be competitive with FCEV near and long term
- HPDI requires minimal changes to the base engine. Only fuel system is replaced and major changes to the aftertreatment system are avoided, which translate into short time to market.
- Existing production lines can be used and value creation kept within the OEM company
- Potential to utilize same injector hardware for both LNG and H_2. Unsensitive to fuel quality and purity.
- Ignition initiator fluid (pilot) can be significantly reduced. Westport is aiming for a Zero CO_2 engine.
- Higher torque and power density than diesel due to the absence of knock
- Even higher efficiency than the excellent efficiency of a diesel engine
- No difference in thermal and mechanical load to combustion chamber, crank train, and exhaust train compared to diesel operation
- Lubricity and safety: No combustible H_2/Air mixture and water vapor passing the ring pack into the crankcase

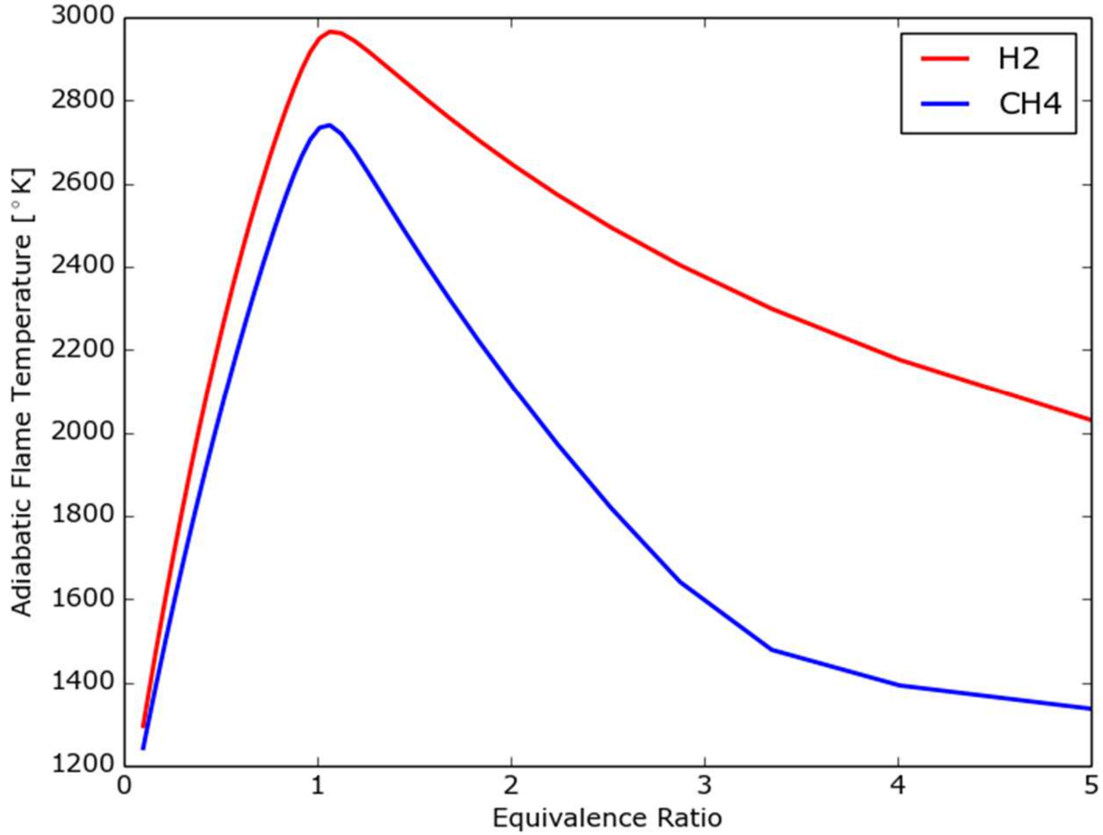
Property of Hydrogen and Its Potential in ICE

	Combustion Related			
	Stoichiometric Fuel Air Mass Ratio	Stoichiometric Fuel Air Volume Ratio	LHV	Air-Specific Heating Value
			MJ/kg	MJ/kg Air
Diesel (Heptane)	15.1	52.4	44.5	2.9
Gasoline (Octane)	16.3	64.3	44.4	2.7
NG (Mehane)	17.2	9.5	50	2.9
H2	34.3	2.4	121	3.5



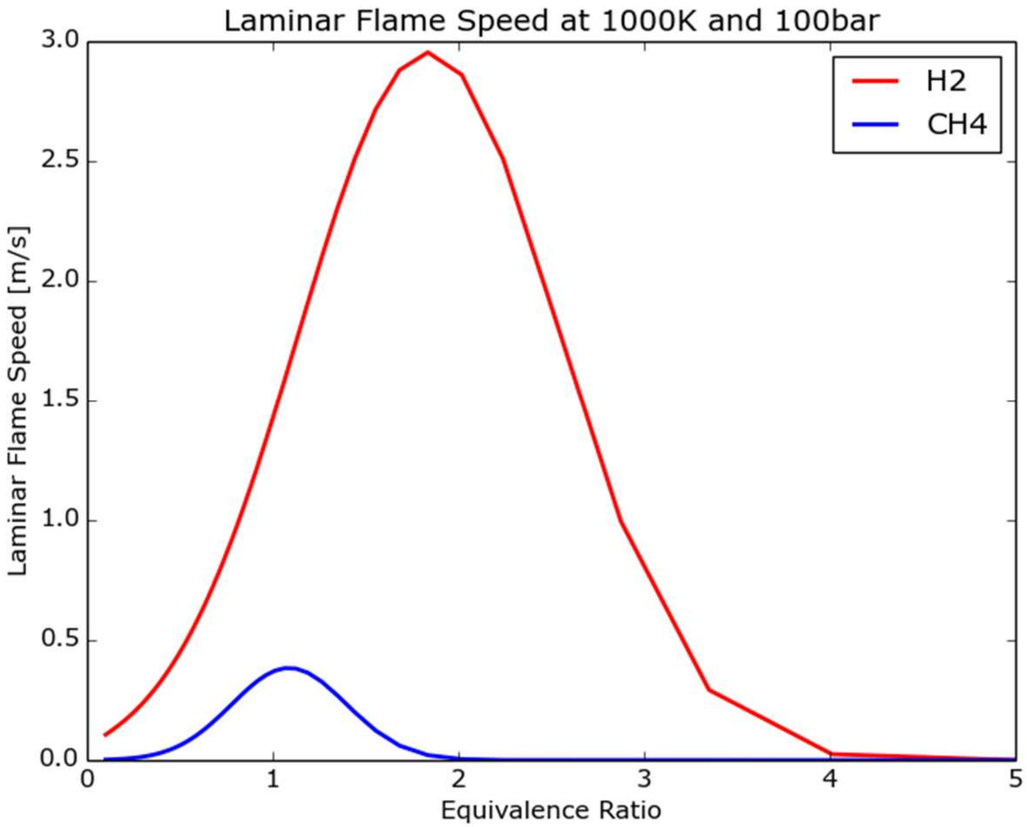


Adiabatic Flame Temperature of Hydrogen



For methane on the fuel-rich side, the AFT decreases much faster compared to hydrogen. This is due to the fact that several reaction mechanisms such as the steam-methane reforming reaction and pyrolysis reactions are strongly endothermic.

Laminar Flame Speed of Hydrogen



- The laminar flame speed for hydrogen is 6 times that of methane
- While the peak LFS for methane appears around stoichiometry, the peak for hydrogen appears significantly to the fuel-rich side (equivalence ratio = 1.8)
- Hydrogen combustion has high tolerance to fuel-rich operation

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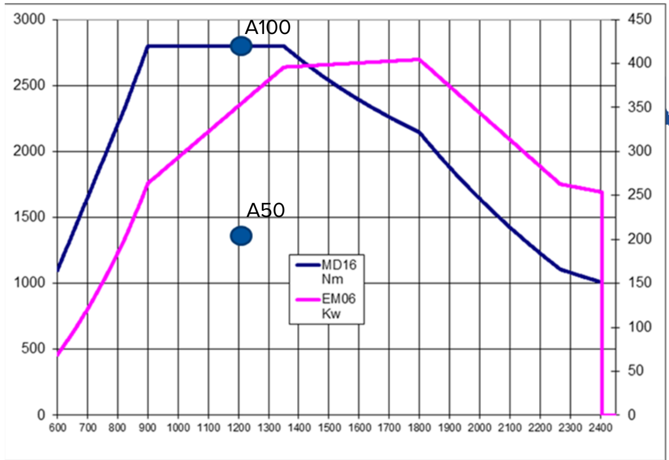
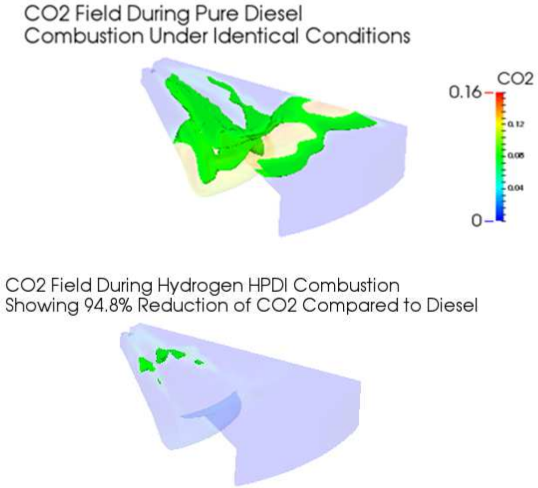
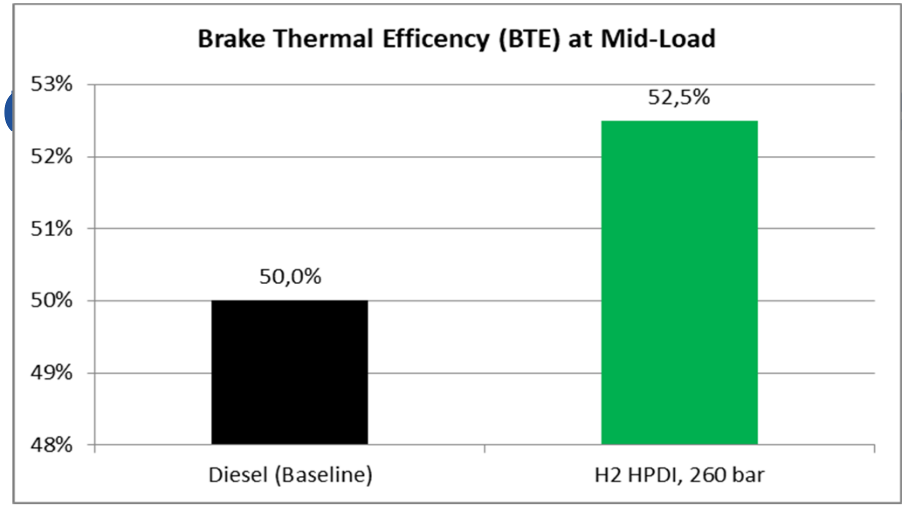


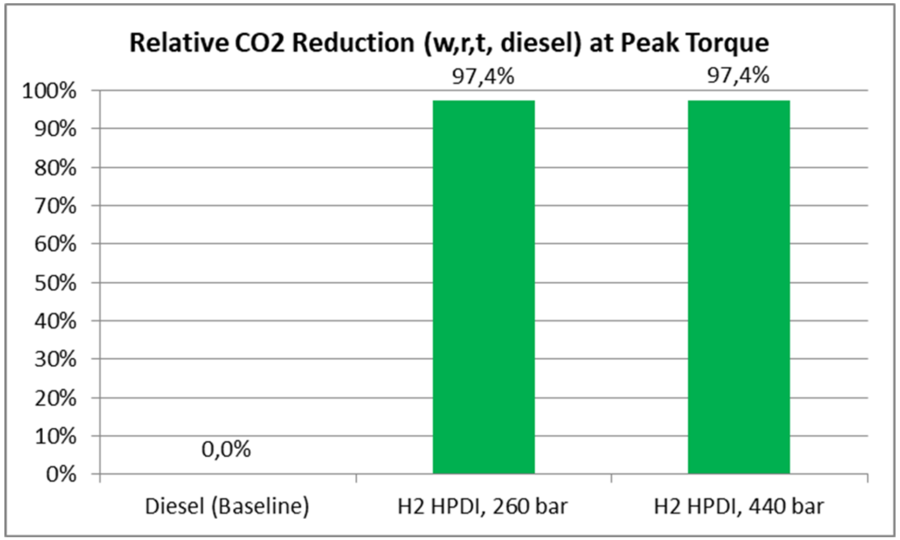
Torque Curve of Base Diesel Engine and Simulated Points



CO2 Mass Fraction of Diesel (Above) and H2 HPDI (Below)



Over 50% brake thermal efficiency was predicted for H2 HPDI at the mid load point



CO_2 reduction of 97.4% from diesel baseline at the high load point with H2 HPDI


Thank you