Westport HPDI ™: an efficient and affordable path for decarbonization

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DEKRA Zukunftskongress
Nutzfahrzeuge 2023, Berlin

We’re Changing the Way the World Moves

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

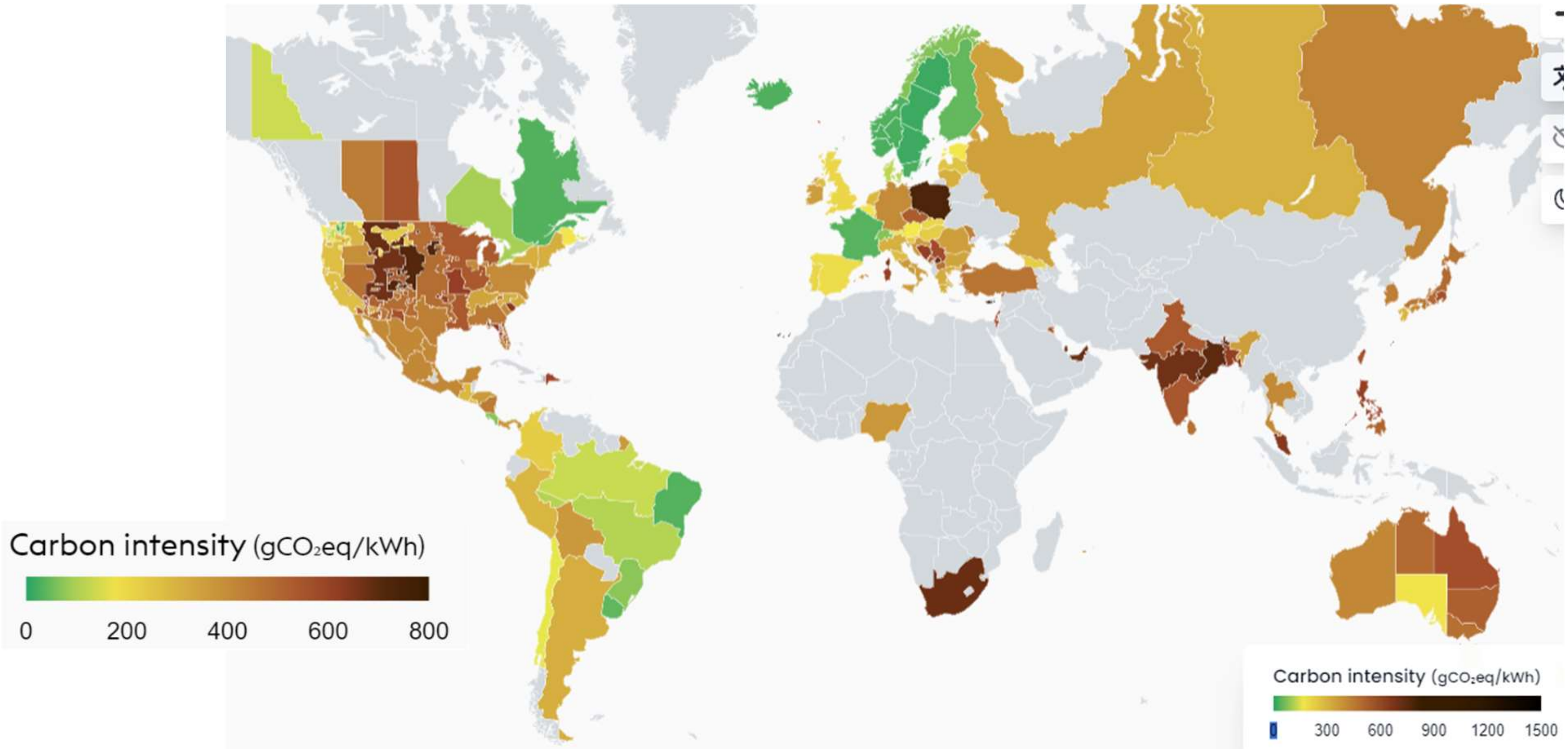
>100
Global distributors worldwide

>1,400 Patents & Applications
Robust patent portfolio

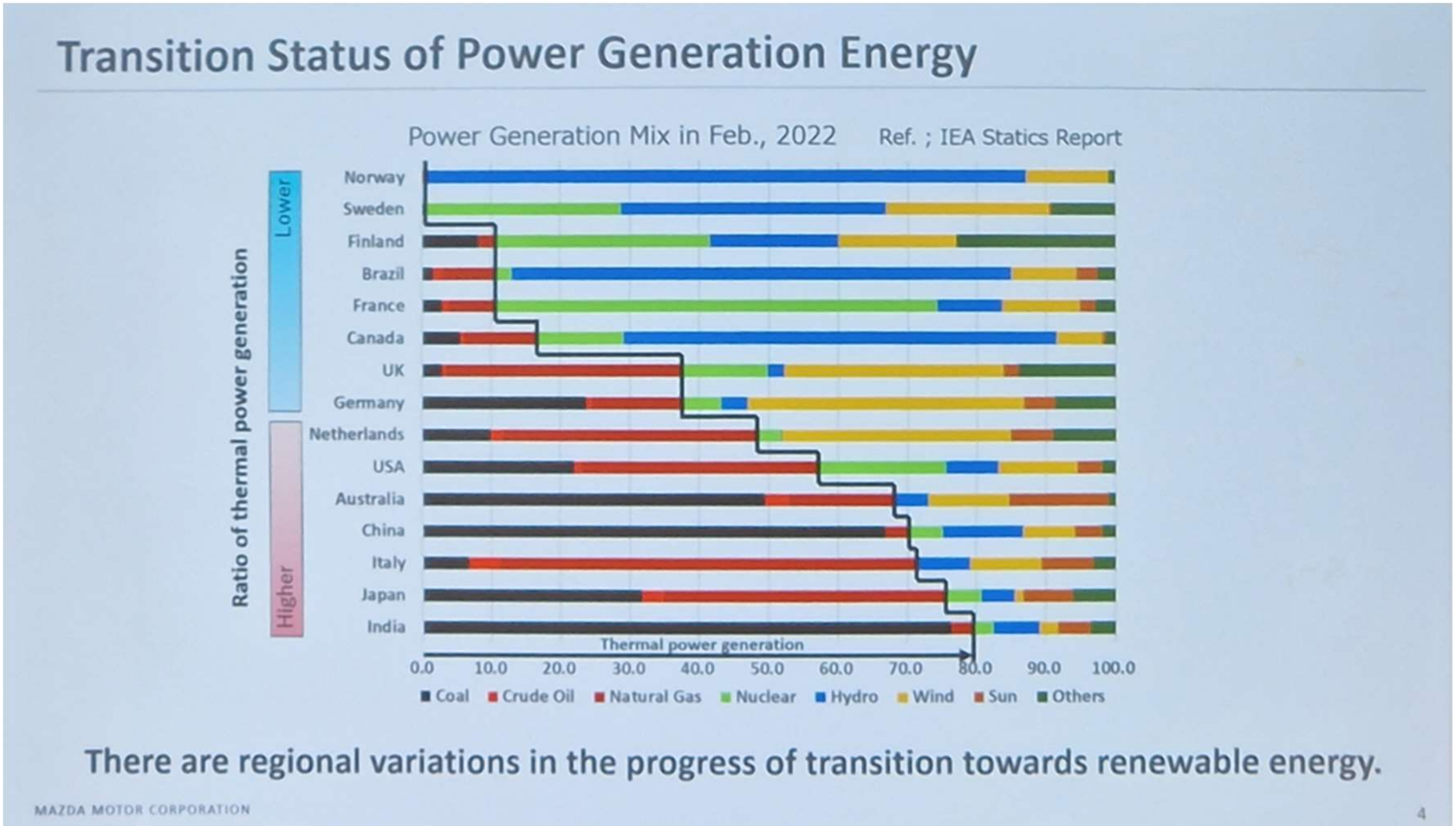
We design, engineer & manufacture gaseous fuel systems & components to enable cleaner, affordable transportation

Electricity Map

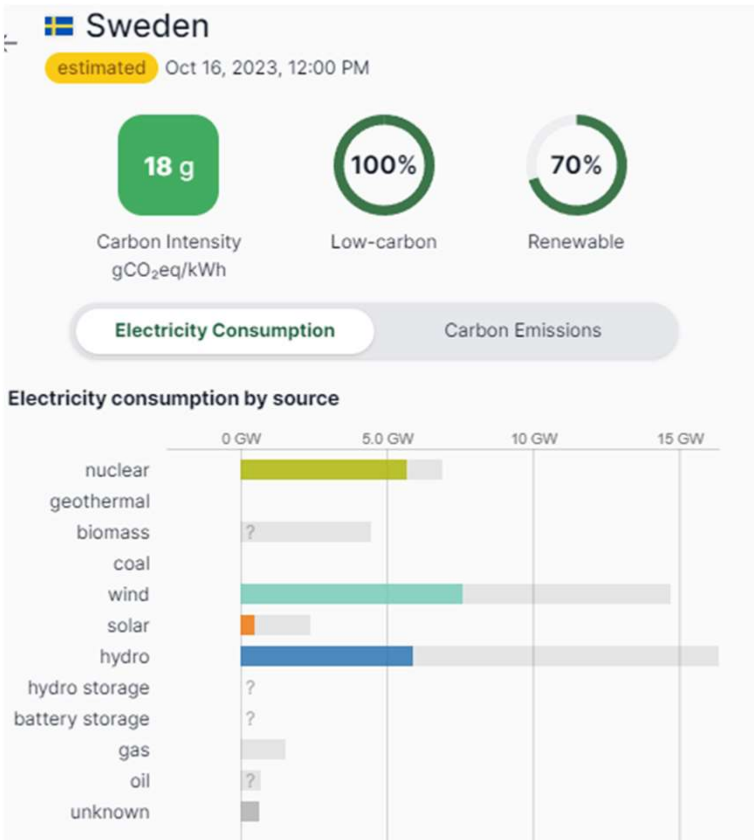
Electricity carbon footprint last 12 months

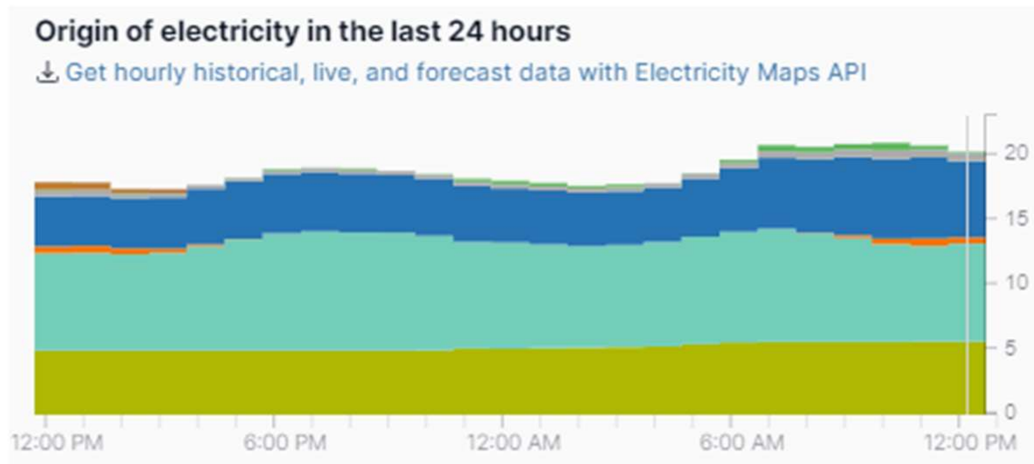


Status of transition towards electricity with low CO2 footprint

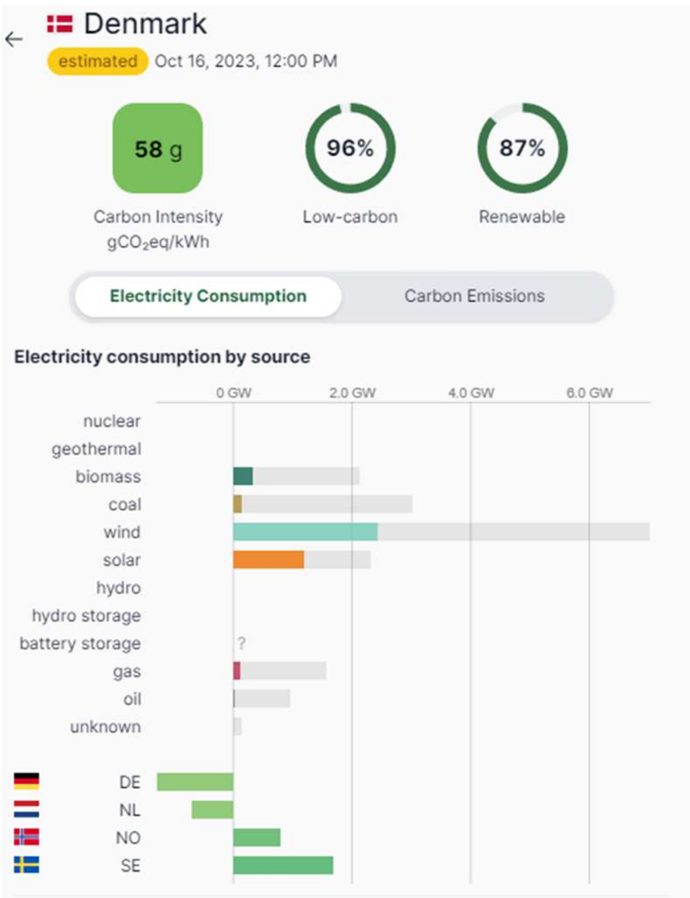


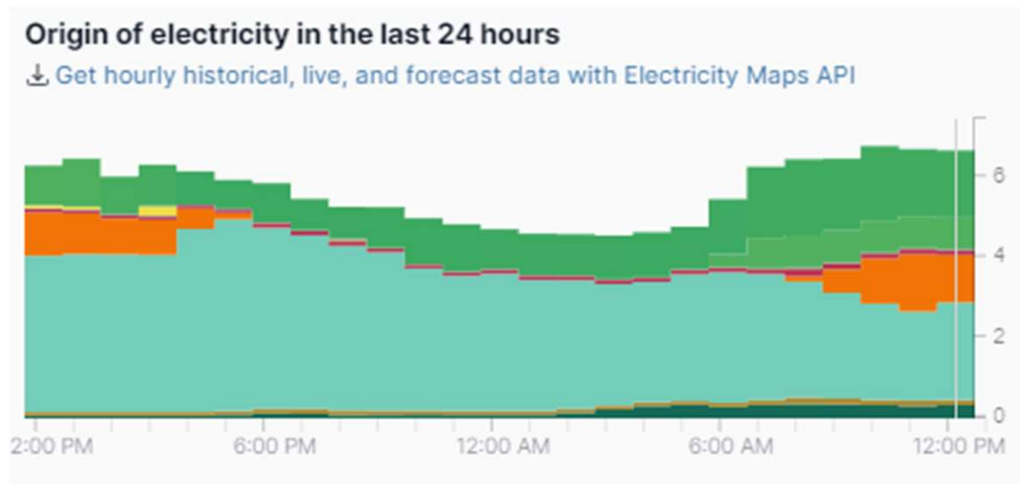
Green Electricity Production





Green Electricity Production





Green Electricity Production and the challenge with storage and transportation

The challenge with a Battery Electrical Vehicle is that electricity needs to be produced at the same **time** as the battery is charged and preferable **nearby** to avoid transition losses.

H2 can be produced when electricity is **cheap** and as well at **distance** from the tank station. Transporting energy in H2 pipeline is 7-20 times cheaper than that via electrical grid.

BEV vs. H2 Vehicle – Energy efficiency

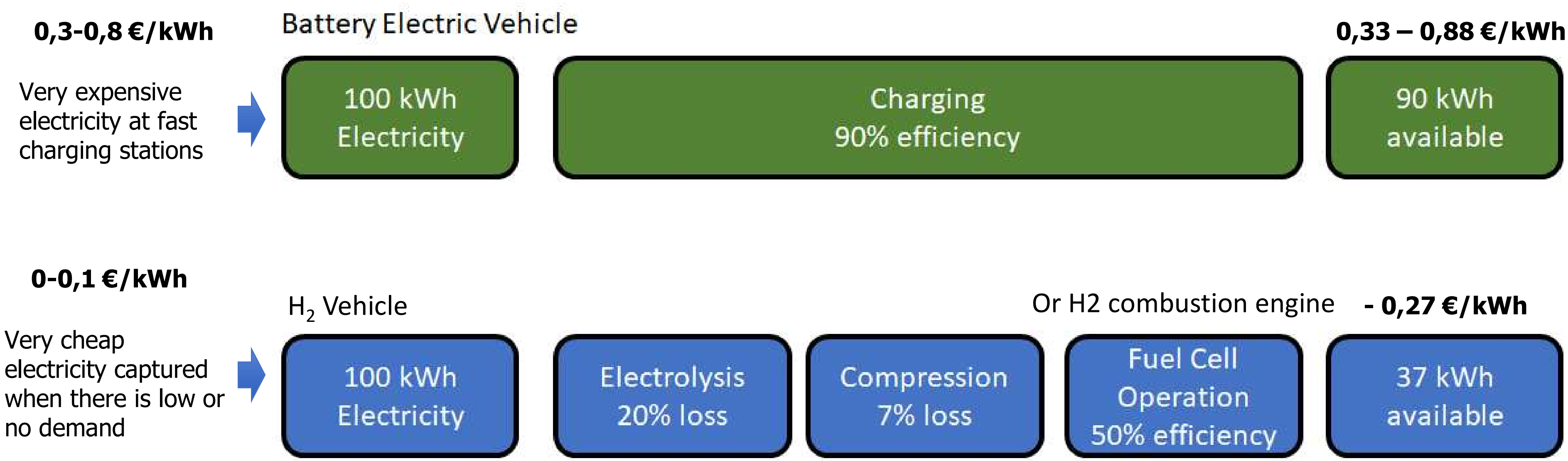
Battery Electric Vehicle

100 kWh Electricity	Charging 90% efficiency	90 kWh available

H_2 Vehicle

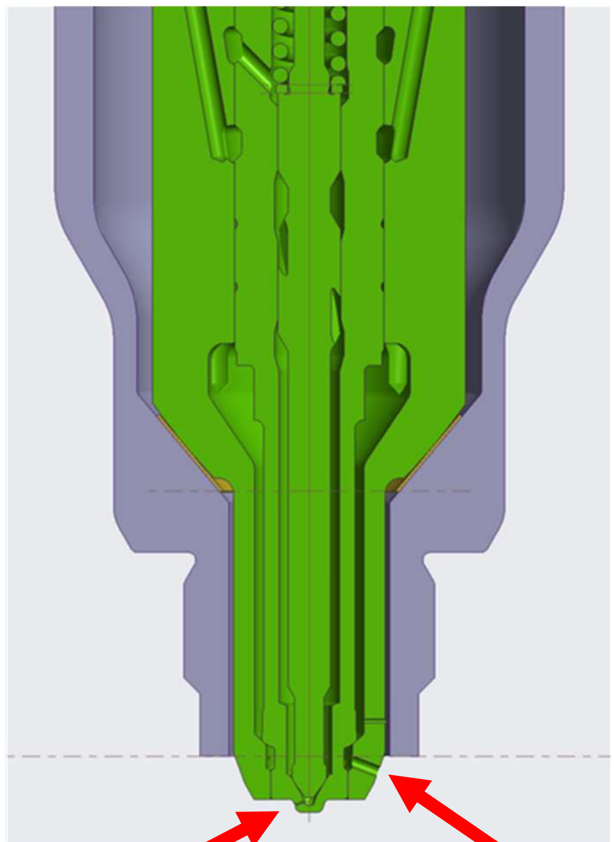
100 kWh Electricity	Electrolysis 20% loss	Compression 7% loss	Fuel Cell Operation 50% efficiency	37 kWh available

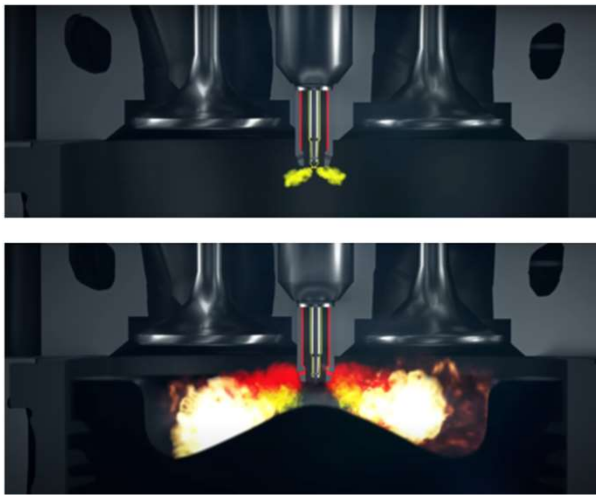
BEV vs. H2 Vehicle – Cost comparison



HPDI NG & H2


Electric connector
Pilot fluid supply
Gas supply


HPDI nozzle with 2 concentrical needles
Pilot fluid injection holes
Gas fuel injection holes



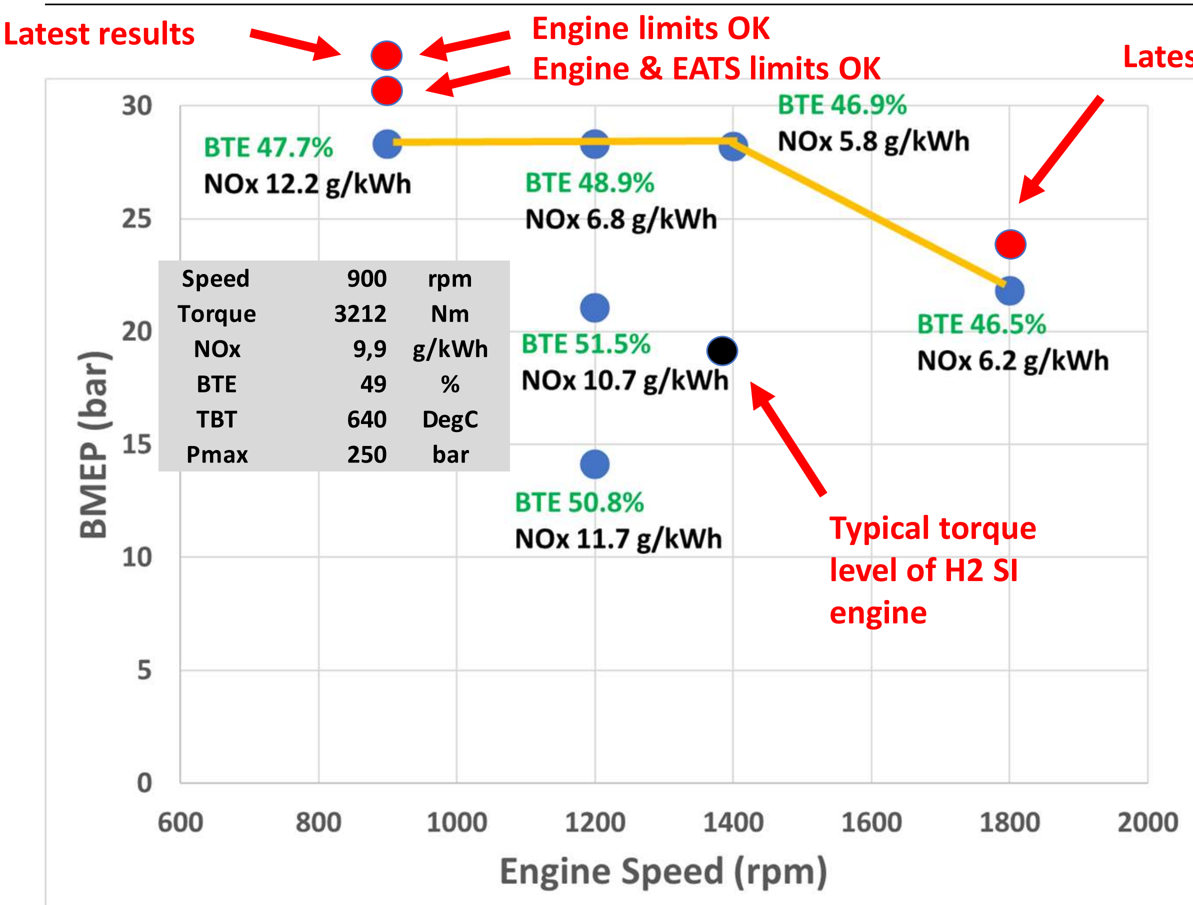
Looking to the Future – A Flexible System

Engine platform commonality

One of the beauties with the HPDI technology is the great commonality with engine suitable for other fuels

Item	Diesel	LNG HPDI	CNG HPDI	H2 HPDI	LNG/CNG SI	H2 SI
Base engine	Baseline	->	->	->	->	Displacement increse
Cylinderhead	Baseline	Injector fit	Injector fit	Injector fit	Sparkplug cooling	Access for DI
Piston	Baseline	->	->	->	New ring pack	New ring pack
Piston bowl	Baseline	->	->	->	New	New
Camshaft	Baseline	->	->	->	New?	New?
Charging system	Baseline	->	->	->	New	New (2 stage)
Exhaust manifold	Baseline	->	->	->	New?	->
Aftertreatment system	Baseline	->	->	->	New	Stoich => New
Fuel storage system	Baseline	LNG - cryopump	CNG - Compressor	700 bar (LH2)	LNG or CNG	700 bar (LH2)

H2 Combustion on H2 HPDI 13L Scania Engine



- Latest results 32 bar BMEP (3200 Nm)
- **Peak BTE at 51.5%**
- Engine-out NOx levels equates to ~6-12 g/kWh during initial. In line with current diesel EATS strategy
- Note: cooled EGR can efficiently reduce NOx further to ~3g/kWh
- Pilot quantities as low as 2-3mg have been tested, equating to **ZEV levels for CO_2 emissions**

Why do H2 HPDI enable higher power & Torque

Torque and power on a diesel engine is limited by **max cylinder pressure** and **exhaust temperature**.

- For a given airflow thru the engine H2 can release **24% more energy** than combustion of diesel. Therefore the H2 HPDI engine needs less boost pressure lowering max cylinder pressure.
- The compressed and cold H2 injected at TDC gives 50 – 100 K lower exhaust temperature. H2 has **2,5 times** higher **cooling effect** than diesel including the evaporation effect.

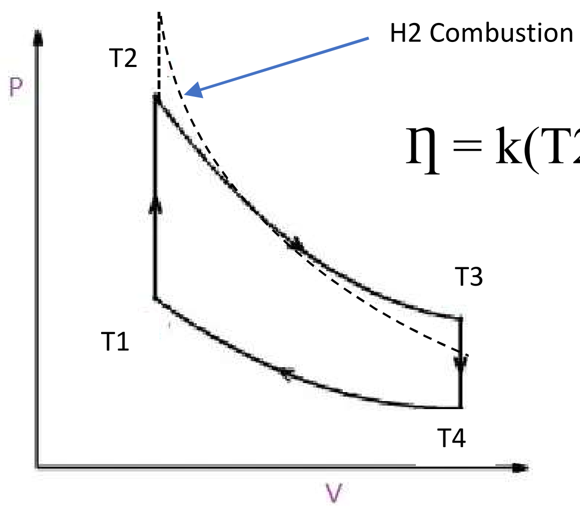
$$O_2 + 2H_2 = 2H_2O \quad \Rightarrow \quad 3.5\ \text{MJ/kg air}$$

$$O_2 + 0{,}41CH_{1,8} = 0{,}41CO_2 + 0{,}37H_2O \quad \Rightarrow \quad 2.9\ \text{MJ/kg Air}$$

Molar expansion Lambda 2

	Added Mole ratio	Combustion molar expansion	Final mole / before injection mole
H2	1,21	0,913	1,11
C7H16	1,01	1,028	1,038

Why do H2 HPDI enable higher efficiency



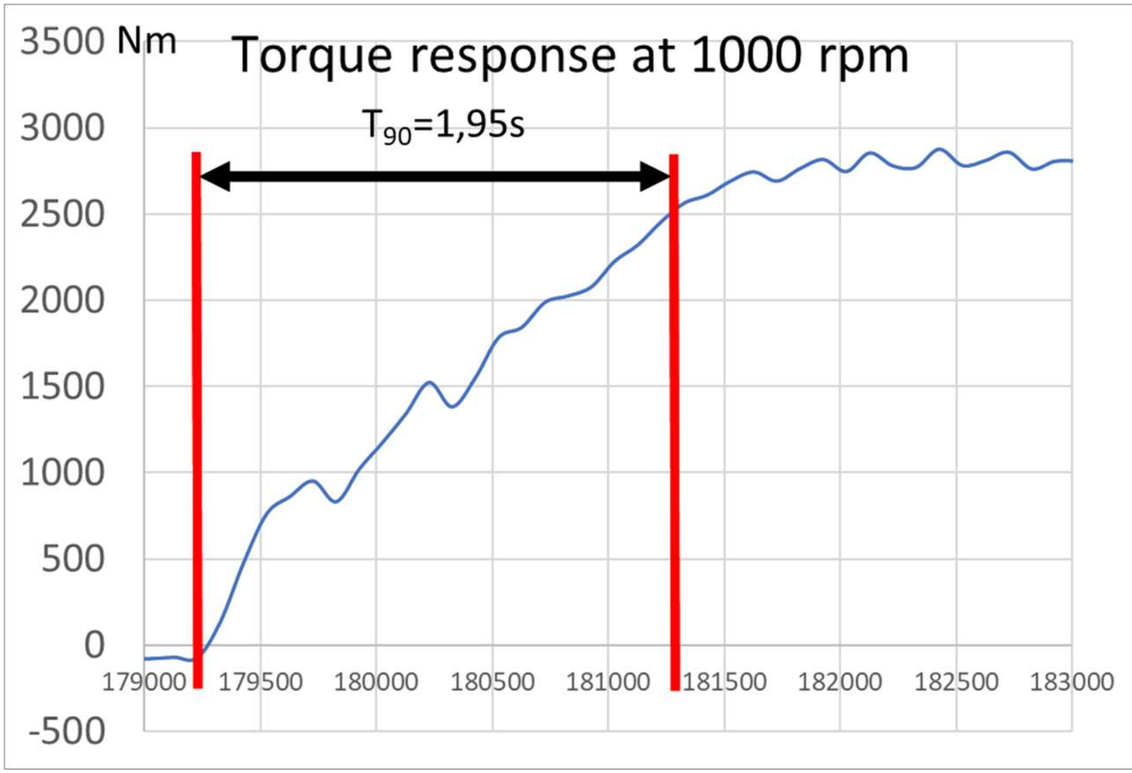
$$\eta = k(T2-T1)/(T3-T4)$$

1. **The low density H2 that is injected at TDC contribute to work when expanded during the expansion stroke.**
2. **The higher flame temp gives directly a better cycle efficiency.**
3. **The higher combustion speed enables a more favourable heat release close to TDC**
4. **As the H2 is injected a low pressure compared to diesel less turbulence is induced and therefore lower heat flux thru the combustion chamber walls.**

H2 HPDI transient response

The H2 HPDI has roughly 40% faster torque response compared to base diesel engine.

- **For a given airflow thru the engine H2 can release more energy than combustion of diesel. Therefore the H2 HPDI engine has higher natural aspirated torque.**
- **H2 HPDI generates no soot. Soot limiter is therefore not required and Lambda close to 1 can be utilized during transient for a limited number of cycles before thermal load becomes to high.**



H2 HPDI transient response

What is the maximum torque in the 1st cycle – after a full torque request from motoring or idle – for different fuels and combustion principles?

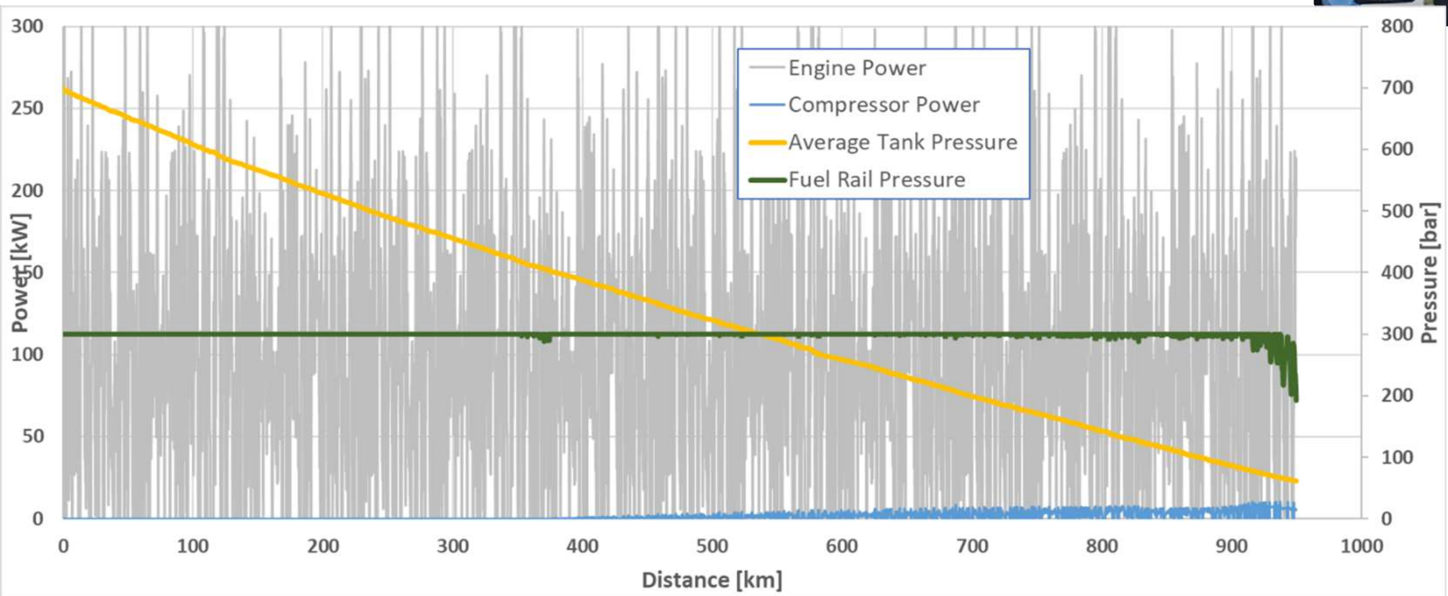
Diesel	**AFR_{stoich} = 14.5**	**LHV = 42.5MJ/kg**	**BTE = 48%**
Trapped amount of air in the cylinder @ IVC;		2.3g	based on 101.3kPa and 325K
Minimum λ due to smoke reasons;		1.3	
=> Maximum added fuel in 1st cycle;		2.3 / (14.5 · 1.3) = 122mg (5.19kJ)	
=> Maximum torque in 1st cycle;		**1.190Nm**	
H_2 HPDI	**AFR_{stoich} = 34.3**	**LHV = 120MJ/kg**	**BTE = 48%**
Trapped amount of air in the cylinder @ IVC;		2.3g	based on 101.3kPa and 325K
Minimum λ;		1.0*	
=> Maximum added fuel in 1st cycle;		2.3 / 34.3 = 67.1mg (8.05kJ)	
=> Maximum torque in 1st cycle;		**1.840Nm**	
H_2 Homogenous SI	**AFR_{stoich} = 34.3**	**LHV = 120MJ/kg**	**BTE = 43%**
Trapped amount of air in the cylinder @ IVC;		1.6g	based on 70kPa** and 325K
Minimum λ due to $EONO_x$ and preignition;		1.9	
=> Maximum added fuel in 1st cycle;		1.6 / (34.3 · 1.9) = 24.6mg (2.95kJ)	
=> Maximum torque in 1st cycle;		**605Nm**	

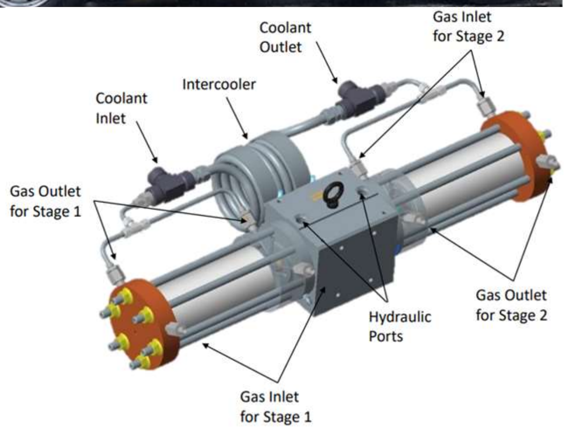
Prototype H2 HPDI Trucks
are already running on the road

H_2 Demonstration Trucks – Next Steps

- With increased fuel storage:
  - 80kg of fuel enables a range of 900km range*

Simulated Highway / Moderately Hilly Route (20-tonne load)





On-board compressor

* Cycle/load dependent

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**
- **More than 100% CO_2 reduction with bio-LNG**
- No change to vehicle or engine architecture

H_2 HPDI

- 20% more power, 15% more torque
- **ZEV complient according to latest EU proposal**
- **Lowest cost to CO_2 compliance**
- Preserve existing engine manufacturing

Contact Info

Thank you!

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