High Efficiency Hydrogen ICE

Carbon Free Powertrain for Passenger Car Hybrids and Commercial Vehicles

Webinar on H_2 ICE, October 25, 2022

Paul Kapus, Bernhard Raser

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Today’s Presenters

Dr. Paul KAPUS

Manager Spark Ignited Engine Development and Concept Cars @ AVL List GmbH

Engineering studies at Graz University of Technology

PhD at Graz University of Technology

Executive Engineer @ AVL List GmbH

33 Years of Experience in Automotive Industry

Bernhard RASER

Vice President Commercial Vehicles @ AVL List GmbH

Master Degree in Automotive Engineering

Master Degree in International Industrial Management

15 Years of Experience in Automotive Industry

Facts and Figures

Global Footprint

Represented in 26 countries

45 Affiliates at over 93 locations

45 Global Tech and Engineering Centers (including Resident Offices)

1948

Founded

10,700

Employees Worldwide

12%

Of Turnover Invested in Inhouse R&D

70+

Years of Experience

68%

Engineers and Scientists

2,500

Granted Patents in Force

97%

Export Quota

Three Disciplines Under One Roof

ENGINEERING SERVICES

- Design and development services for all elements of ICE, HEV, BEV and FCEV powertrain systems
- System integration into vehicle, stationary or marine applications
- Supporting future technologies in areas such as ADAS and Autonomous Driving
- Technical and engineering centers around the globe

INSTRUMENTATION AND TEST SYSTEMS

- Advanced and accurate simulation and testing solutions for every aspect of the powertrain development process
- Seamless integration of the latest simulation, automation and testing technologies
- Pushing key tasks to the start of development

ADVANCED SIMULATION TECHNOLOGIES

- We are a proven partner in delivering efficiency gains with the help of virtualization
- Simulation solutions for all phases of the powertrain and vehicle development process
- High-definition insights into the behavior and interactions of components, systems and entire vehicles

High Efficiency Hydrogen ICE
Agenda

1 **H_2 Production and Distribution**
Renewable Energy as Boundary

2 **H_2 ICE Technologies**
Combustion Systems for different Applications

3 **Commercial Applications**
The AVL HD Hydrogen Engine

4 **Passenger Car**
Passenger Car Hydrogen Engine

5 **Way to zero impact**
Exhaust Aftertreatment and Emissions

6 **Summary and Conclusions**

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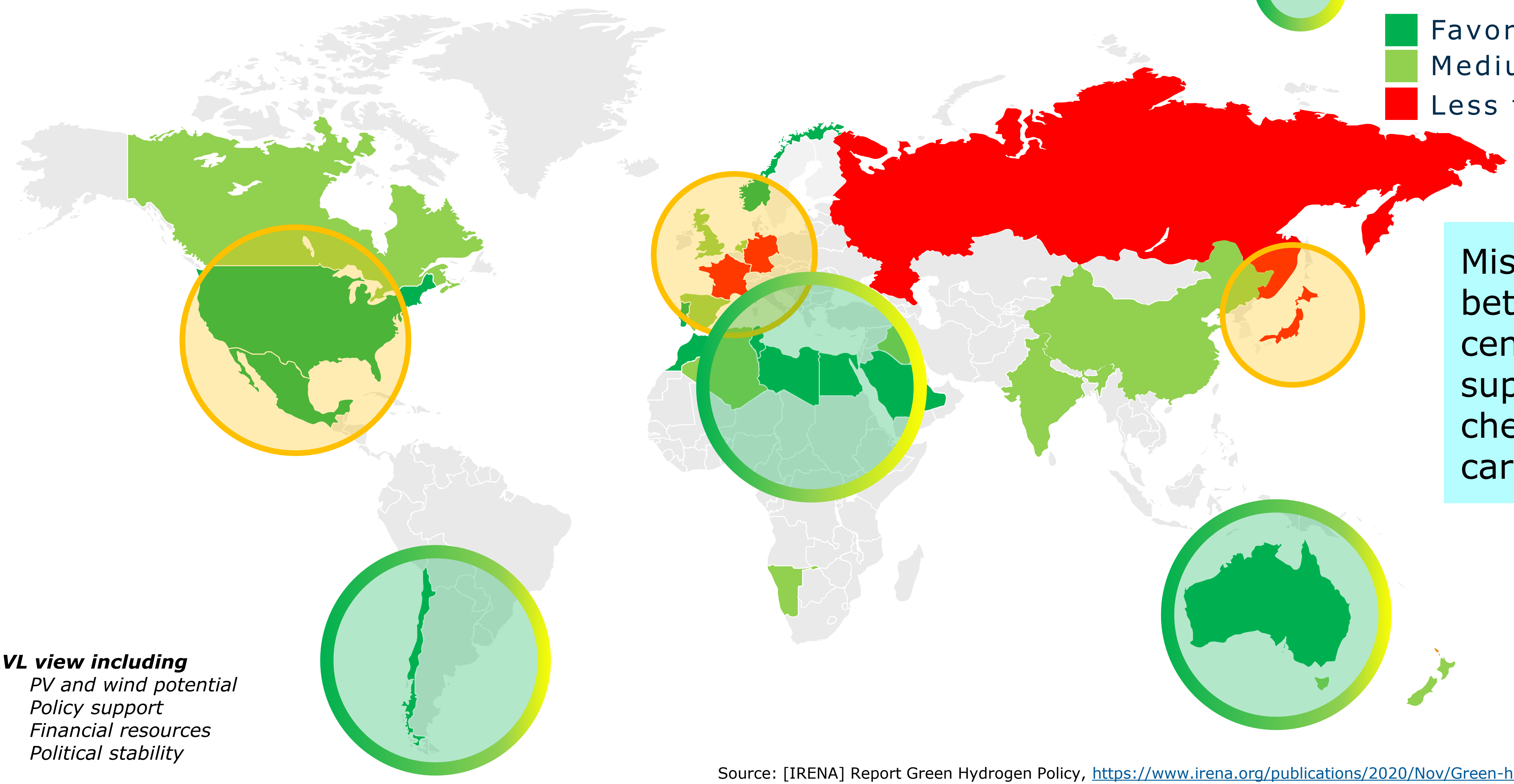
Green Energy Production and Demand

Demand Centers
USA, SE Asia, Europe

Supply Regions

- Favorable Conditions
- Medium Conditions
- Less favorable



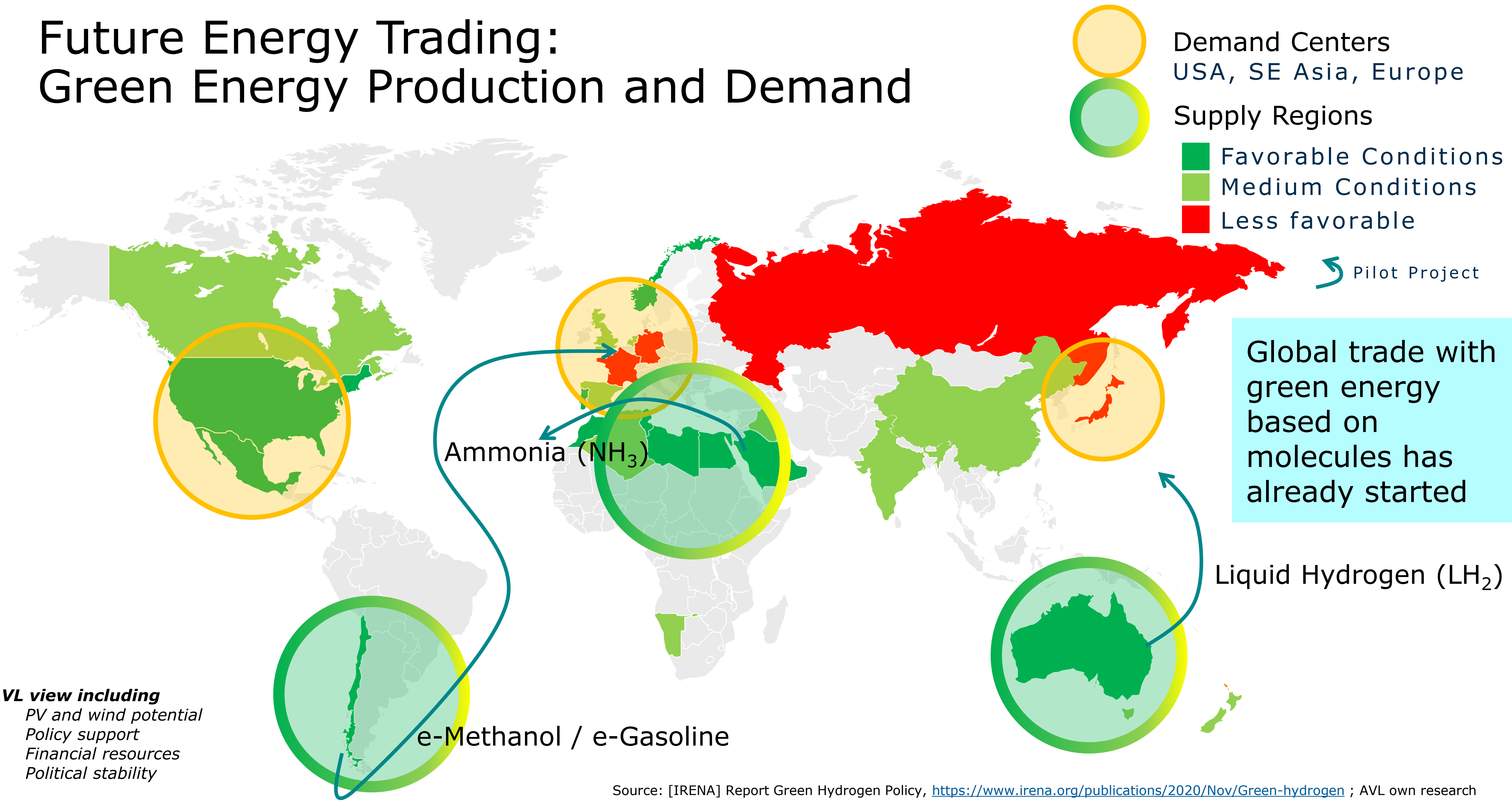
Mismatch between demand center and supply region: chemical energy carrier required

AVL view including

- *PV and wind potential*
- *Policy support*
- *Financial resources*
- *Political stability*

Source: [IRENA] Report Green Hydrogen Policy, https://www.irena.org/publications/2020/Nov/Green-hydrogen ; AVL own research

Future Energy Trading: Green Energy Production and Demand



Global trade with green energy based on molecules has already started

AVL view including

- *PV and wind potential*
- *Policy support*
- *Financial resources*
- *Political stability*

Source: [IRENA] Report Green Hydrogen Policy, https://www.irena.org/publications/2020/Nov/Green-hydrogen ; AVL own research

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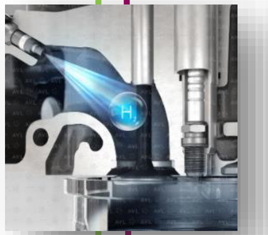
Hydrogen Combustion Concepts for Commercial Applications and Passenger Cars




MPI or Low Pressure DI

Mixture formation **swirl** based



MPI or Low Pressure DI

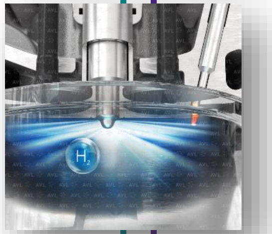
Mixture formation **tumble** based

H_2 Low Pressure

Homogeneous combustion / spark ignited

High Pressure DI

Diesel pilot
Mixture formation: Diesel carry over



High Pressure DI

Carbon neutral ignition
Mixture formation: Diesel carry over

H_2 High Pressure

Diffusion combustion / Diesel ignited

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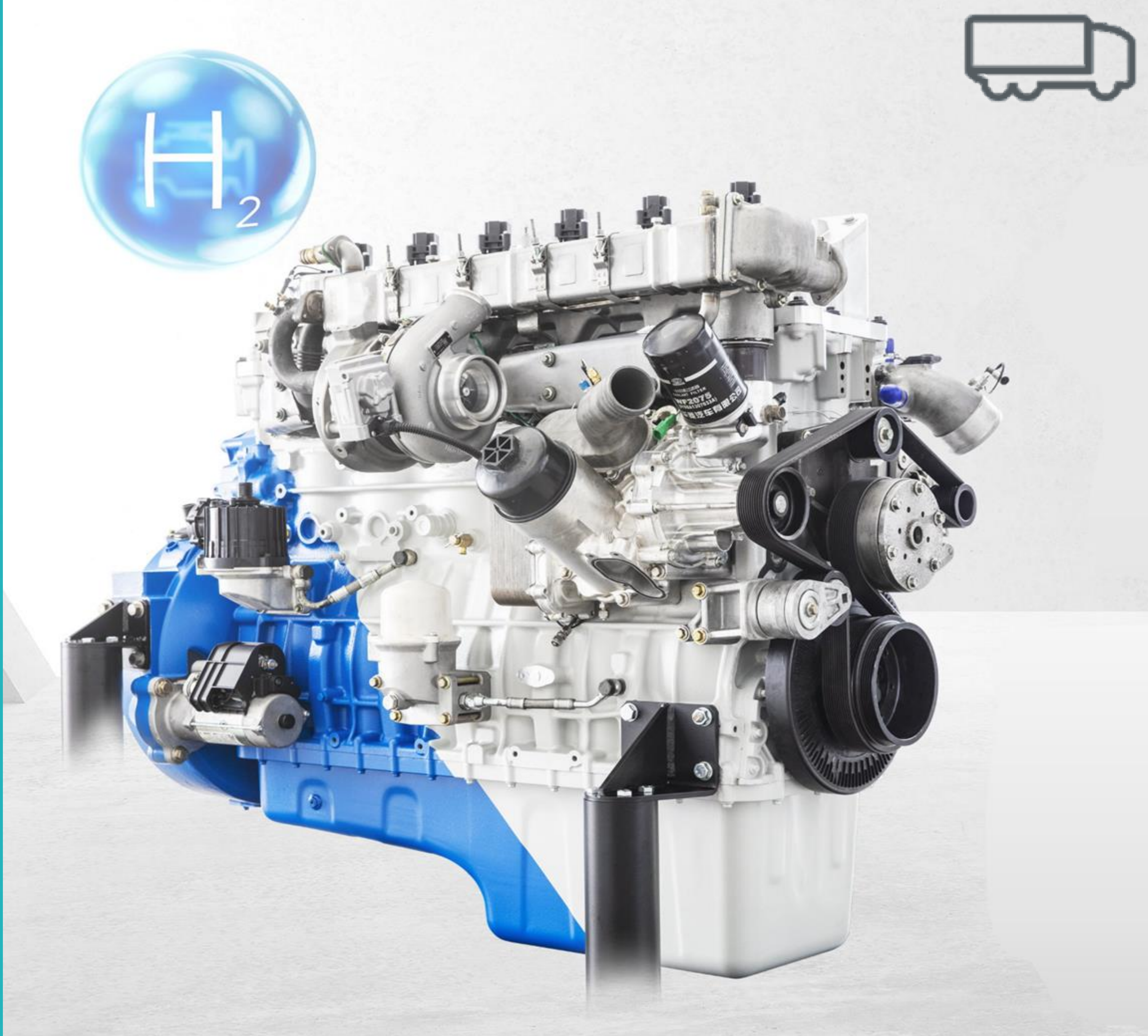
HYDROGEN
ENGINE
AVL

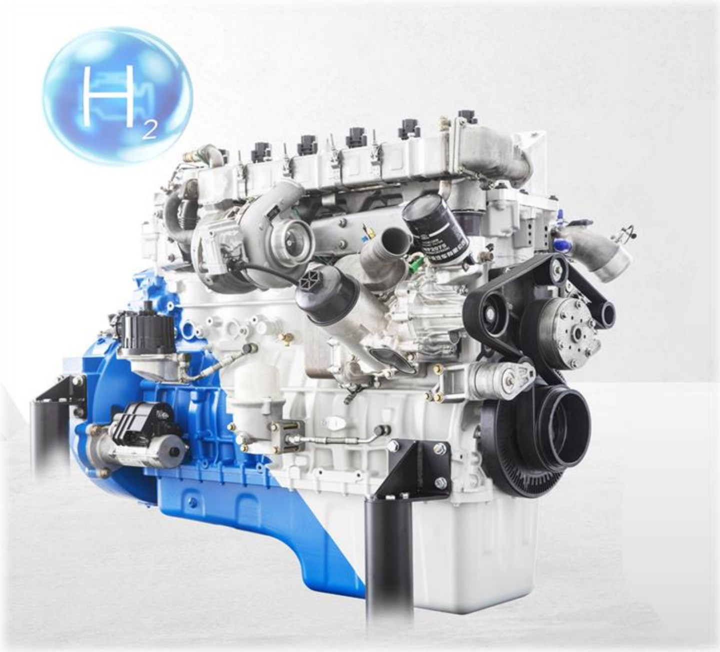
AVL

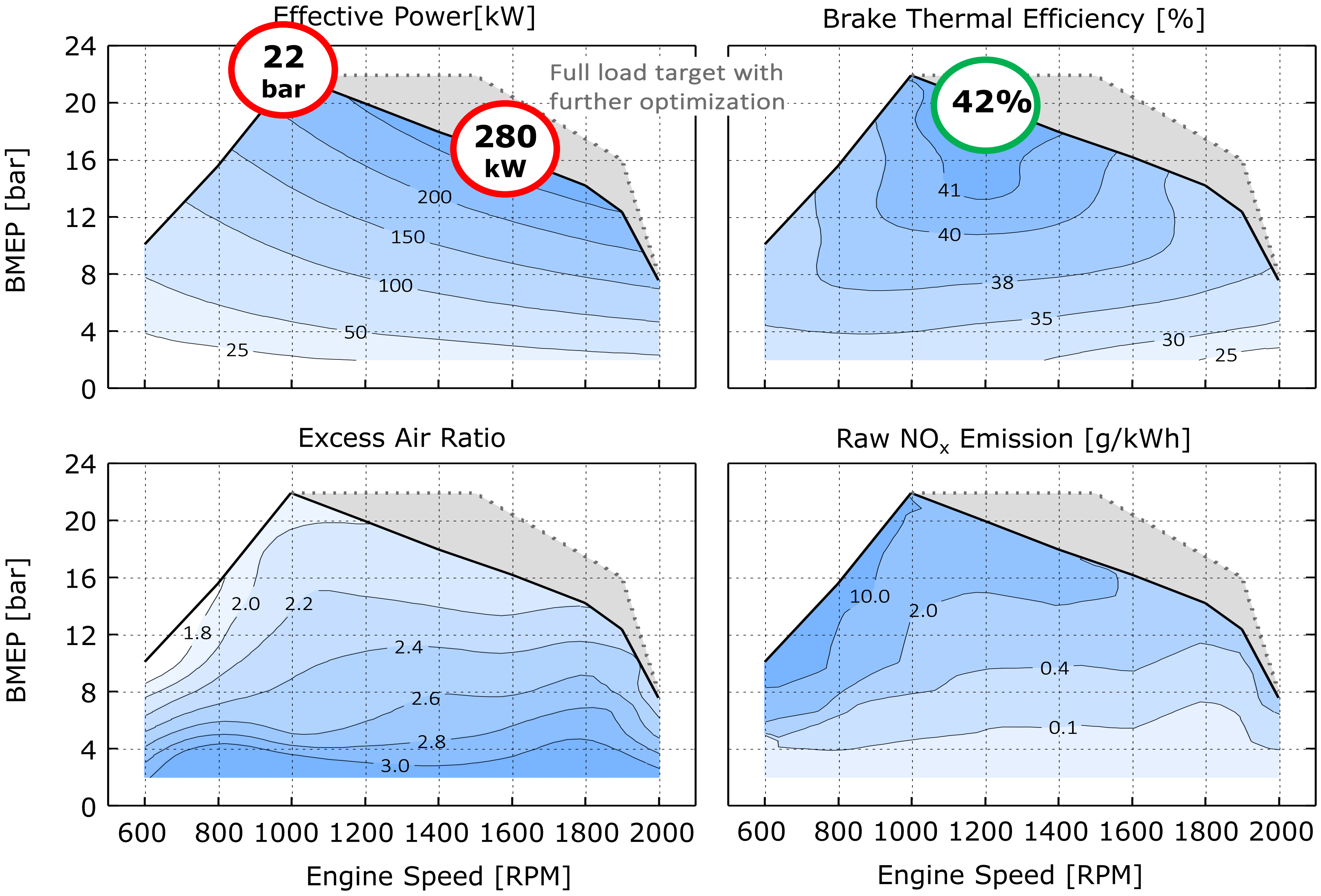
AVL Hydrogen Engine Targets

- BMEP level: 24 bar
- Power: 350 kW
- BTE: > 42 %
- Post Euro VI emission
- Transient performance for commercial vehicles
- Maximum similarities to base engine



High Efficiency Hydrogen ICE
The AVL Hydrogen Engine: Power, BTE, EAR and Raw NO_x





Main Limitation

Backfire

Preignition

Knocking

Homogenization

High Efficiency Hydrogen ICE
The AVL Hydrogen Engine: Optimization steps

Main Limitation

Backfire
Preignition
Knocking
Homogenization

Cooling of fire deck and spark plug

- AVL advanced Top-Down Cooling (TDC*)
- Improved spark plug heat dissipation

Gas exchange improvement

- High efficiency turbocharger
- Optimized valve lift curves

Optimized spark plugs and ignition coils

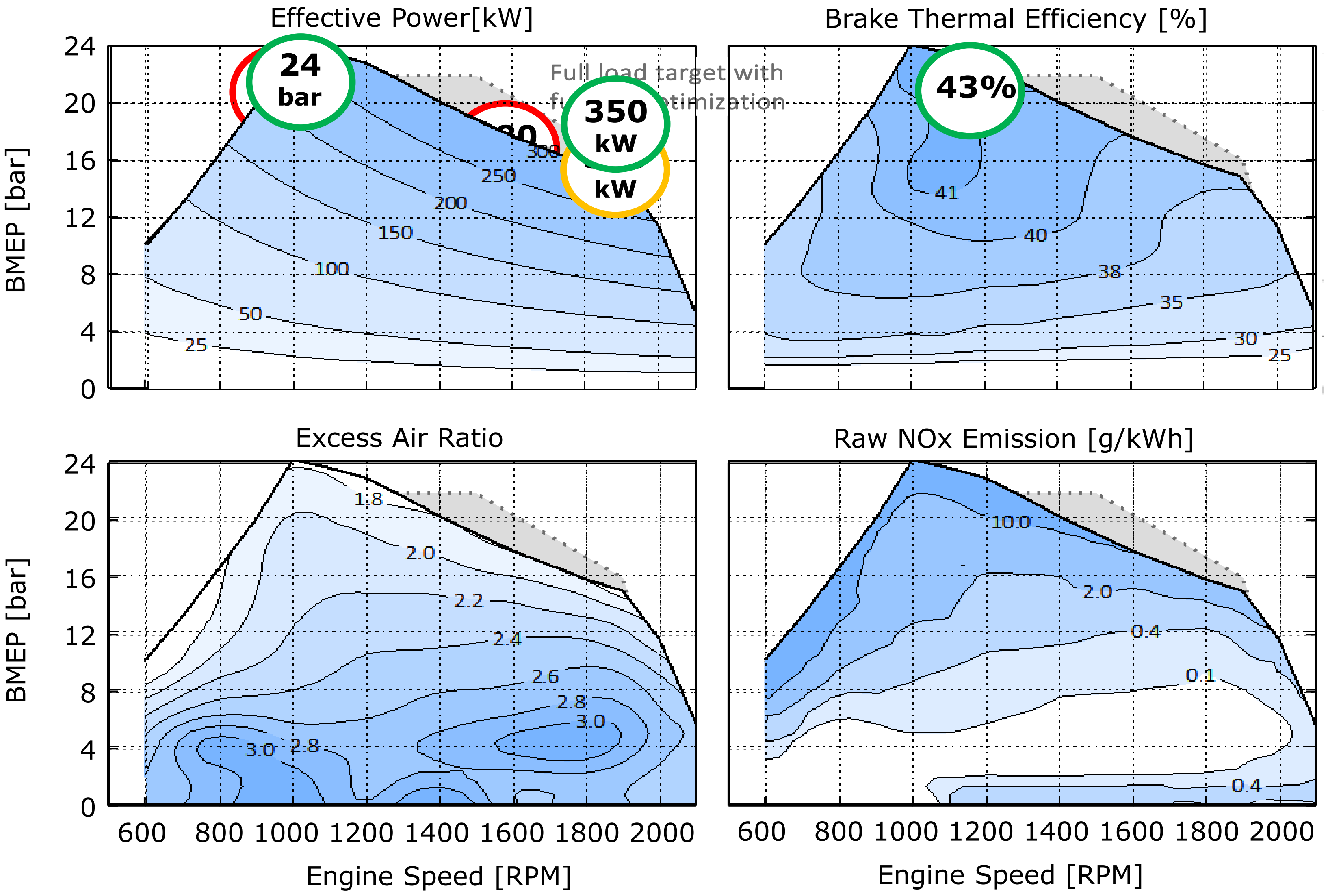
Optimized operation strategy

- Upgraded AVL H_2-RPEMS software
- CFD optimized operation

* AVL patent application

High Efficiency Hydrogen ICE

The AVL Hydrogen Engine: Power, BTE, EAR and Raw NO_x



Main Limitation

Backfire

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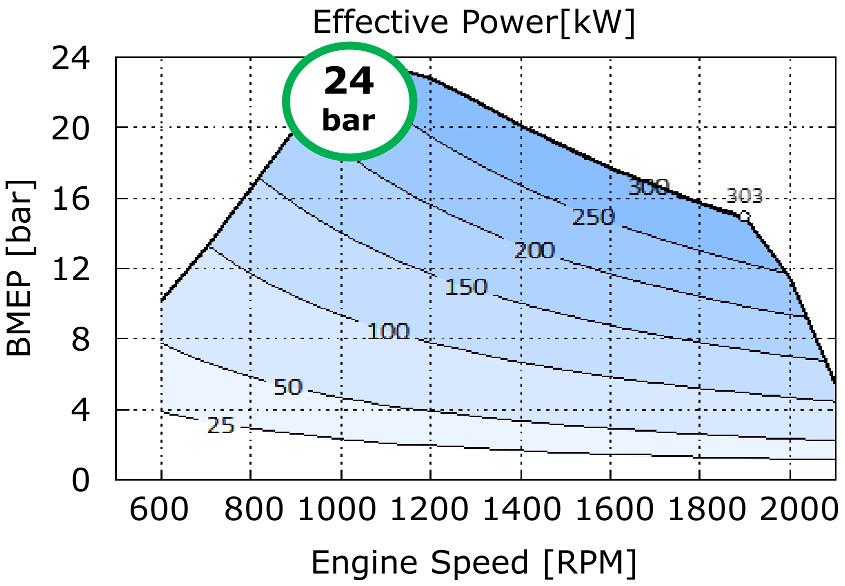
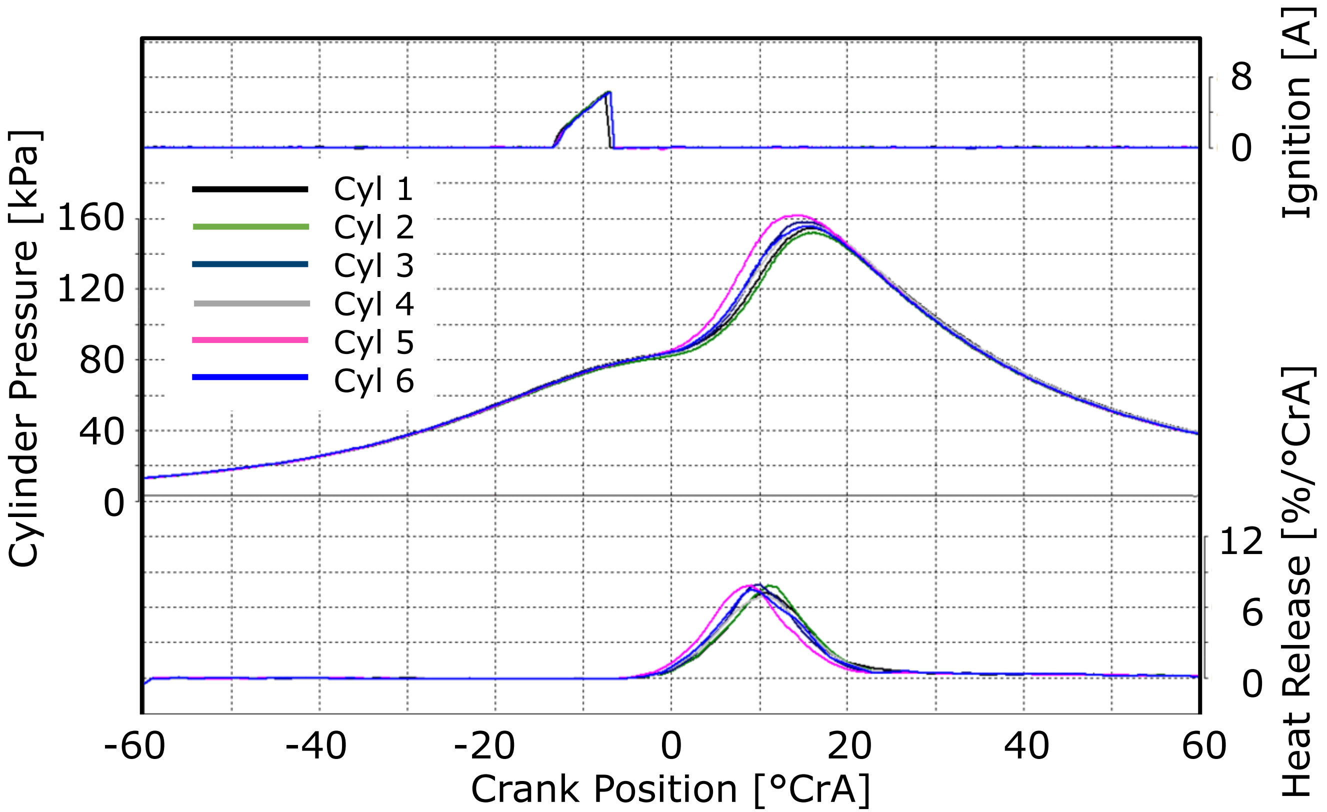
Homogenization

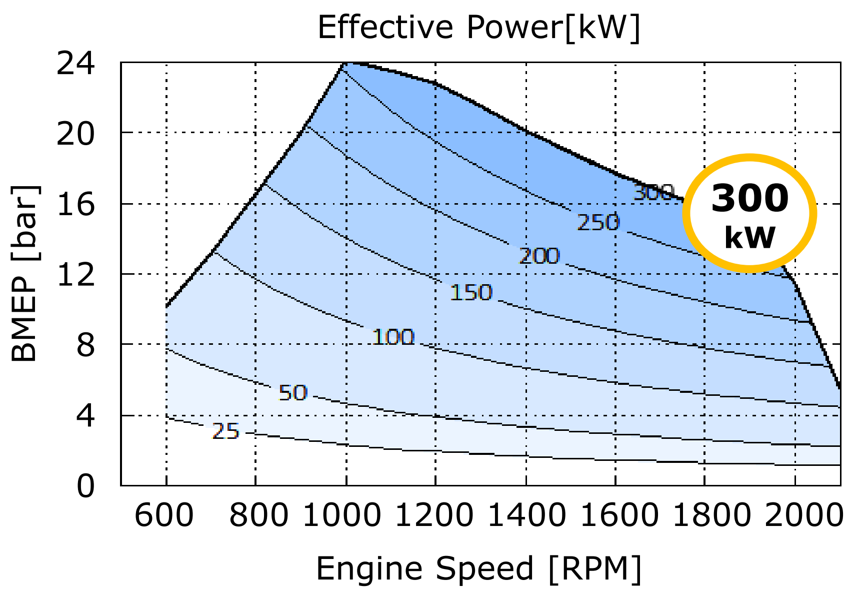
High Efficiency Hydrogen ICE
The AVL Hydrogen Engine: max. BMEP

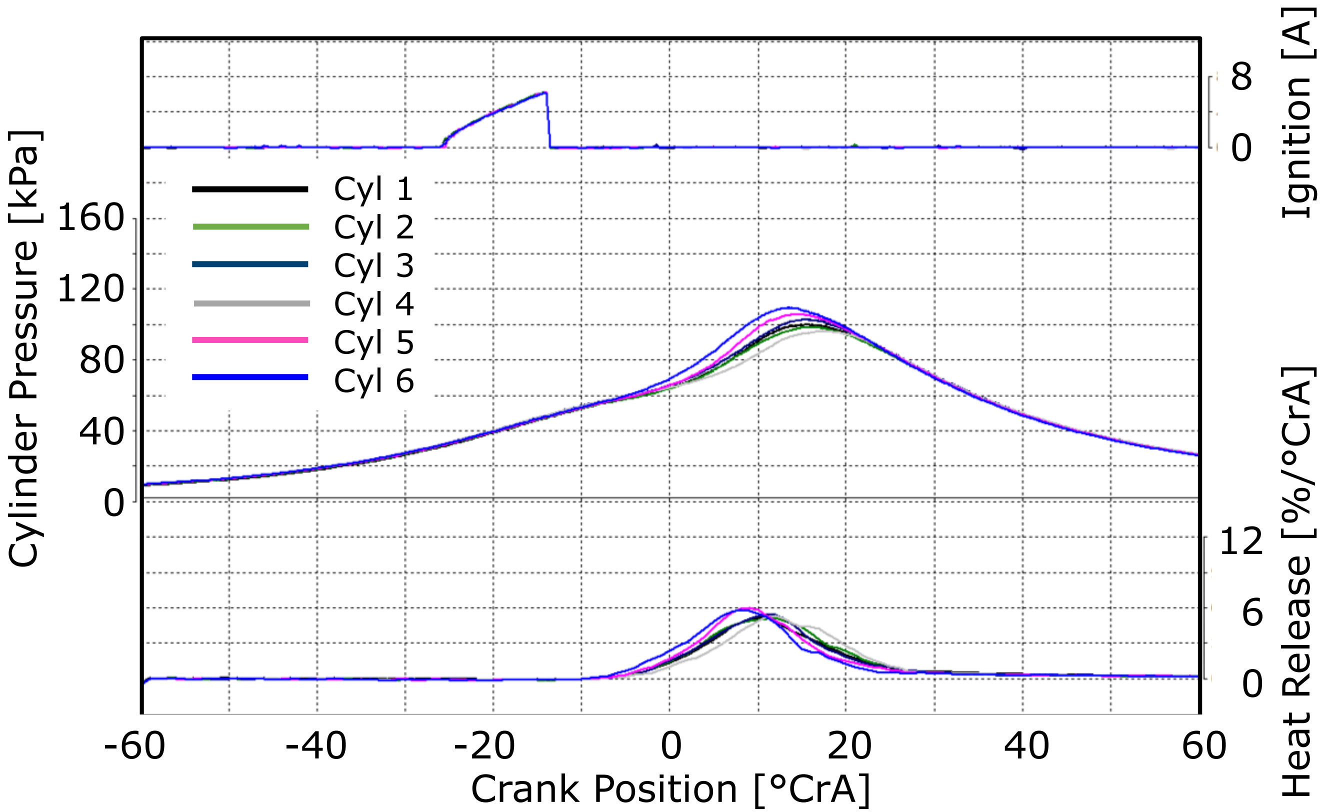




Stable engine operation with 24 bar BMEP @ 1000 rpm

High Efficiency Hydrogen ICE
The AVL Hydrogen Engine – MPI peak power

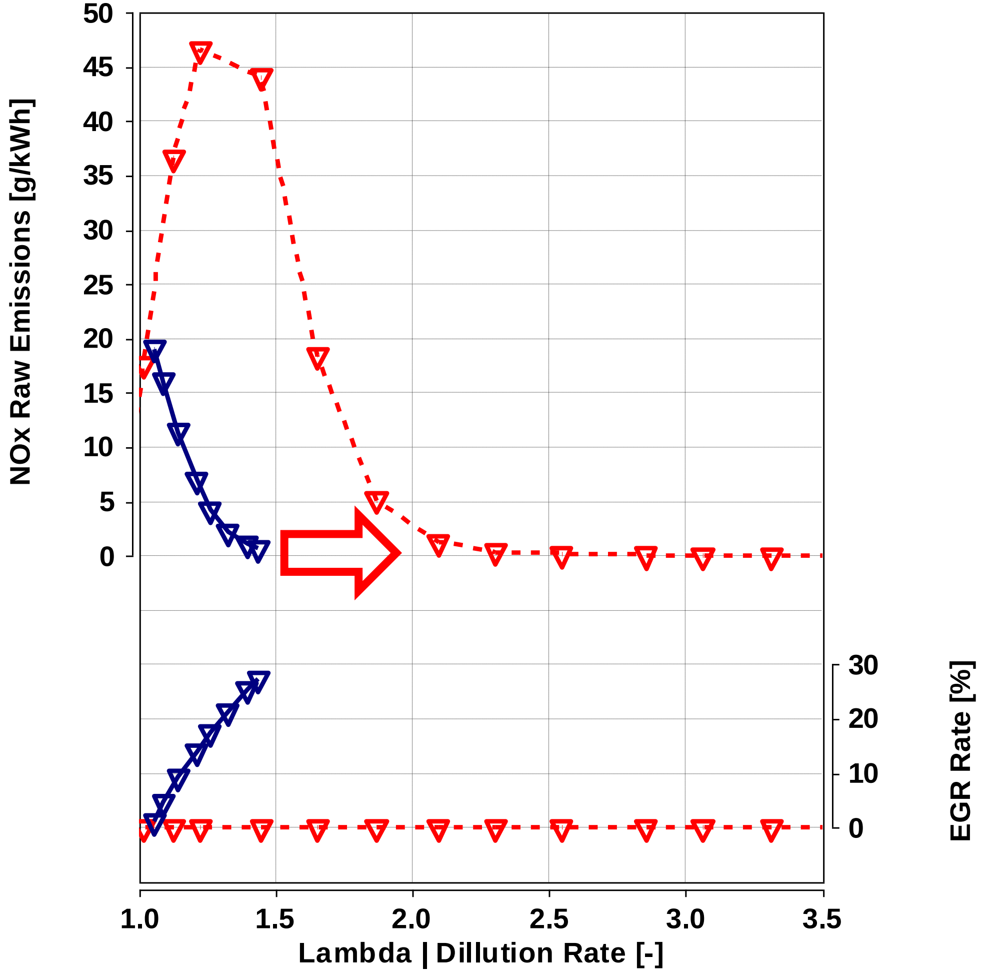


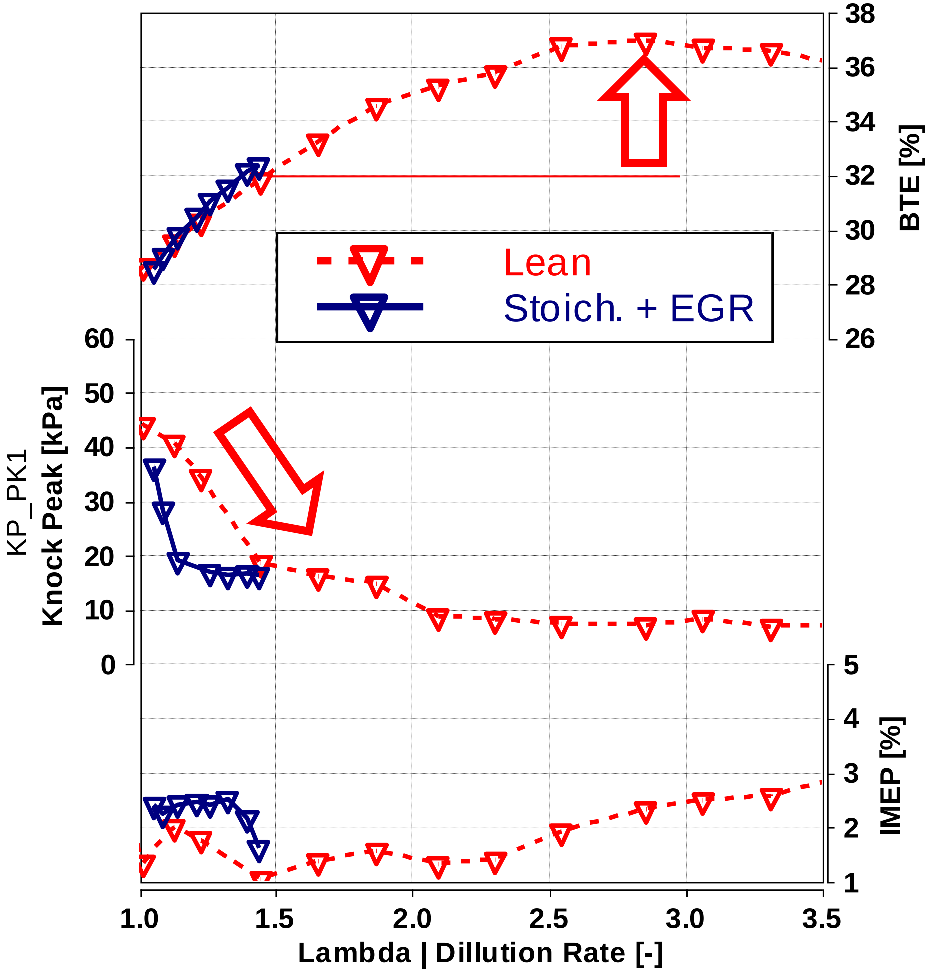


Stable engine operation with 300 kW @ 1900 rpm

Paul KAPUS, Bernhard RASER | | 25 Oktober 2022 | AVL

Hydrogen ICE NO_x, Efficiency, Knock Tendency and Combustion Stability; Lean vs Stoichiometric & EGR; Part Load





H_2 allows very lean operation; this results in excellent part load efficiency

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H_2 ICE @ Passenger Car
H_2 ICE Basic Operation Concepts

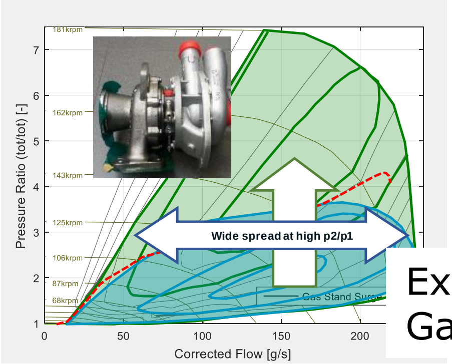
H_2-ICE Operation Concepts

I. Pure Lean Operation
- $\lambda \approx 2.5$ for lowest NO_x
- Very high boost pressure
- NO_x aftertreatment with or w/o SCR

II. Lean + EGR
- Slightly lower boost pressure
- EGR reduces NO_x
- NO_x aftertreatment with or w/o SCR

III. Lean in PL & λ=1 at HL/FL
- Lowest boost pressure
- λ=1 most prone to **IRC!**
- NO_x aftertreatment @ HL/FL w. TWC

IV. Lean in PL & λ=1/combustion moderator at HL/FL
- Moderate boost pressure
- Water inj. and/or EGR to handle IRC!
- NO_x aftertreatment @ HL/FL w. TWC



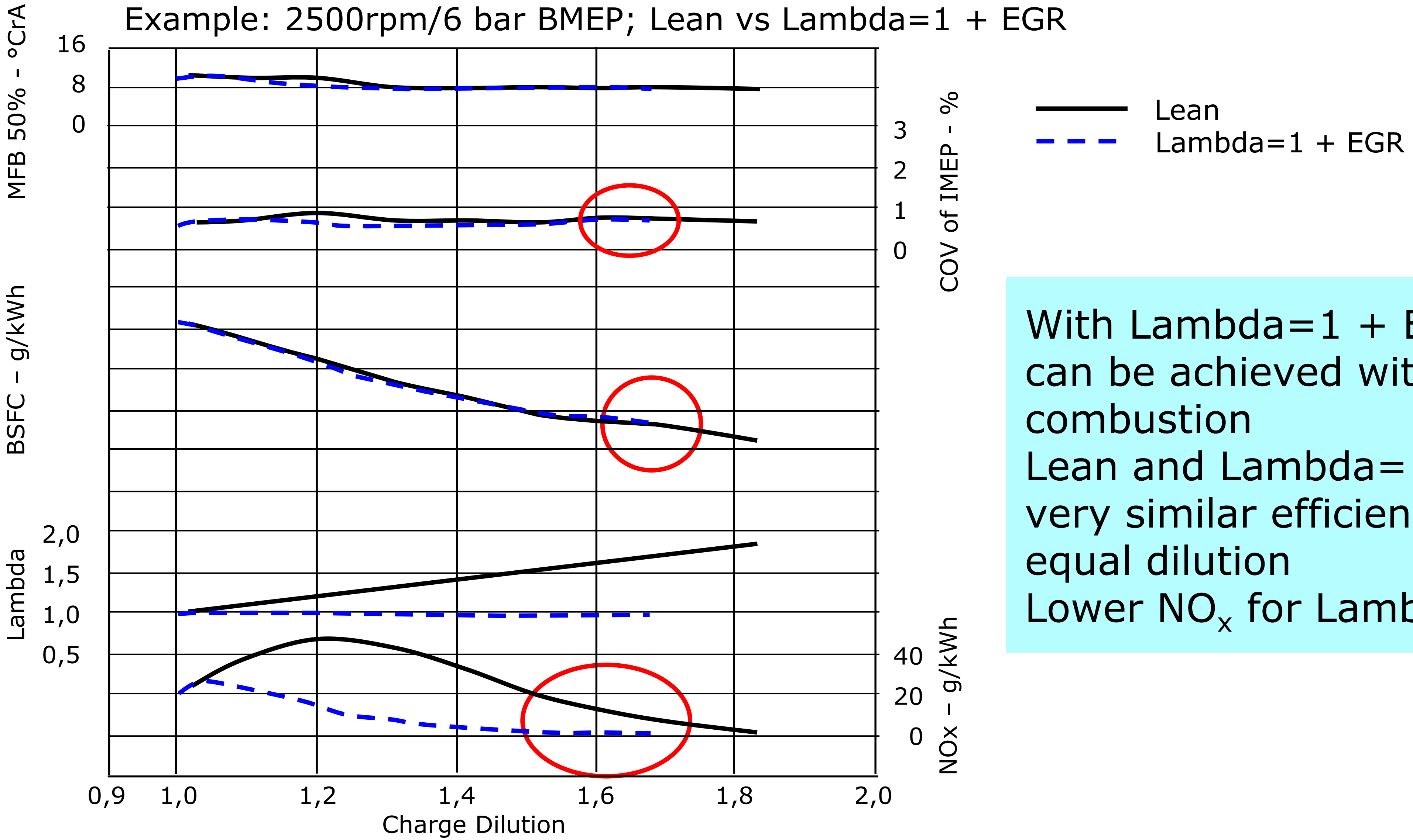
Example:
Garrett SC-TC

H_2 requires high boost pressures and needs a combustion moderator

H_2 ICE @ Passenger Car

AVL H_2 PC ICE R&D – Results

Example: 2500rpm/6 bar BMEP; Lean vs Lambda=1 + EGR

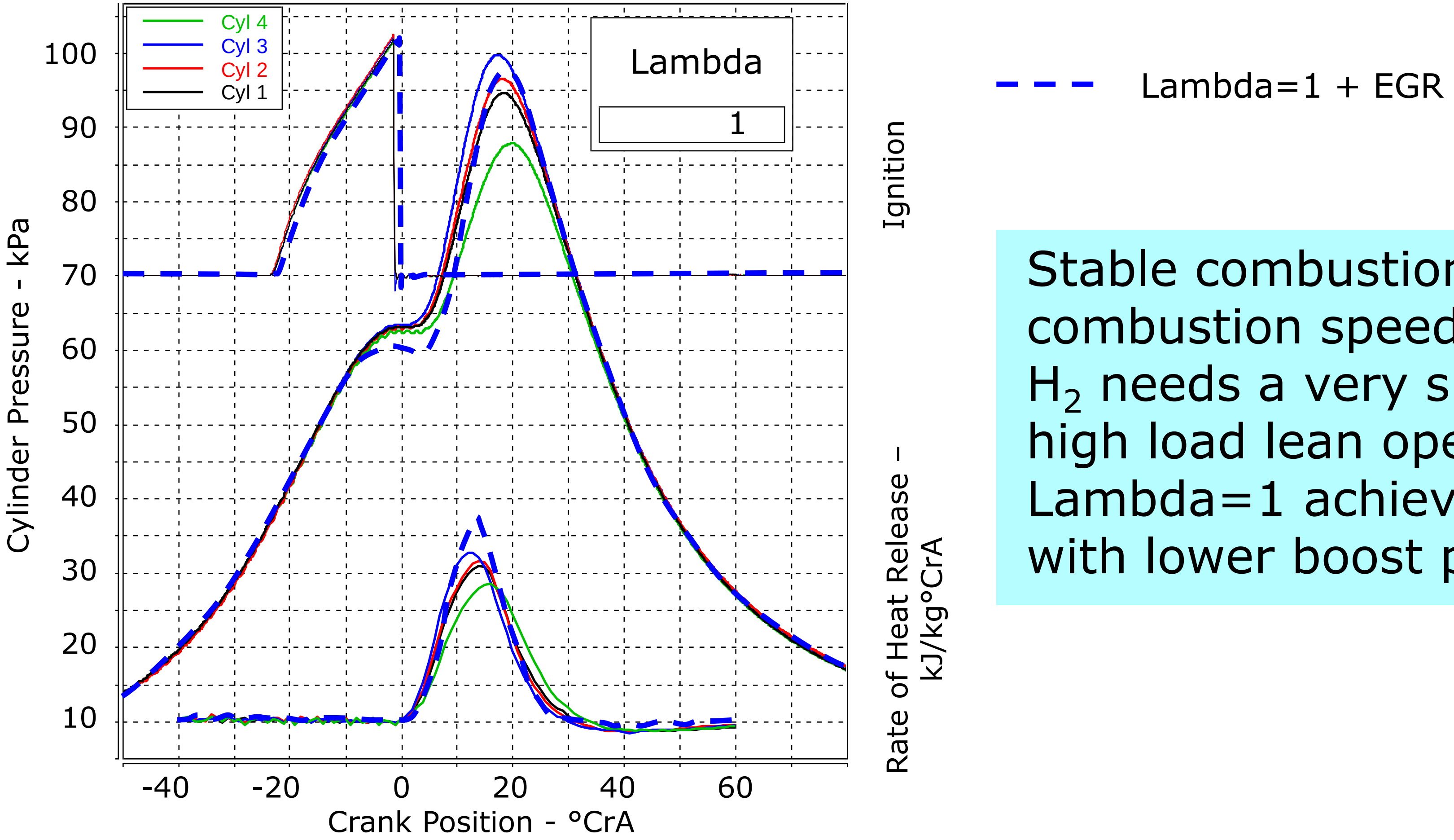


With Lambda=1 + EGR high dilution can be achieved with stable combustion
Lean and Lambda=1 + EGR achieve very similar efficiency levels at equal dilution
Lower NO_x for Lambda=1 + EGR

H_2-ICE @ Passenger Car

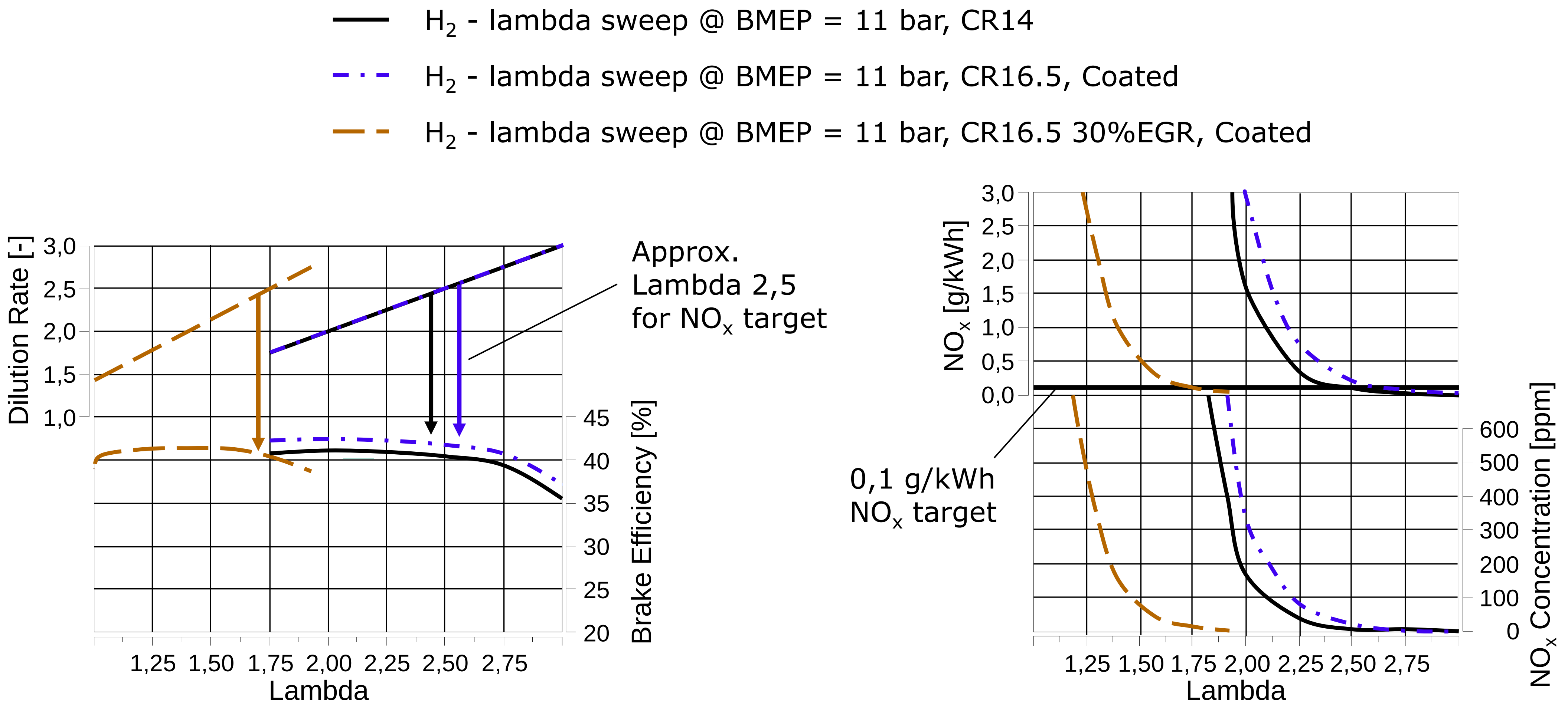
AVL H_2 PC ICE R&D – Results

Example: 2500rpm High Load/λ 1,9 (TPS=100% / WG=Fully Closed)



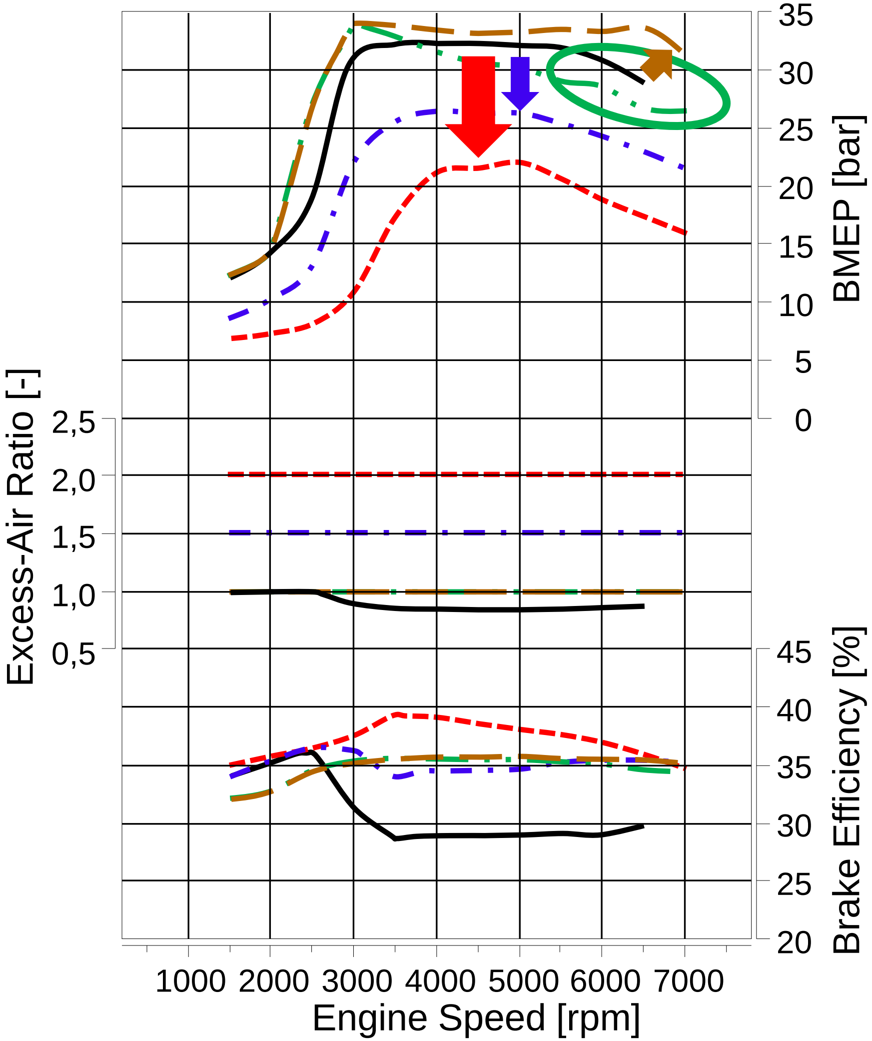
Stable combustion with reasonable combustion speed at Lambda=1,9
H_2 needs a very specific TC for high load lean operation
Lambda=1 achieves similar results with lower boost pressure

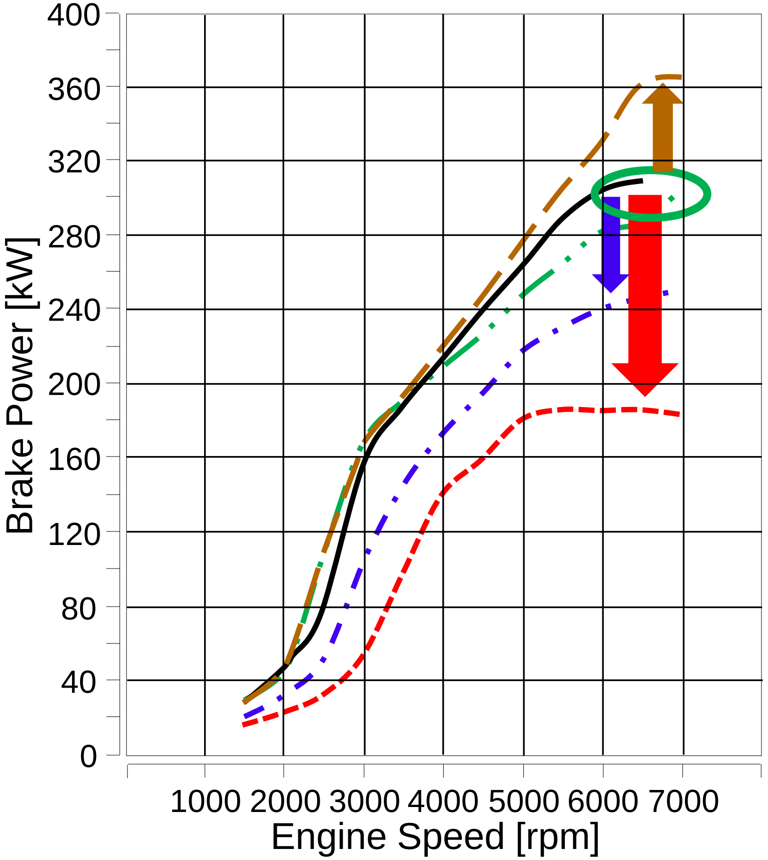
H_2 Dedicated Hybrid Engine; BSFCmin - λ vs EGR; Efficiency; Simulation



High compression ratio, lean operation and thermo swing coatings allow excellent efficiency

Highest Performance H_2 Engine
Full Load; Single Stage TC; Simulation



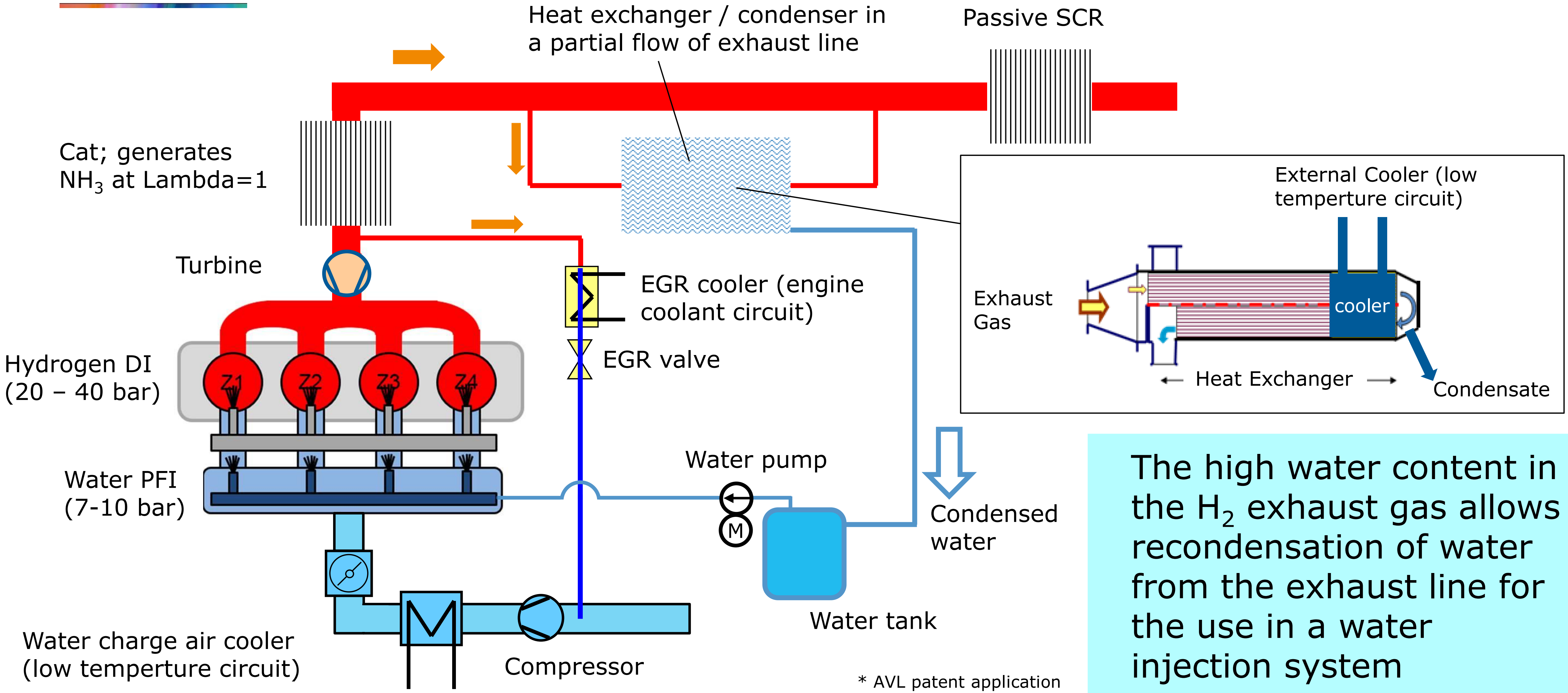


Boundary conditions:

- 4Cyl inline, 2L Miller engine
- CR 10.0:1
- Single stage TC
- H_2 direct injection
- Exhaust gas temperature limit 1000°C

Highest power and torque can be achieved by combining Lambda=1 operation and water injection

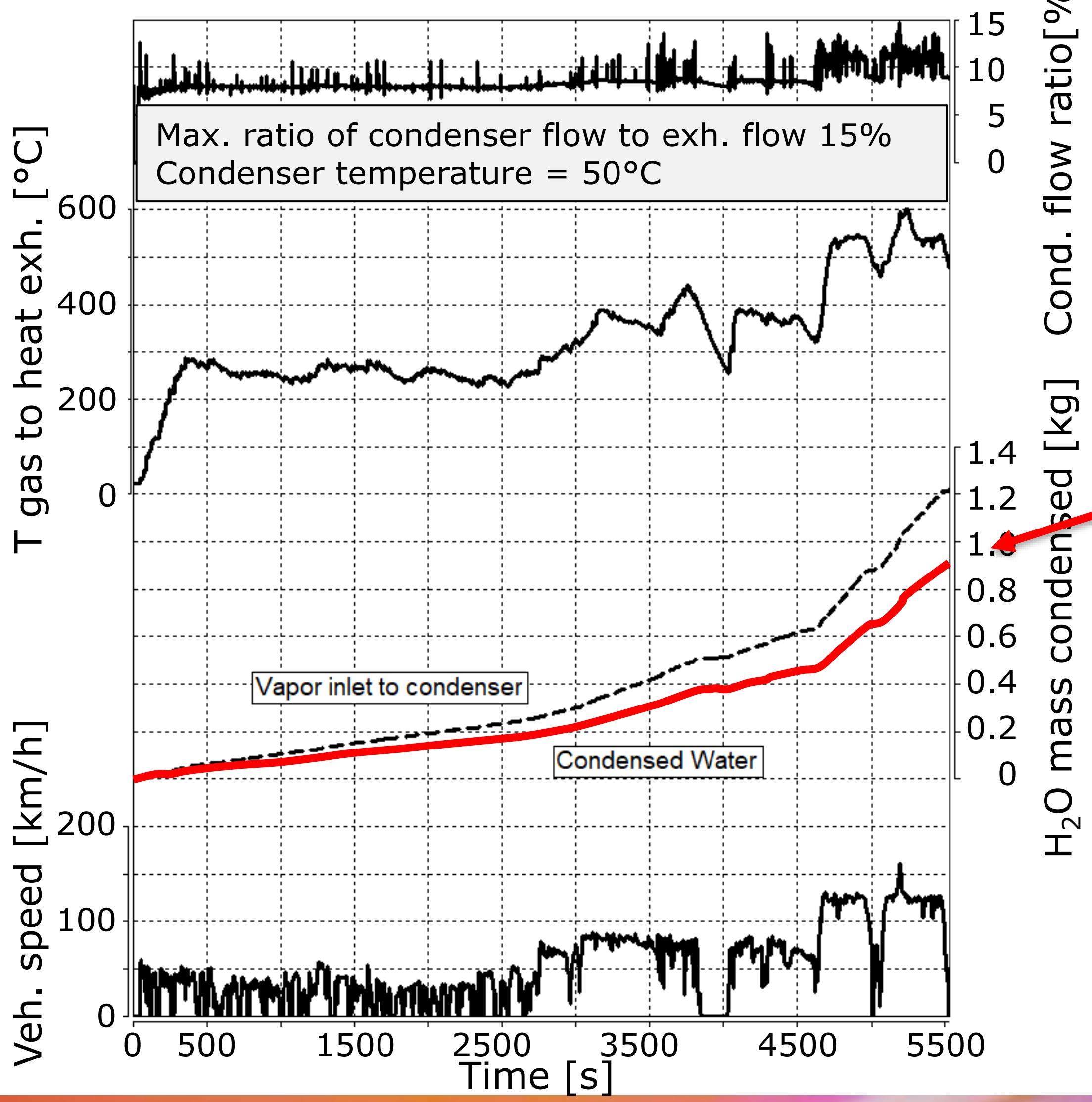
H_2 Low Pressure DI with Water Injection*



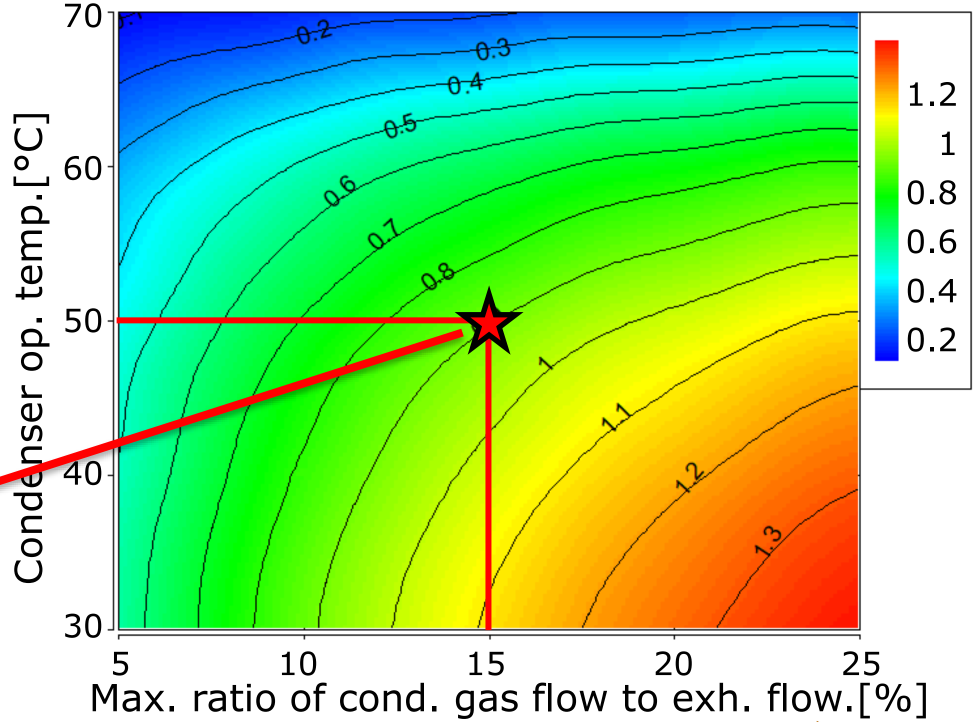
The high water content in the H_2 exhaust gas allows recondensation of water from the exhaust line for the use in a water injection system

* AVL patent application

Example: Water Condensed from Exhaust Gas
RDE Cycle with Lambda=1, H_2 Combustion



Condensed water mass at the end of the drive cycle [kg]



Increasing size of heat-exchanger and condenser layout

Required amount of water is between 0,4 and 0,9kg

The water amount required to drive RDE and the water amount that can be condensed from the exhaust can be matched

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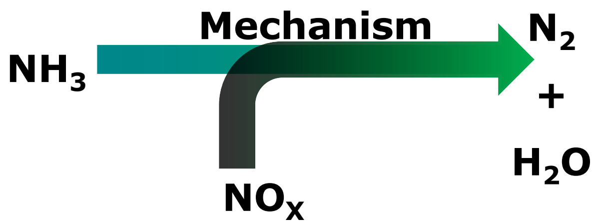
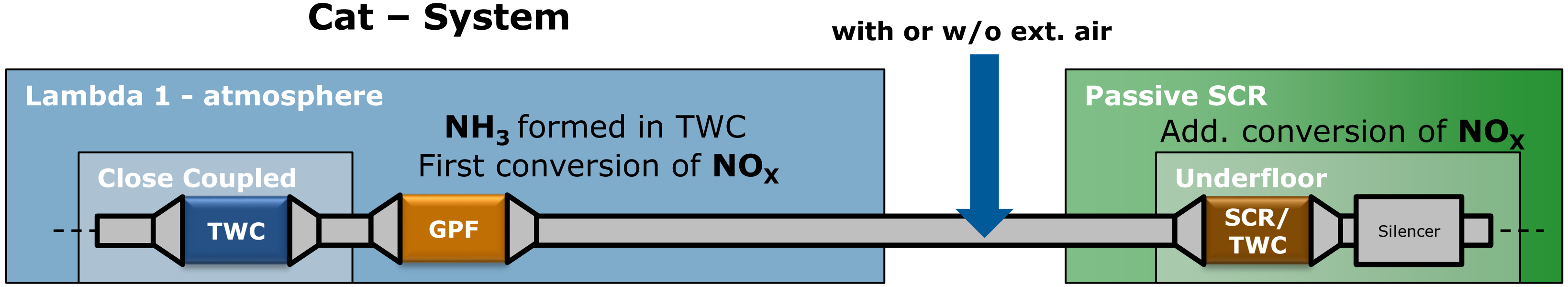
EAS Layout for Passenger Car Engines

λ=1 Operation: Special Feature

- **Passive** SCR operation
- No active Urea dosing required



Cat – System

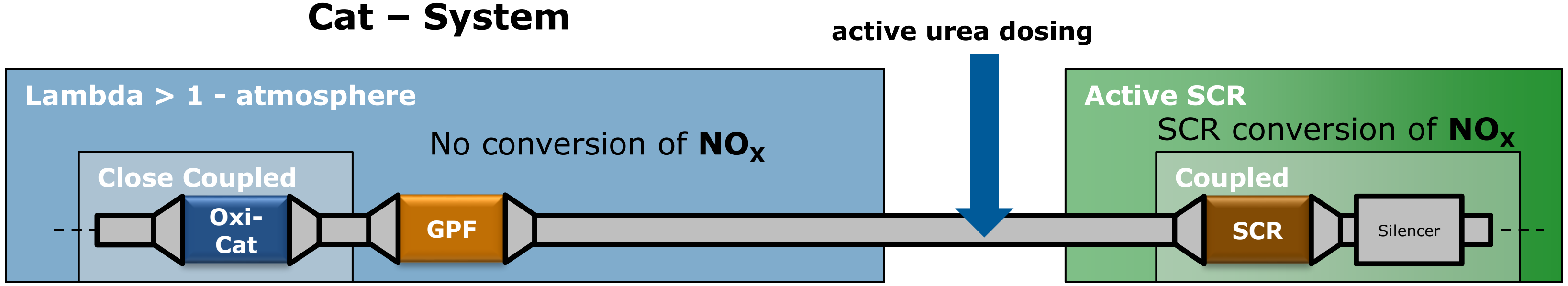


Mechanism: ammonia (NH_3) that is formed in the TWC in λ=1 atmosphere is used as a reduction agent for further NOx emission reduction; tested with gasoline on AVL's ZIE demo car!

λ>1 Operation: Conv. SCR

- **Active** SCR operation
- active Urea dosing required
- Needs NOx engine out approx. 1 g/kWh

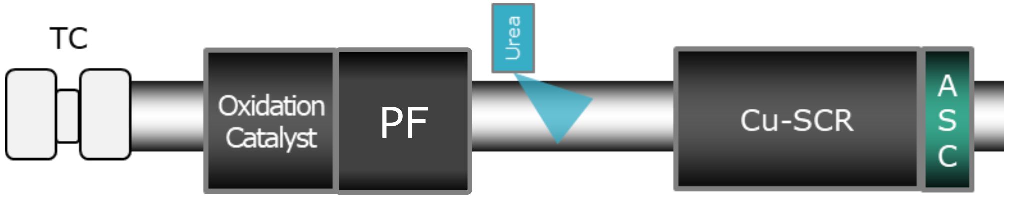
Cat – System



Mechanism: ammonia (NH_3) that is formed in λ>1 atmosphere by external dosing of urea is used as a reduction agent for NO_x emission reduction (conventional SCR)

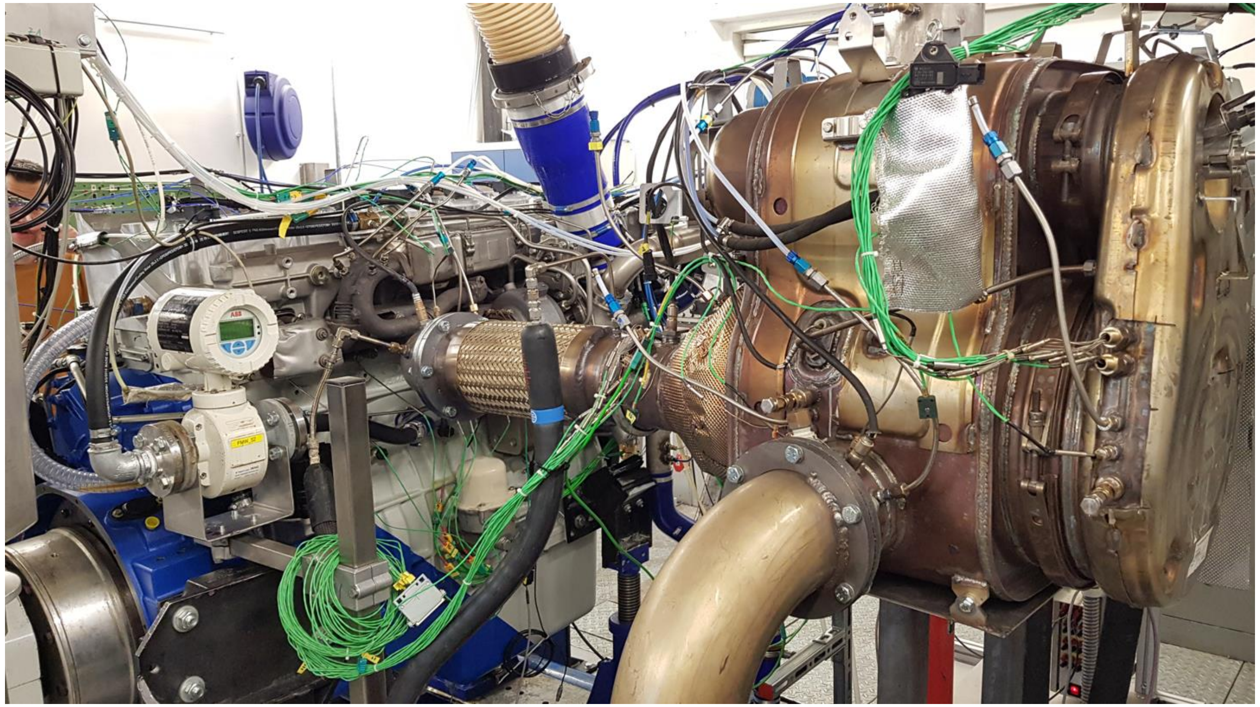
Aftertreatment systems known from Diesel and gasoline applications can be used for H_2 engines

High Efficiency Hydrogen ICE
AVL Hydrogen Engine: EAS Layout for Euro VI



EAS specifications

Diesel derived EAS



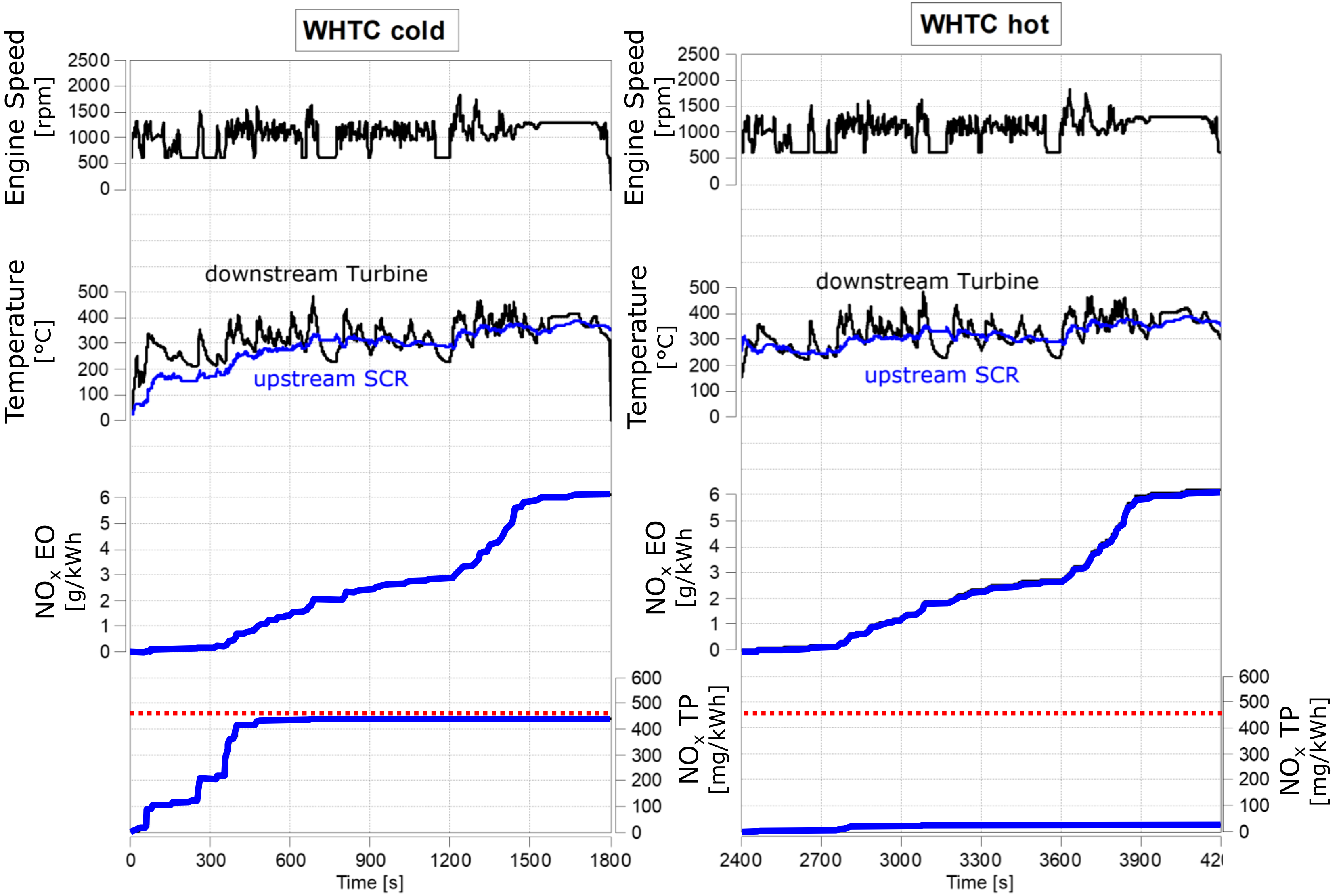
High Efficiency Hydrogen ICE
AVL Hydrogen Engine: EAS Layout for Euro VI; Simulation

EAS specifications

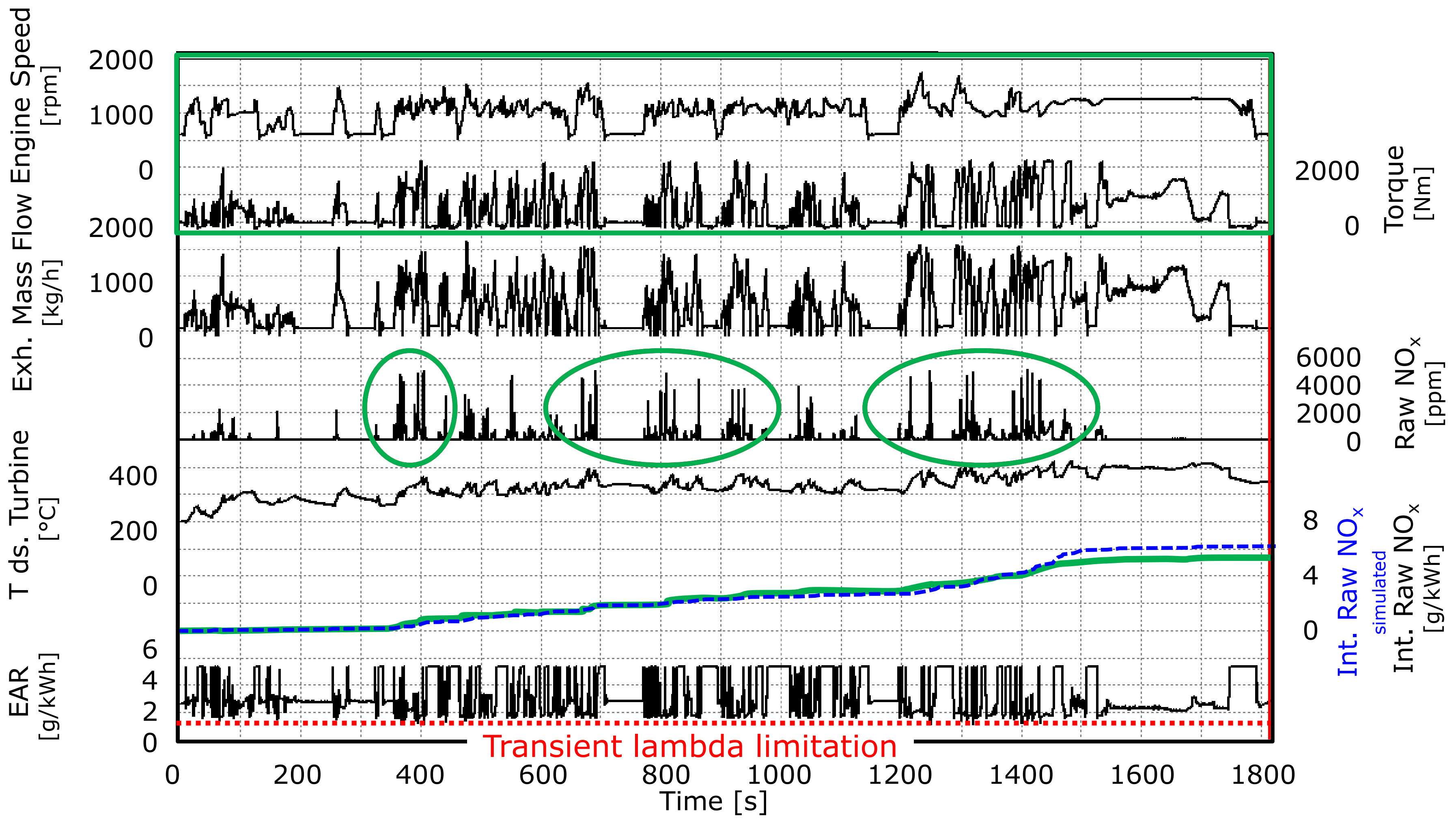
Diesel derived EAS

Syngas based & simulation optimized SCR (for 6 g/kWh EO)

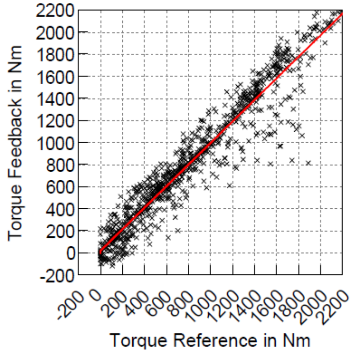
Model based SCR control



High Efficiency Hydrogen ICE
AVL Hydrogen Engine: WHTC Test Results

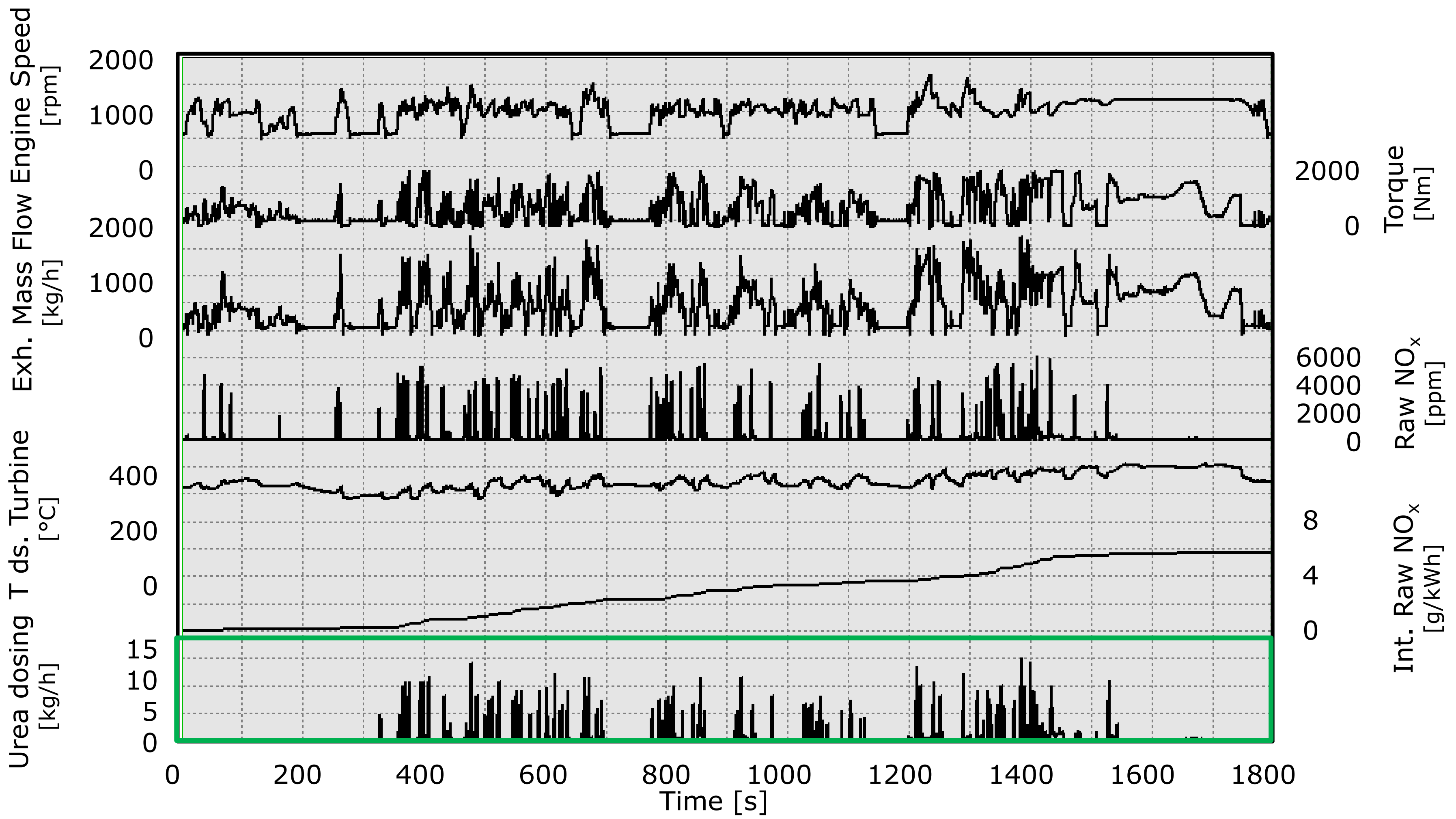


22 bar BMEP
300 kW



Lambda limit: 1,8 for transient NO_x limitation

High Efficiency Hydrogen ICE
AVL Hydrogen Engine: WHTC Test Results



Urea dosing activated

WHTC characteristics

Work: **29 kW**

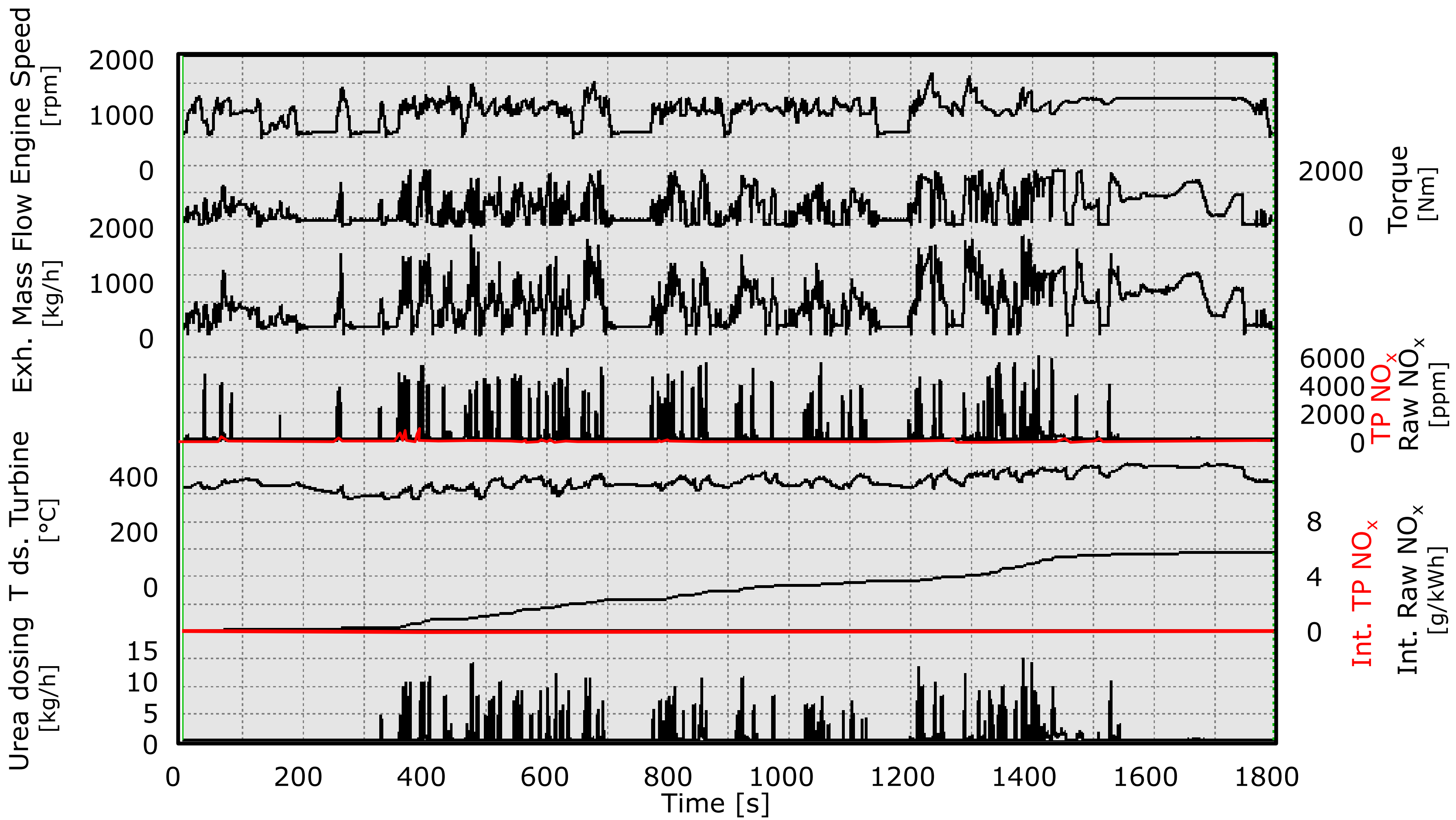
Avg. power: **57 kW**

Avg. speed: **1000 rpm**

Results EO

NOx	H2O	H2	CO2_Oil	THC	CO	BSFC
g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh
5.84	802.90	1.23	0.23	0.005	0.01	83.33

High Efficiency Hydrogen ICE
AVL Hydrogen Engine: WHTC Test Results



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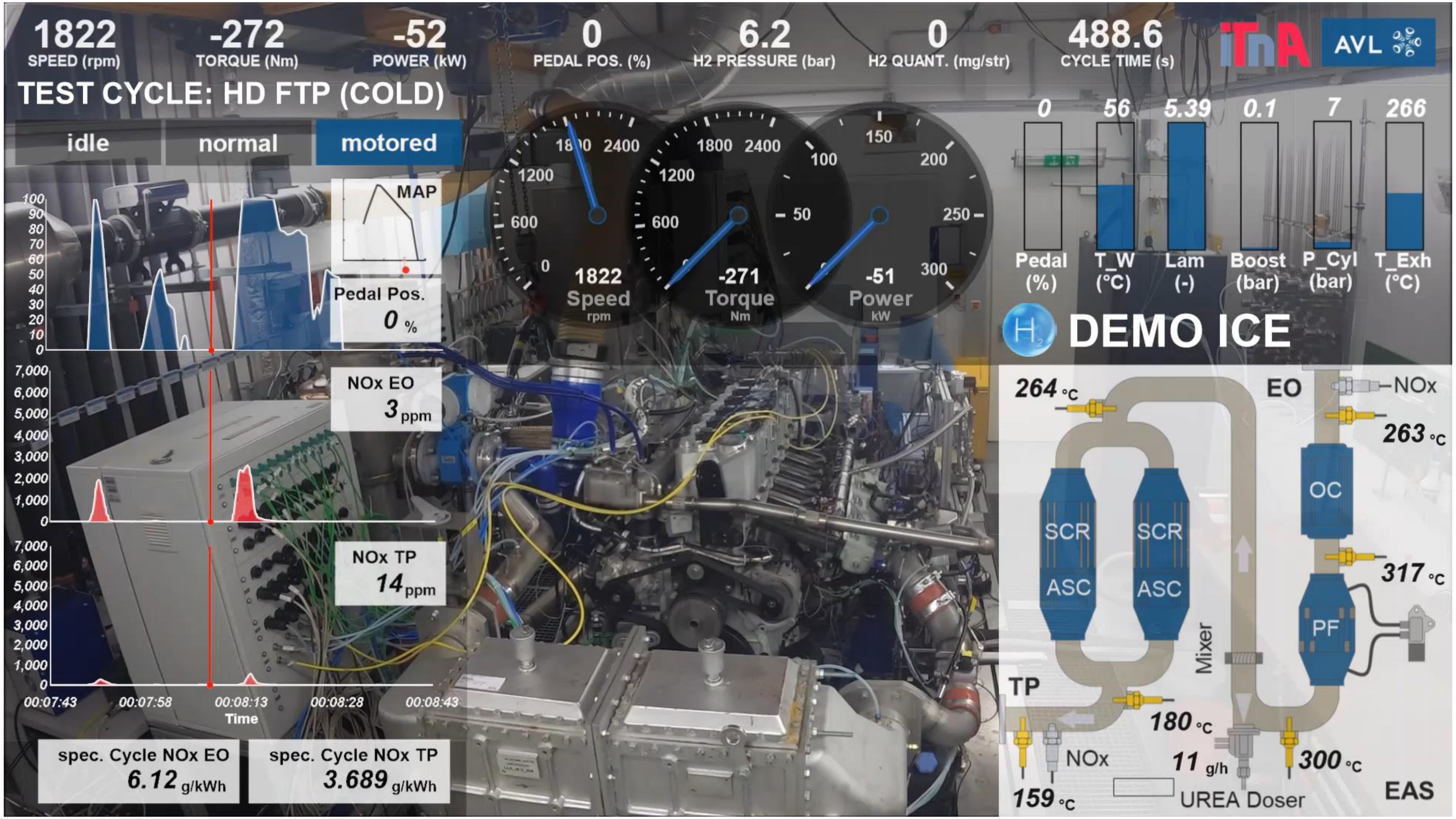
g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh
5.84	802.90	1.23	0.23	0.005	0.01	83.33

NOx Tailpipe
g/kWh
0.06

Confirmation of simulation results & EU VI capability

High Efficiency Hydrogen ICE
Example Video #1: Full load step at middle speed range



The AVL Hydrogen Engine – Status and Achievements

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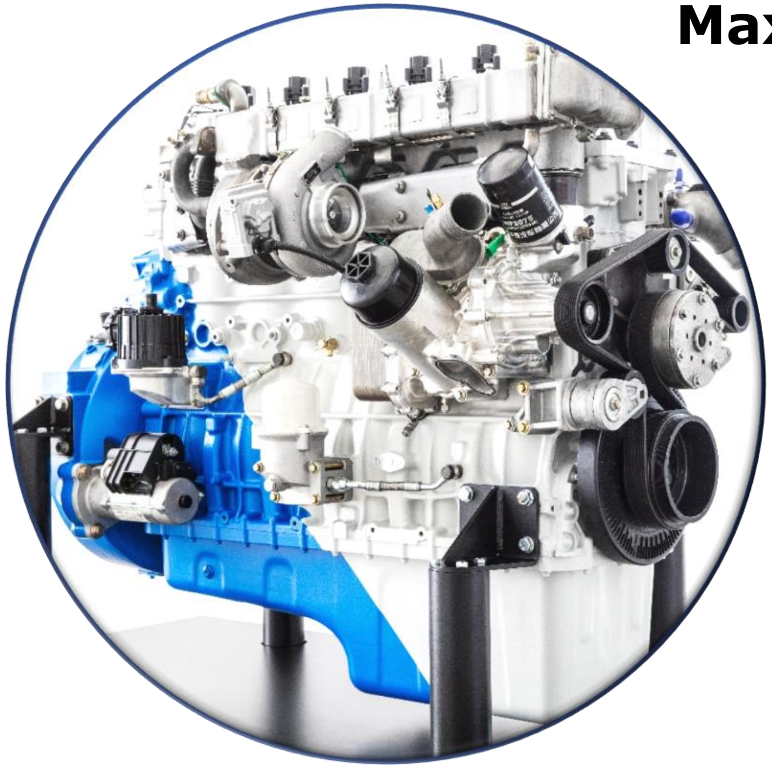


Maximum similarities to base engine
ensured

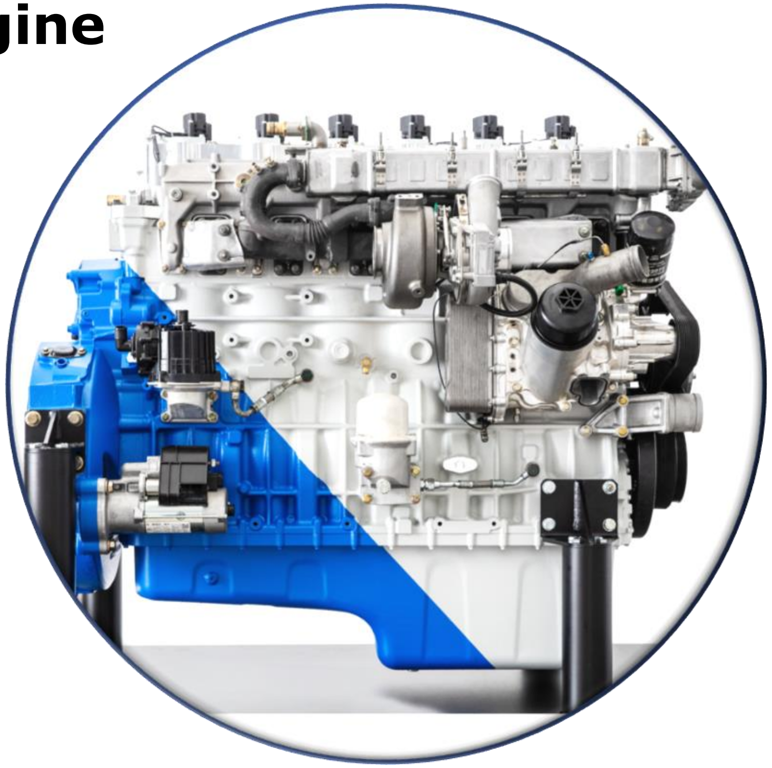
BMEP 24 bar
demonstrated

BTE 43 %
demonstrated

Performance target demo
ongoing

Stage V & Euro VI emissions
demonstrated

Transient performance for conventional PT-vehicle
confirmed



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High Efficiency Hydrogen ICE, Webinar 25th October 2022
Summary and Conclusions

- A **sustainable** global energy scenario needs a **chemical energy carrier** – **hydrogen** is the simplest one
- Hydrogen will play a **major role in future transportation** – for **commercial application** and possibly also for passenger cars
- Different **engine baselines** and applications require **specific combustion systems**
- The **AVL Hydrogen Engine** demonstrated **highest torque and power levels, excellent efficiency** – even in transient operation – and **lowest emissions** (post EU VI capability)
- **Dedicated hybrid** PC hydrogen engines can achieve **efficiency levels >42%**
- **High performance** PC hydrogen engines can achieve specific power levels of **up to >150kW/l**
- **Lean operation** provides the best option for part load, **Lambda=1 plus EGR** is an alternative
- To limit boost pressure demand and enhancing transient performance a **combustion moderator** enables **stoichiometric operation**
- Next to **EGR** also **water injection** - condensed directly from exhaust gas - can serve as **combustion moderator**
- A reasonable aftertreatment system uses an **oxidation or three-way catalyst** plus a passive or active **SCR system**. A particulate filter is used to cope with long term PN originating from oil consumption in worn-out engines.

Acknowledgement

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iTnA BOSCH Garrett ADVANCING MOTION VENTREX ACT BLUE

High Efficiency Hydrogen ICE

Q&A

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