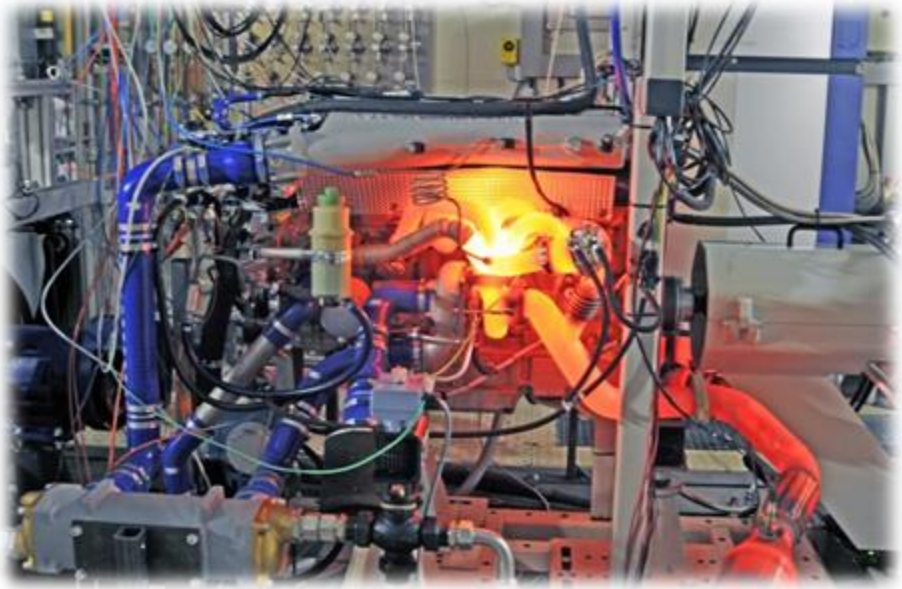
More than just the past:
Perspectives of future combustion engines as sustainable drive systems

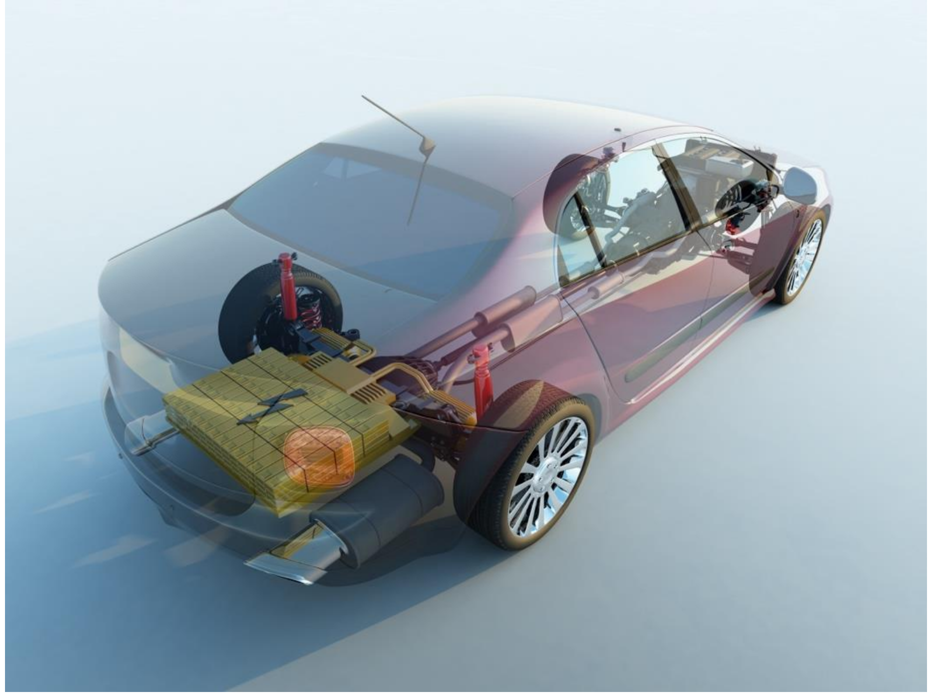


Univ.-Prof. Dr.-techn. Helmut Eichlseder, Univ.-Prof. Dr.-Ing. Christian Trapp

Agenda

More than just the past:
Perspectives of future combustion engines as sustainable drive systems

- ➢ Propulsion systems and challenges
- ➢ State of the art (example passenger cars)
- ➢ Possible pathways
- ➢ Hybrid powertrain architectures
- ➢ Dedicated hybrid engines
- ➢ Outlook

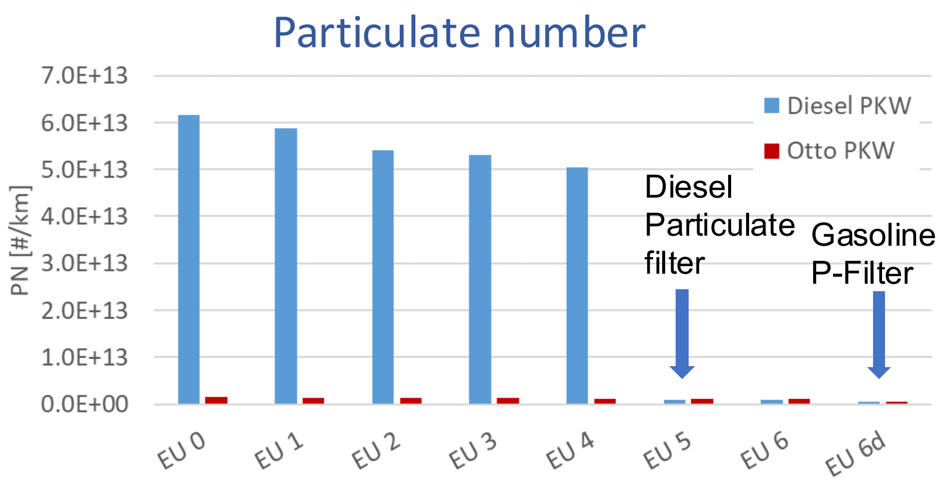


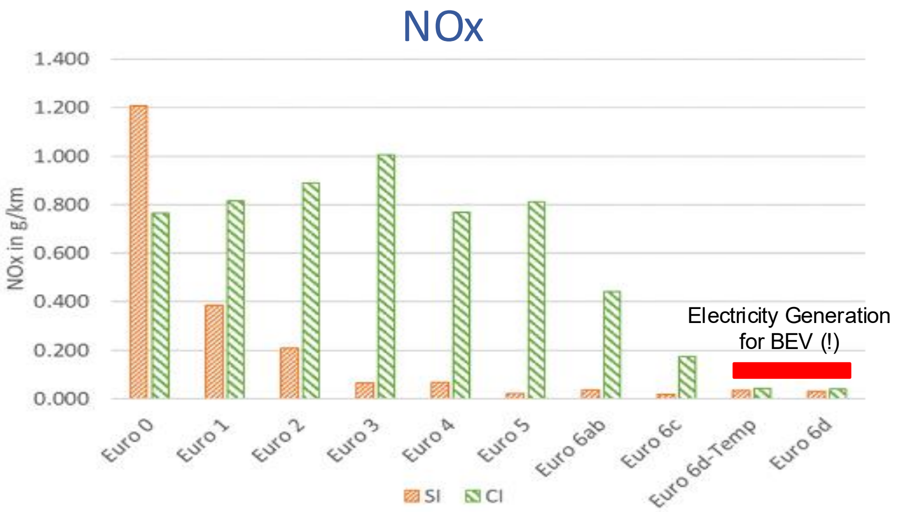
Future Combustion Engines – Motivation and Challenges

Challenge Emissions

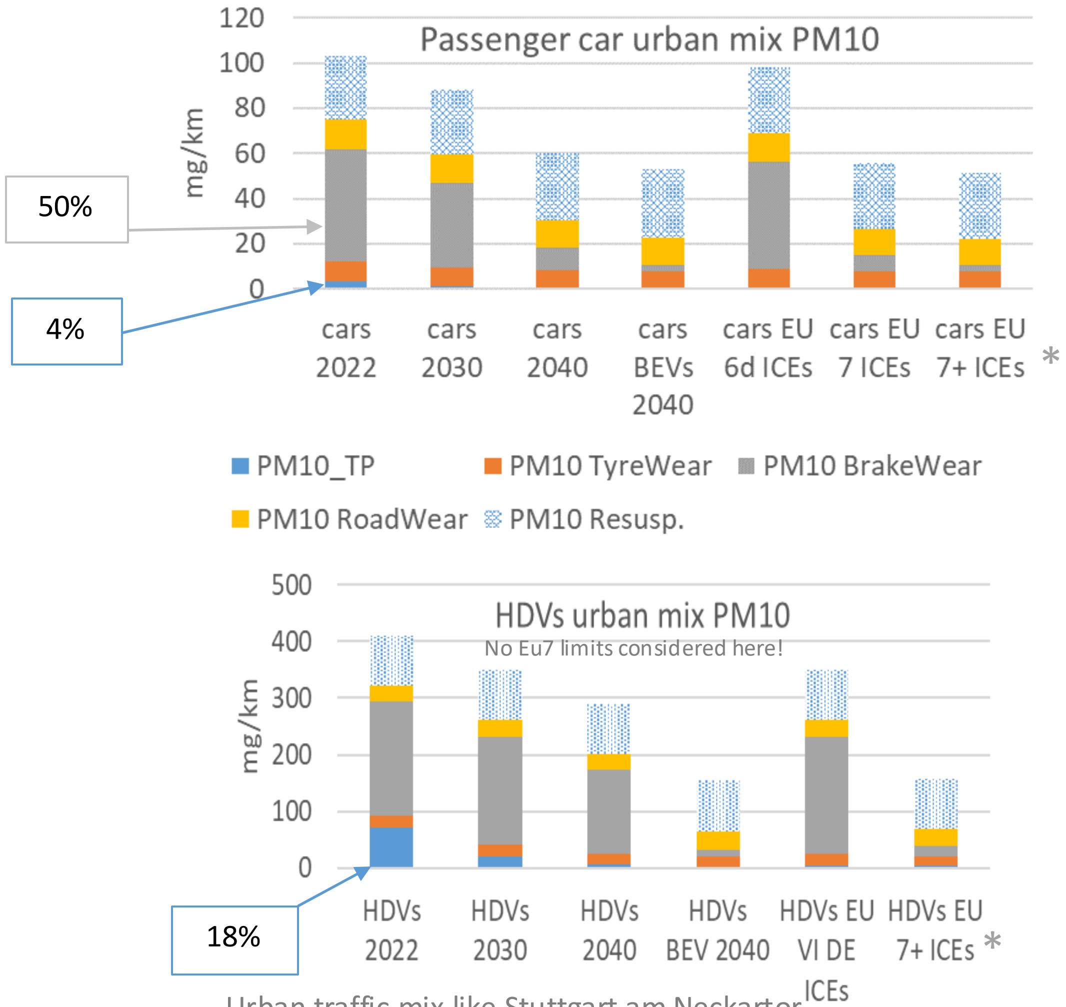
Example: Boundary Conditions for Passenger Cars in Europe

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
EMISSION	EU 6b			EU 6c, 6d temp, 6d							EU 7	
RDE	Development Phase			Application								
Test-Cycle	NEDC			WLTP								





Challenge Emission PM



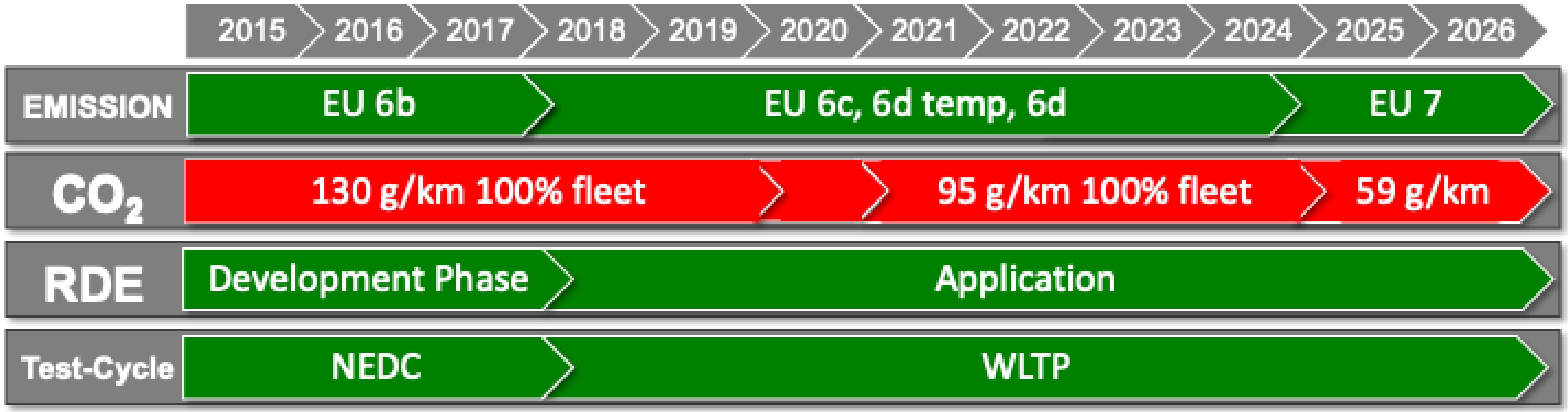
Urban traffic mix like Stuttgart am Neckartor
* Eu7+: further improved brakes, higher HEV shares for cars

Source: ITnA / Hausberger, 2024

- Exhaust emissions hardly relevant anymore
- BEV, HEV, EU7 ICE have roughly the same PM10 and PM2.5 emissions in total
- Brake wear is currently dominant in urban areas. However, this is significantly reduced by electrification and EURO 7 limits
- Potential for reduction in tire and road abrasion and resuspension currently low
- PM10 air quality limits for 2030 critical

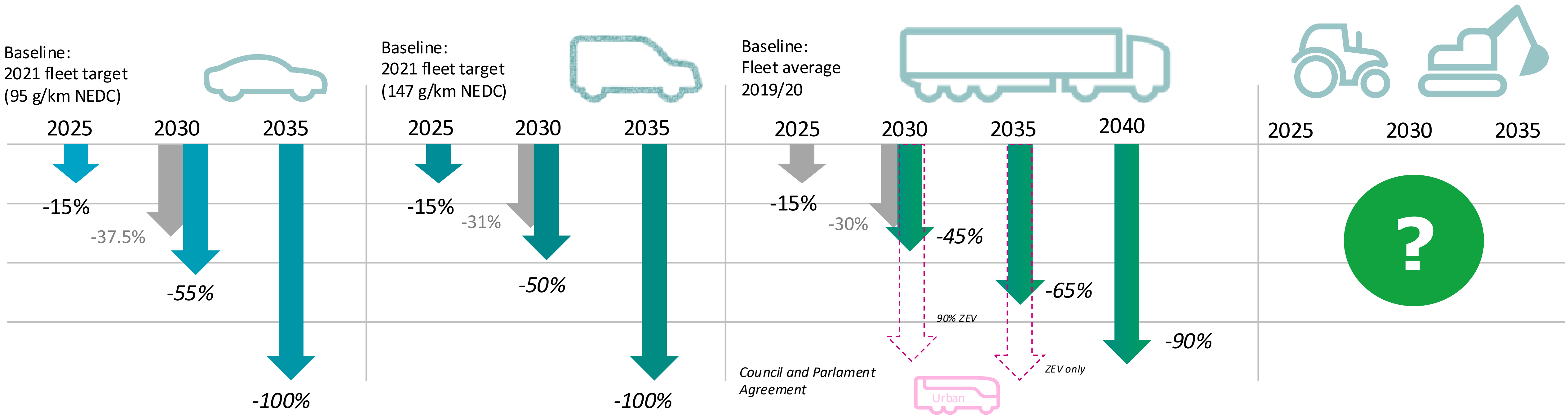
Challenge Emissions

Example: Boundary Conditions for Passenger Cars in Europe



EU CO_2 Standards

Outlook across segments



Accepted ZEV_{CO2}:
BEV, FCEV
H_2-ICE & ICE with E-Fuel ?

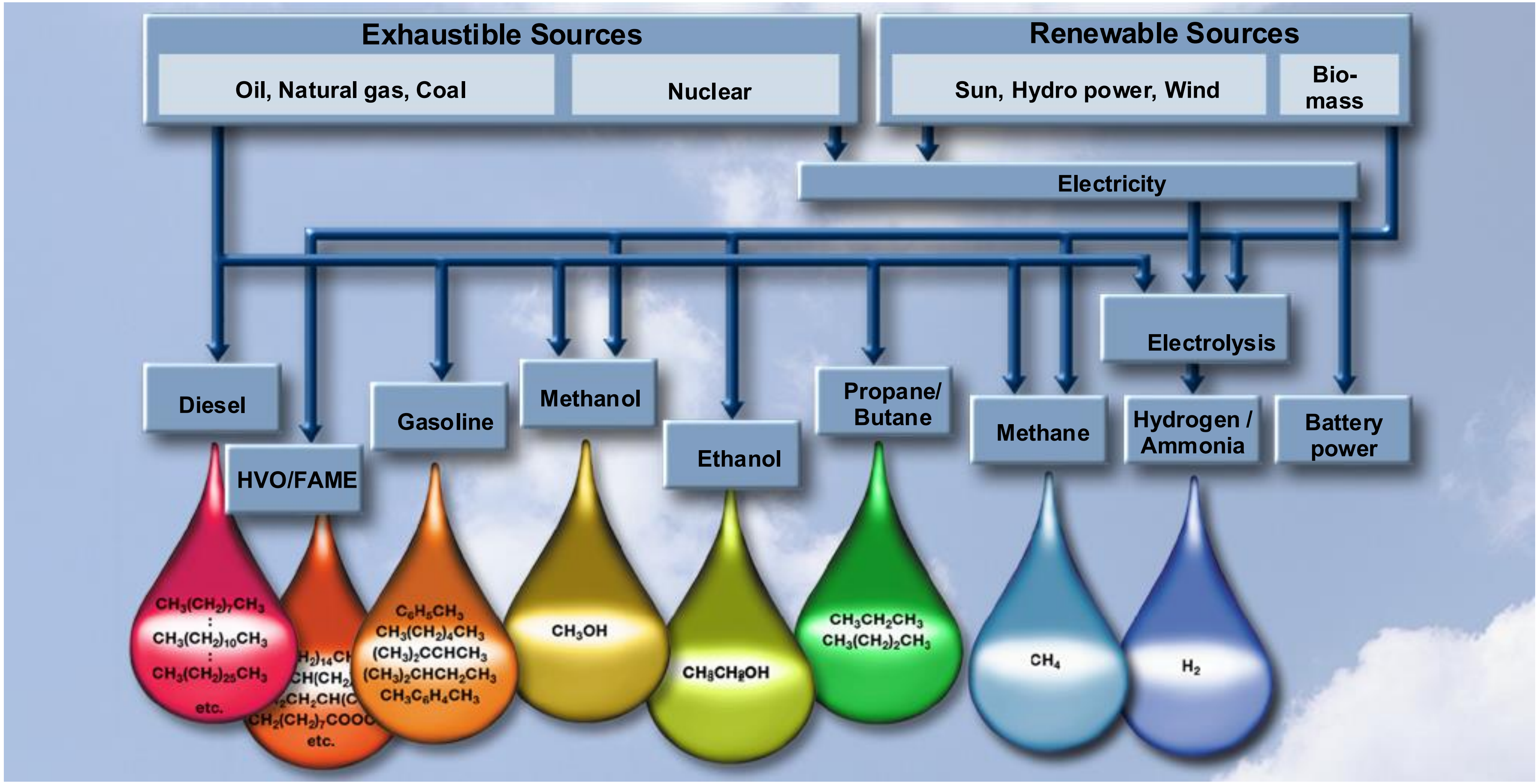
Accepted ZEV_{CO2}:
BEV, FCEV, H_2-ICE*
**ZEV: max. 3 g/(t·km) or 1 g/(p.km)*

Potential ZEV_{CO2}:
BEV, FCEV, H_2-ICE
(E-Fuel, Alcohols)

Grey: targets in current regulation. ***Italics*: proposed.**

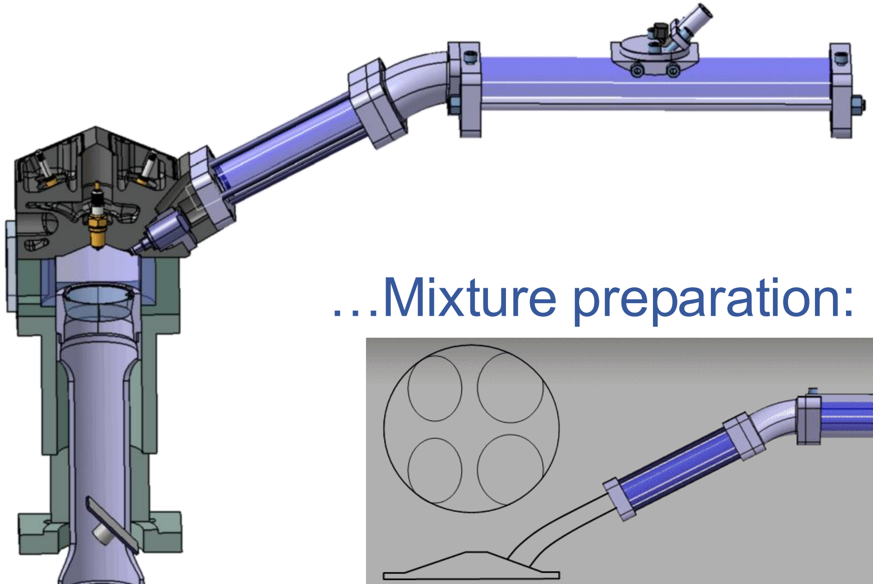
Source: AVL / Wieser, 2024

Various forms of Energy and Fuels for propulsion systems

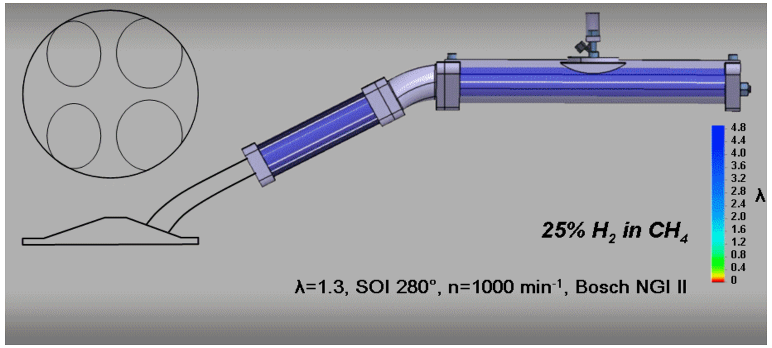


Source: Göschl BMW adapted

Mixture Prep. and Combustion Hydrogen ICE

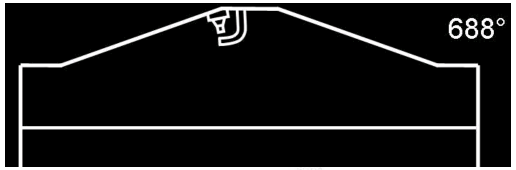


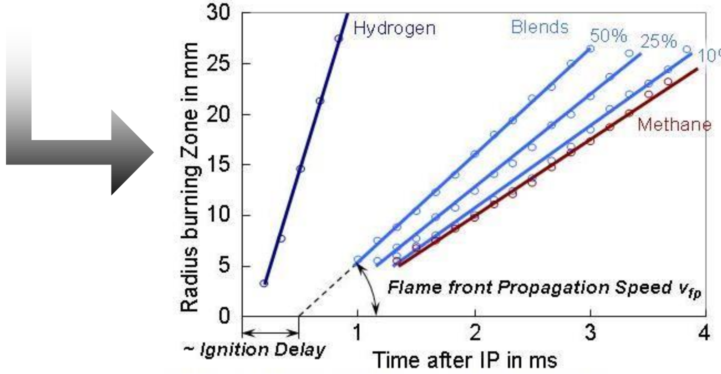
…Mixture preparation:



- Mischungsverhalten, Ladungsschichtung, Einfluss auf Verbrennung & Anomalien

…combustion:





- Kenngrößen der Verbrennung, Beherrschbarkeit, Anomalien, Wirkungsgradpotentiale

Measured Tailpipe Emissions in Transient Cycles

- Very promising results demonstrated on the transient test bed

NO_x Tailpipe	**1,7** mg/km	**26,7** mg/km	**280** mg/kWh	**22,6** mg/kWh
Test Cycle	WLTC *23°C*	ERMES *23°C*	WHTC *combined*	NRTC *combined*
Configuration	SCR Late Post Inj.	SCR Early Post Inj.	OC / SCR VNT	OC / SCR VNT
Engine	2 lit. IL4	2 lit. IL4	13 lit. IL6	13 lit. IL6

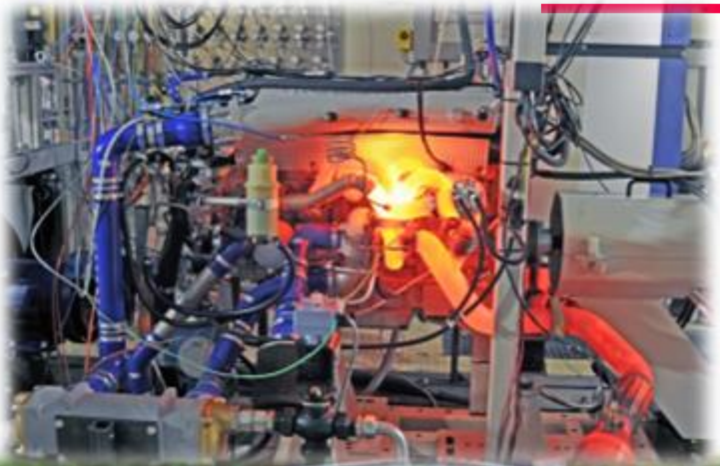
Stage V 2000 mg/kWh
Euro 7 Truck 220
Tier5 220 / 2031 (40/2033)

Source: H. Eichlseder | P. Grabner | E. Schutting / M. Schneider 2023

Hydrogen ICE for Aston Martin

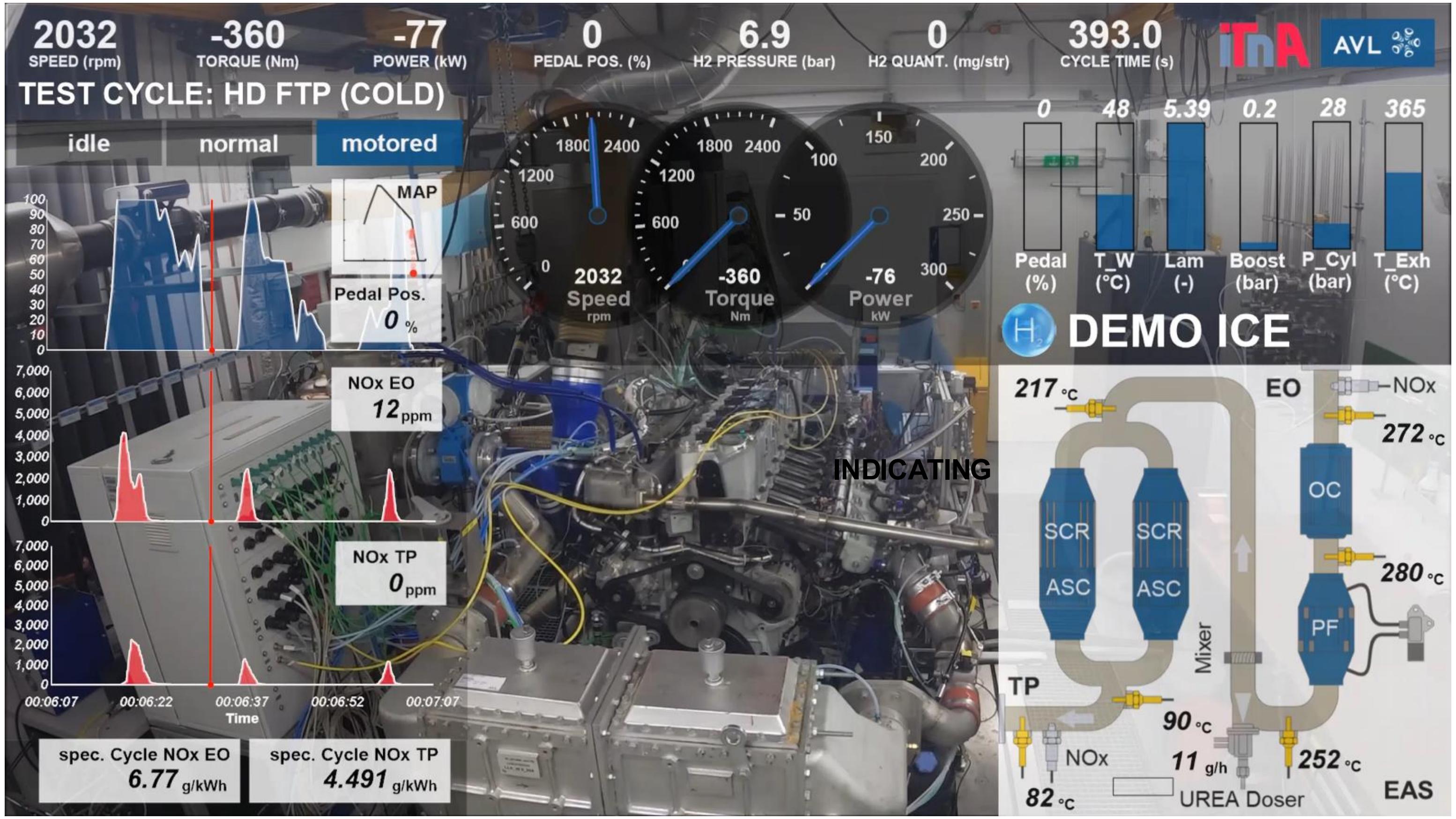
Example for robusteness: 24h Race Nürburgring

- Base engine
  - Aston Martin AM11
  - Gasoline NA
  - 6 dm^3 capacity
- Race engine
  - Implementation
    - H_2-Injection
    - BiTurbo, AirRestrictor
  - Operation with
    - Hydrogen
    - Gasoline or
    - Mixture of both



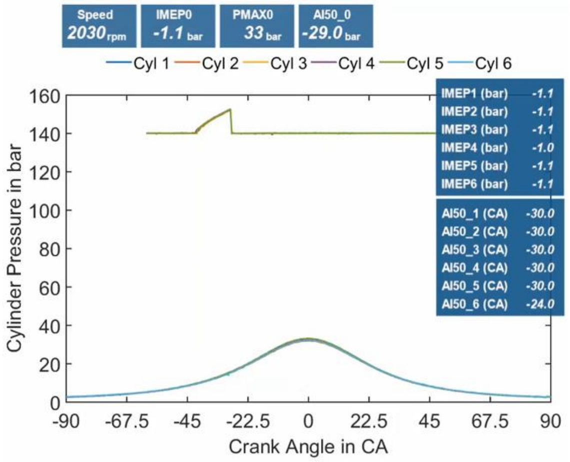
Challenges Hydrogen HD engine

Transient operation (FTP cold)



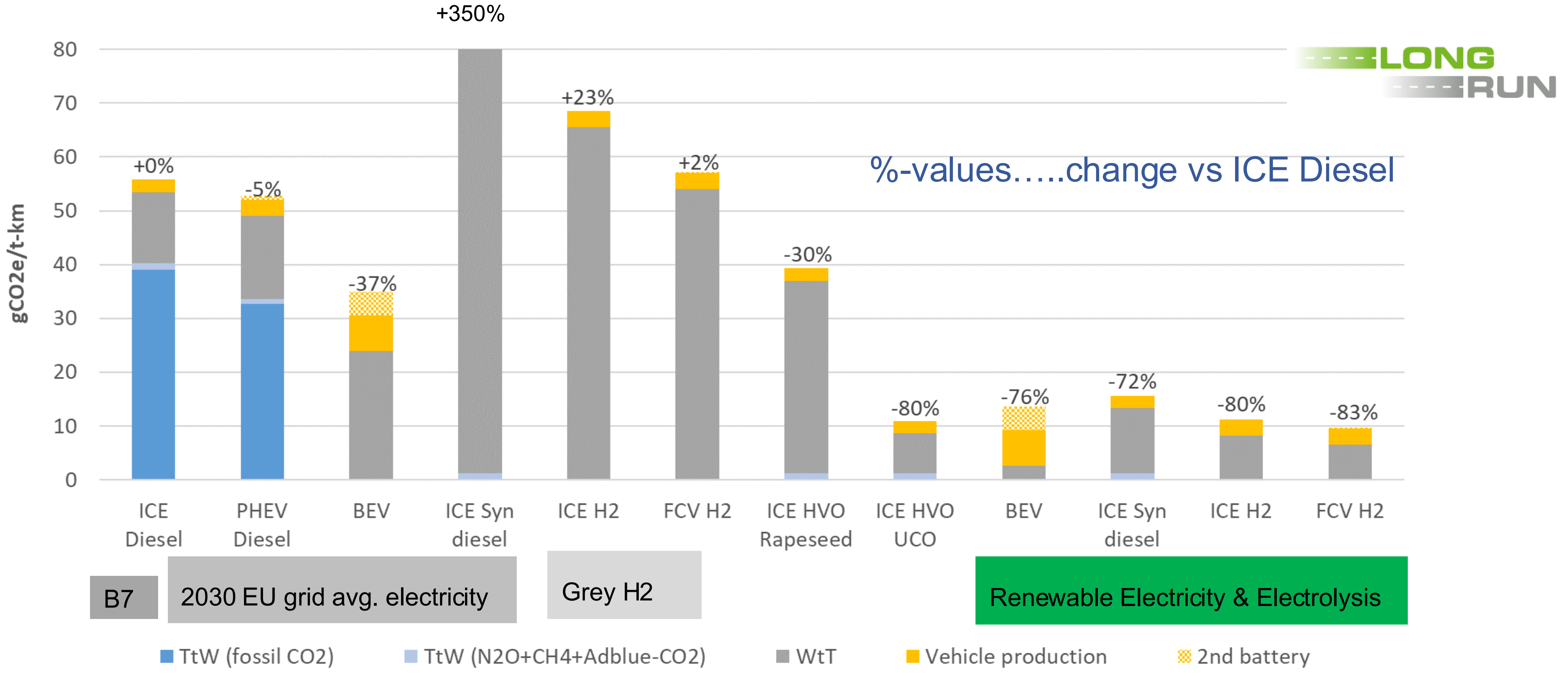
Source: Schneider ITnA

- Pre-ignitions during transient load changes
- **Possible triggers**
  → Increased residual gas content due to temporary increased exhaust backpressure
  → Enrichment
  → Increased oil combustion after motored or idling operation



Results CO_{2e} (VECTO + LONGRUN LCA for 2030 technologies)

Reference 2030, EU Mix 254 g CO2e / kWh_{el}; Renewable: 28 g CO2e / kWh_{el}; 1,2 Mio km



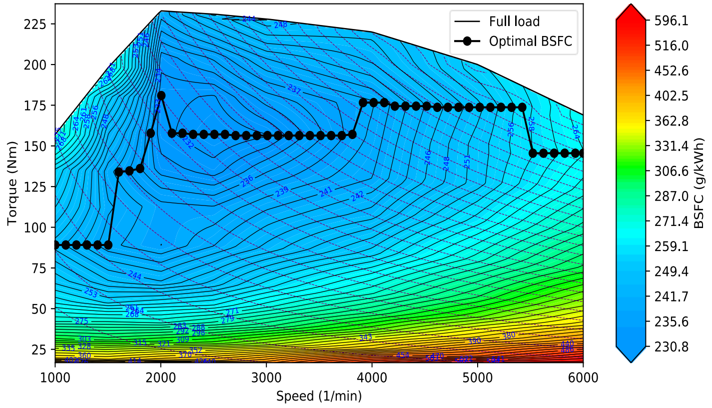
Mission profile mix: Long haul (90%) and Regional delivery (10%)

Source: Hausberger / ITnA 2024

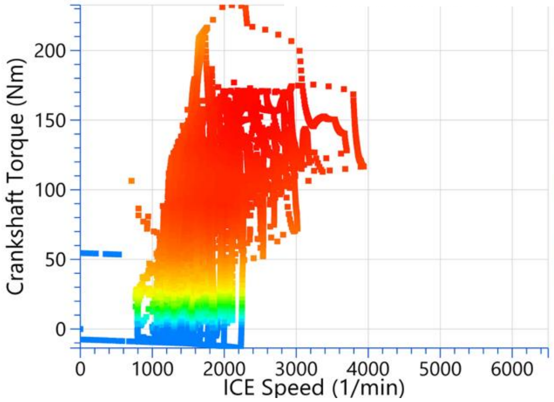
Hybrid powetrains and dedicated hybrid engines using renewable fuel

Transient operation of ICE in LD vehicles

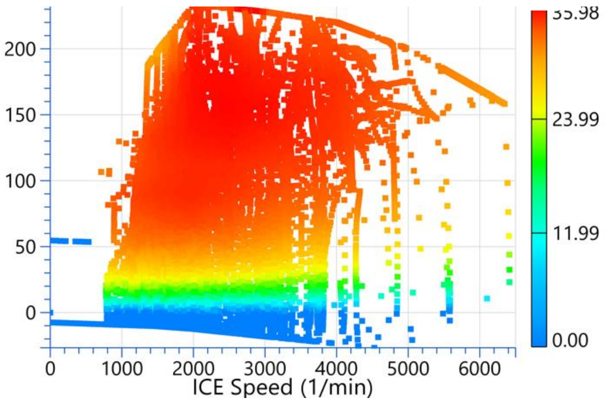
Transient BSFC Map



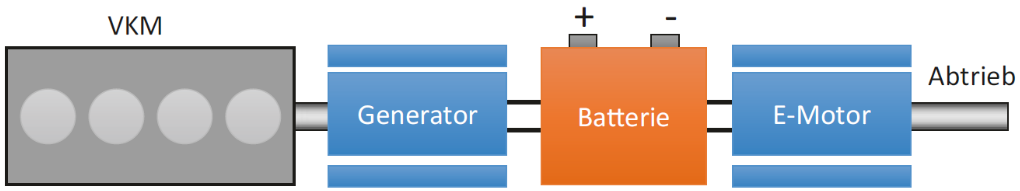
Efficiency WLTC (lab)



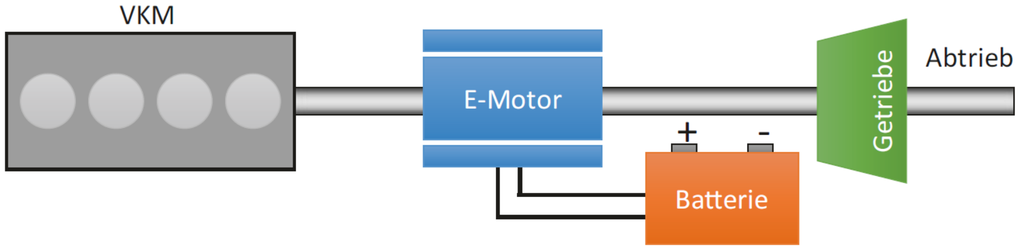
Efficiency rural roads (real world)



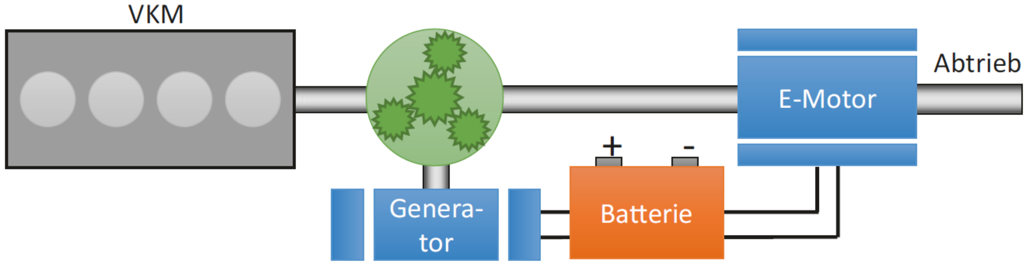
Serial hybrid



Parallel hybrid



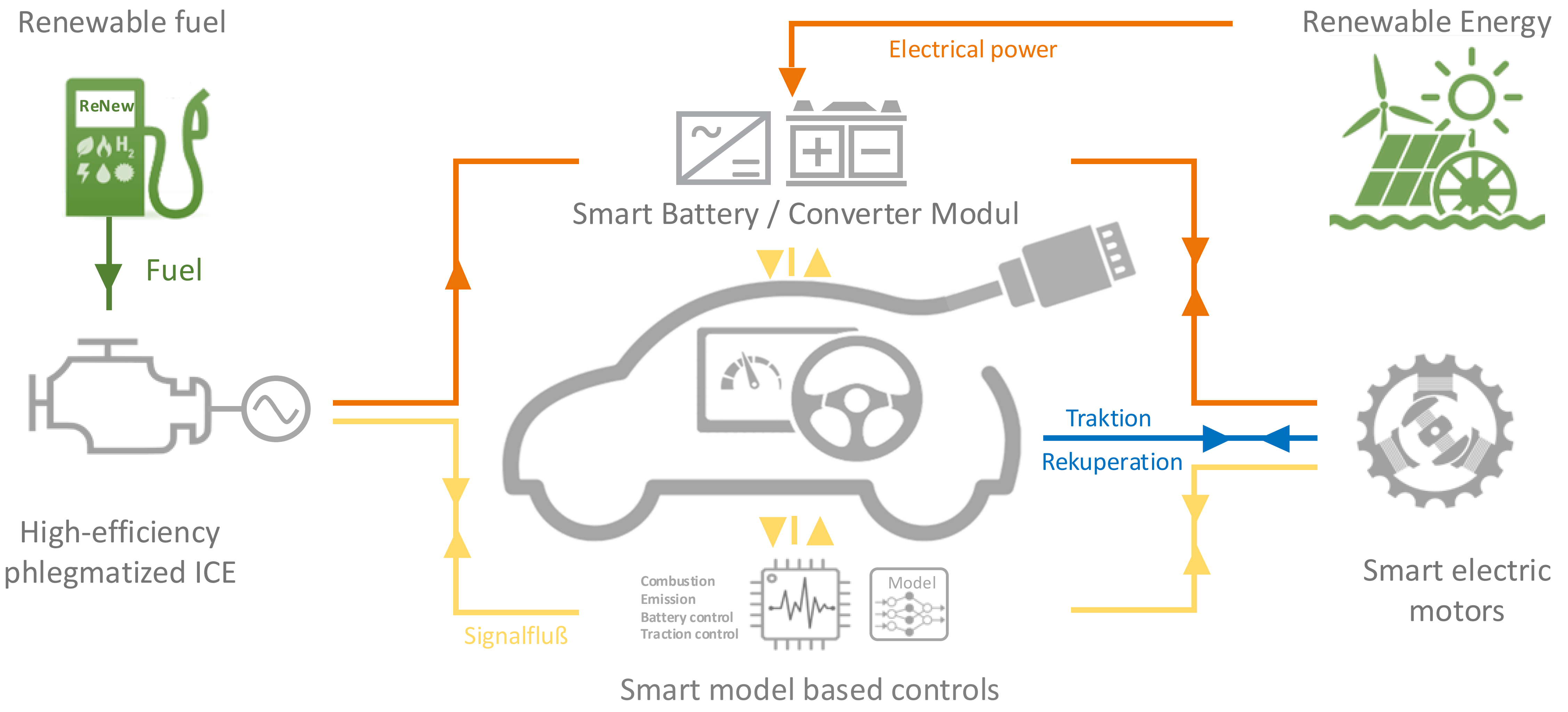
Power-split hybrid



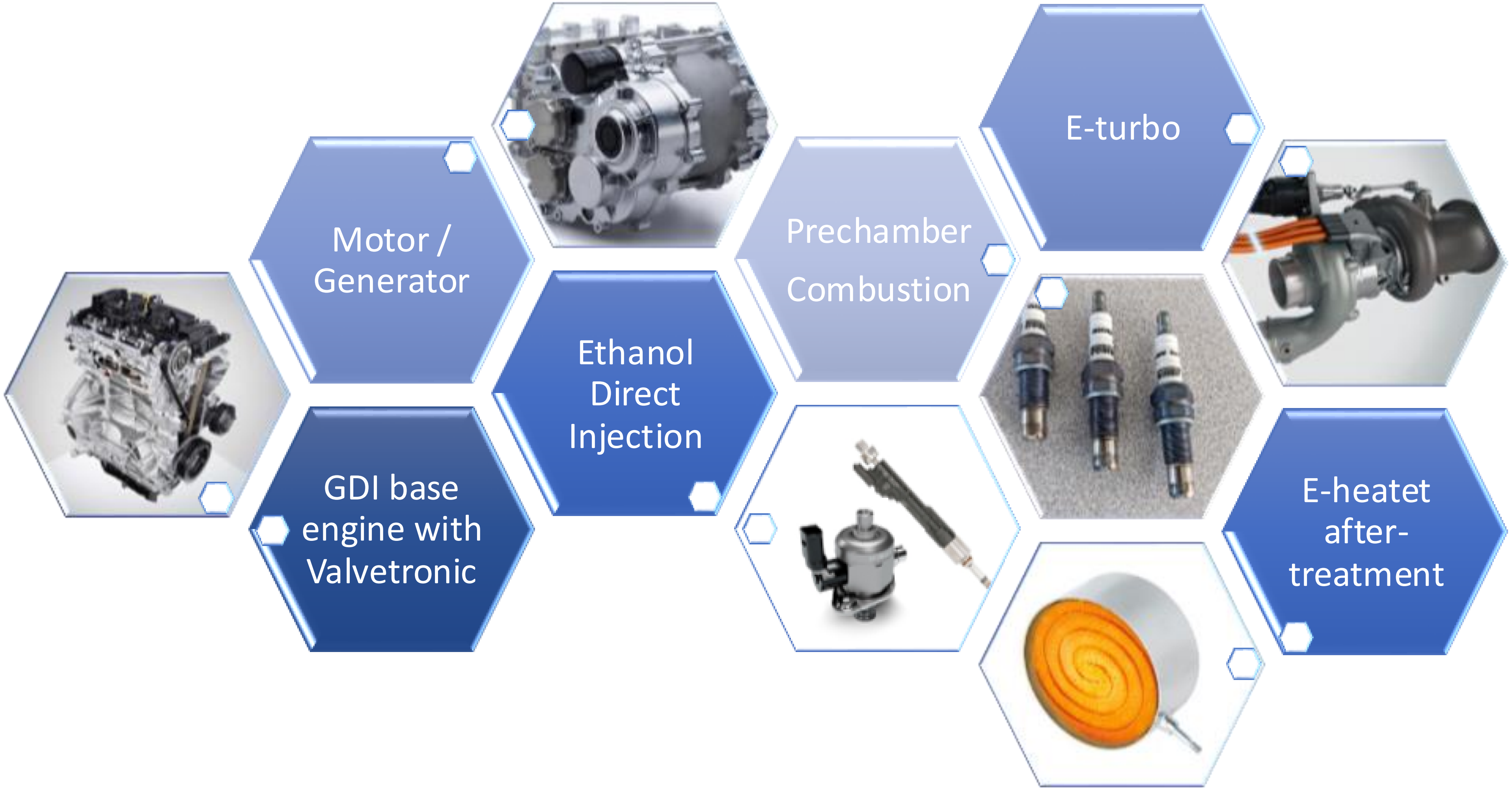
Relevant renewable fuels: Properties

	Unit	Super 95	Methanol	Ethanol	Hydrogen
Calorific value H_u	MJ/kg	42,00	19,70	26,80	120,00
Stoich. air requirement L_{St}	kg/kg	14,50	6,46	9,00	34,20
Heat of Evaporation	kJ/kg	420	1100	910	450
Boiling point	°C	30-190	65	78	-253
Density (15 °C)	kg/m^3	735-785	791	789	0,09
Octane rating RON	-	95,0	116	112	130
Ignition temperature	°C	230-450	455	425	585
Minimum ignition energy	mJ	0,24	0,28	0,28	0,017
Laminar flame speed (λ =1)	cm/s	35	40	40	230

Serial hybrid topology & architecture



Dedicated hybrid engine including aftertreatment

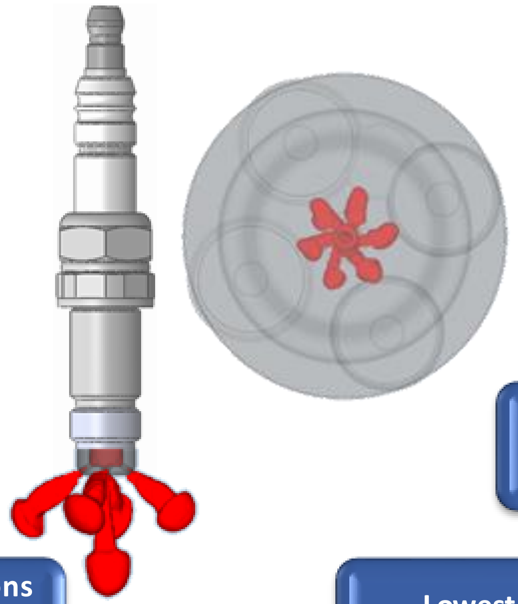


Innovative prechamber combustion concept

Turbulent flame jet ignition

Ultra lean operation in part and full load with wide A/F window

Lowest HC and CO emissions at full and part load operation

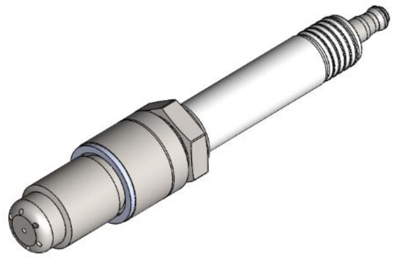


High preignition and knock margin at highest loads

Optimized combustion center of gravity and duration for best fuel economy

Lowest cycle-to-cycle variations

Advanced PCP technology provides maximum operation and application flexibility

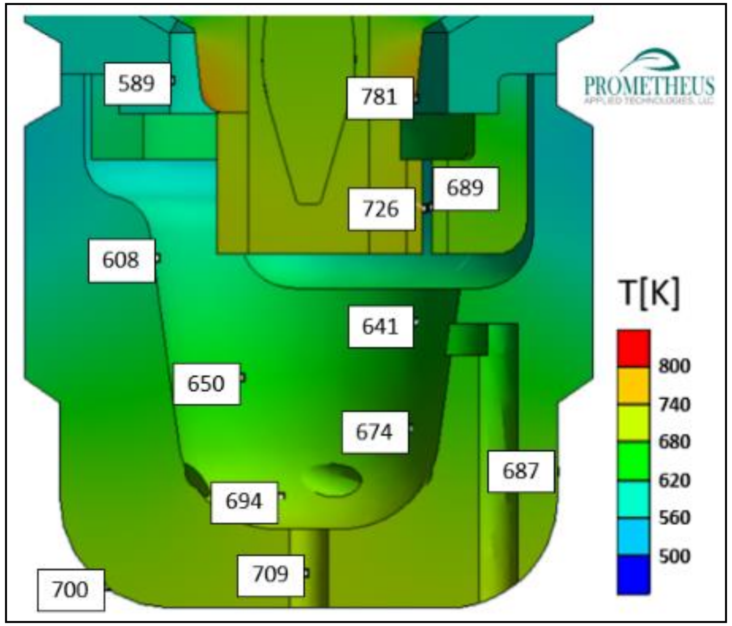


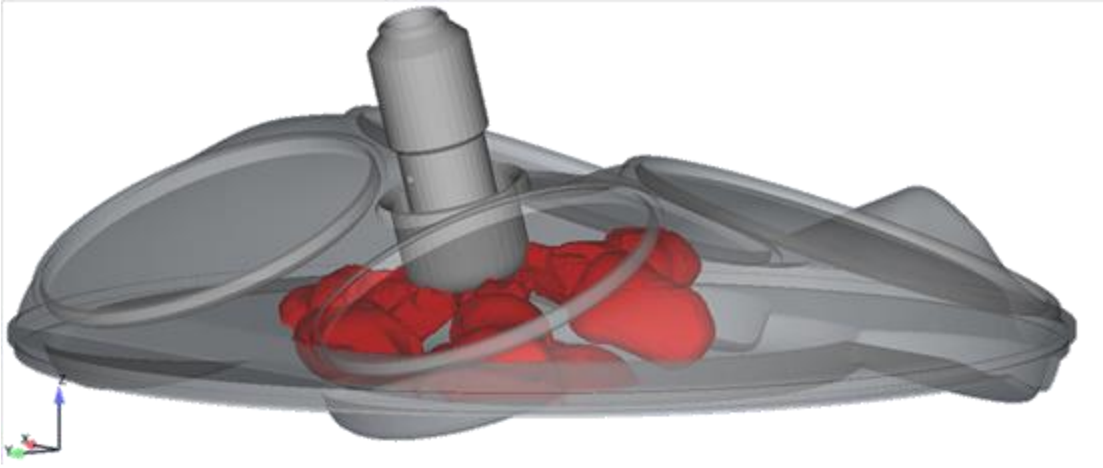
PCP technology is best suited for a phlegmatized engine running WOT operating points:

- ✓ Optimal scavanging & filling
- ✓ Optimal thermal management
- ✓ Optimal flame jet orientation

- ➢ Ultra low NO_x emissions
- ➢ Fast combustion @ 8 °CA MFB50

Combustion concept: key considerations





Thermal management of the PCP

Optimal prechamber and electrode temperatures are required for an extented combustion operating range without knock or preignition at WOT as well as to ensure the longest durability.

- Conjugate heat tranfer calculations considering actual cylinder head cooling.
- Modeling of arc travel and arc development in the prechamber

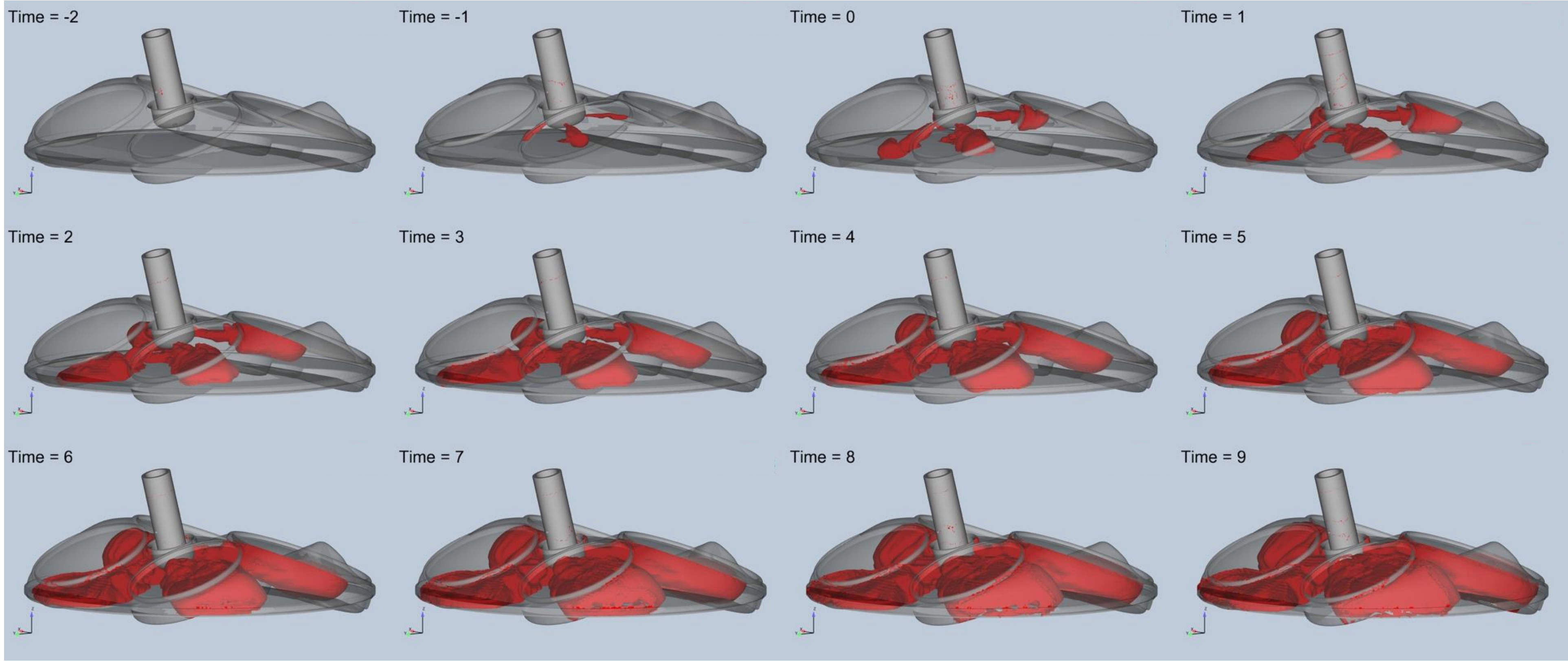
Flame jet orientation and piston geometry

The complete burn of the fuel trapped in the prechamber prior to jet release is key to generating powerful flame jets.

The jet orientation considers the lambda distribution in the main chamber created by residual gas non-unifomity and the injection strategy and geometry.

Combustion concept: flame jet propagation

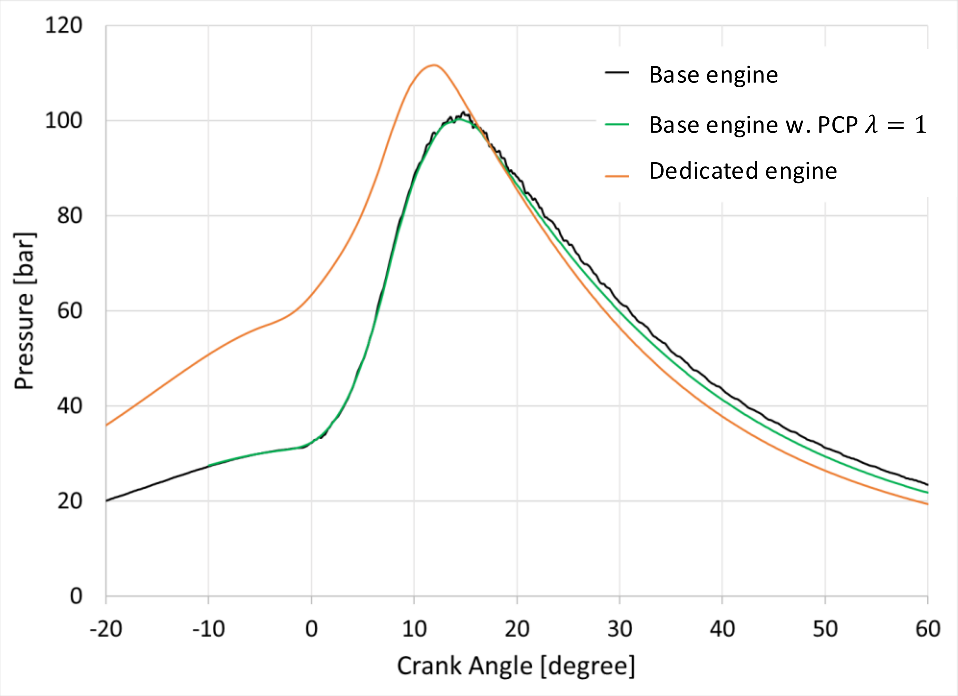
Very powerful flame jets achieve fast flame propagation with ultra-lean mixture (Lambda=1.9)



(2000 1/min 16 bar BMEP)

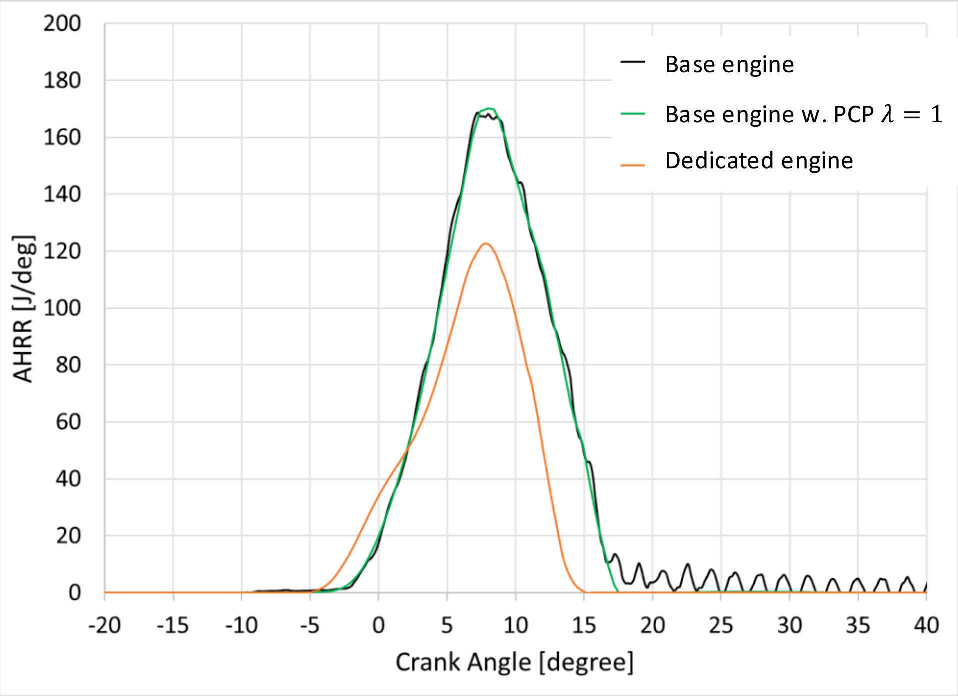
Innovative combustion solution: Results

Cylinder pressure (2000 1/min 16 bar BMEP)



Baseline: 37 % efficiency, 2300 ppm NO_x
Engine compression ratio: 11:1; Mixture Lambda: 1.0
Boost pressure: 1.4bar; Spark Timing: -6 CAD

Heat Release (2000 1/min 16 bar BMEP)

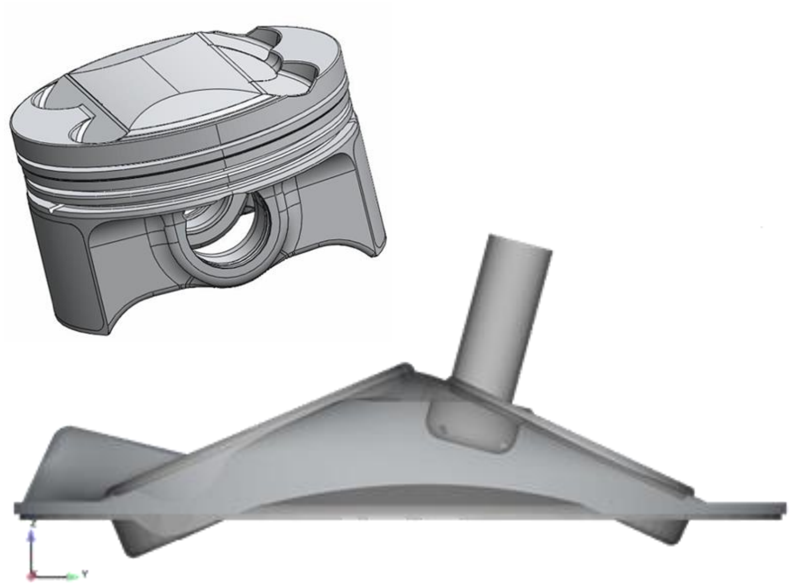


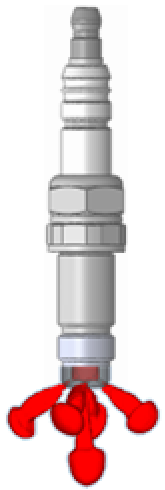
Innovative solution: 45 % efficiency, < 100 ppm NO_x
Engine compression ratio: 13:1; Mixture Lambda: 1.9
Boost pressure: 2.2bar; Spark Timing: -9 CAD

Innovative combustion solution for Ethanol

Combustion Chamber

Power kW	Speed rpm	BMEP bar	BTE %
20	1200	13,3	44
40	2000	16	45
60	3000	16	45

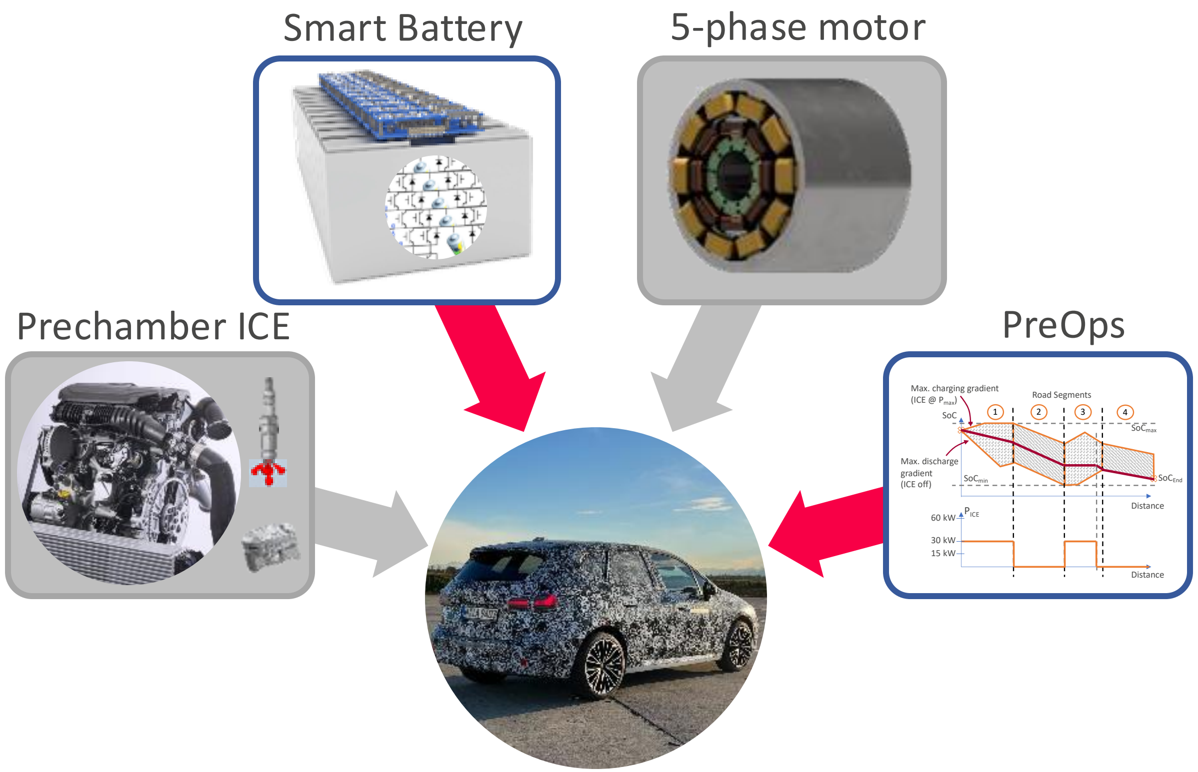




Serial hybrid configuration

Intelligent Predictive Operating Strategy (PreOps)

- Backend- and map-based prediction of actual power requirements
- Two control levels: Dynamic programming long range and model predictive short range control



Traction Motor

- In-house developed 5-phase self-excited synchronous motor
- Neodyme free, electrical excitation through harmonics
- 120 kW (30 s) / 80 kW (cont.) allowing v_{max} 160km/h
- Mech. efficiency between 92,0 - 97,8 %

Battery and Inverter (Step 1)

- Battery: State-of-the-art 400 V Li-Ion
- Inverter: in-house developed multiphase SiC

Phlegmatzied internal combustion engine

- 1.5 l, 3 cylinder (based on BMW B38)
- Mech. efficiency up to 44 % @ 100 ppm NOx
- Ultra-lean, homogenous, prechamber combustion
- Quasi-stationary operation in 3 power levels (20, 40, 60 kW)

Generator – motor

- In-house developed 3 phase permanent magnet syncronous motor
- Mech. efficiency 98,4 %

Serial hybrid: virtual driving results

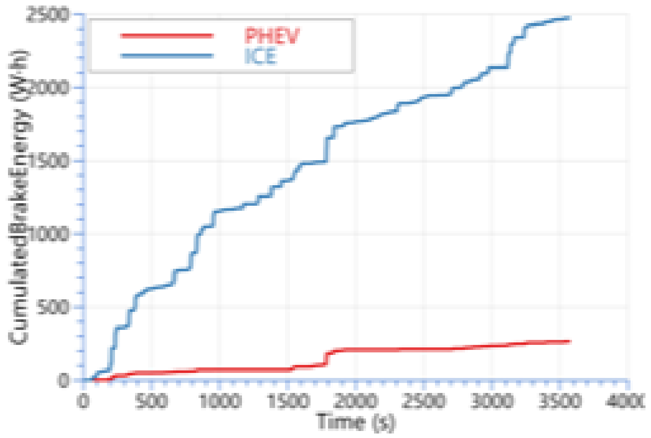
Brake losses & recu potential

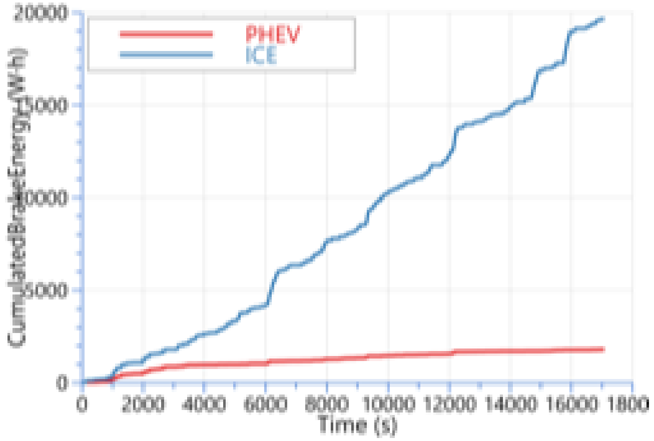
Ø Braking power with conventional ICE:
2.39 kW

⇩ Hybridization

Ø Braking power with hybrid powertrain:
352 W

Brake energy: smooth rural roads

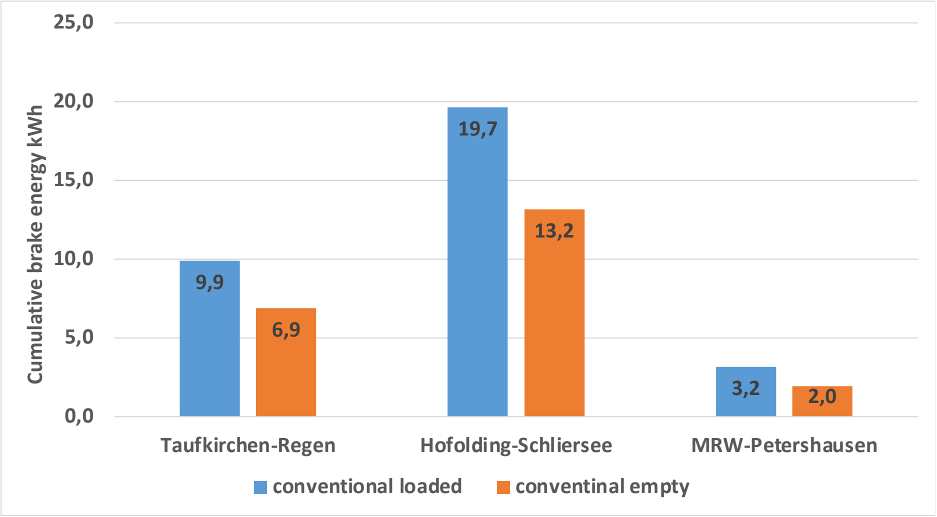




➡ Phlegmatization and hybridization reduce energy dissipation at the brakes by **more than 85 %** (also brake wear!)

Residual brake usage mostly near-standstill (low energetical relevance) or during singular sharp braking maneuvers (high power, not recuperable).

Huge variations in cummulative brake energy due to drive cycle evelvation profile differences.



Serial hybrid: virtual driving results

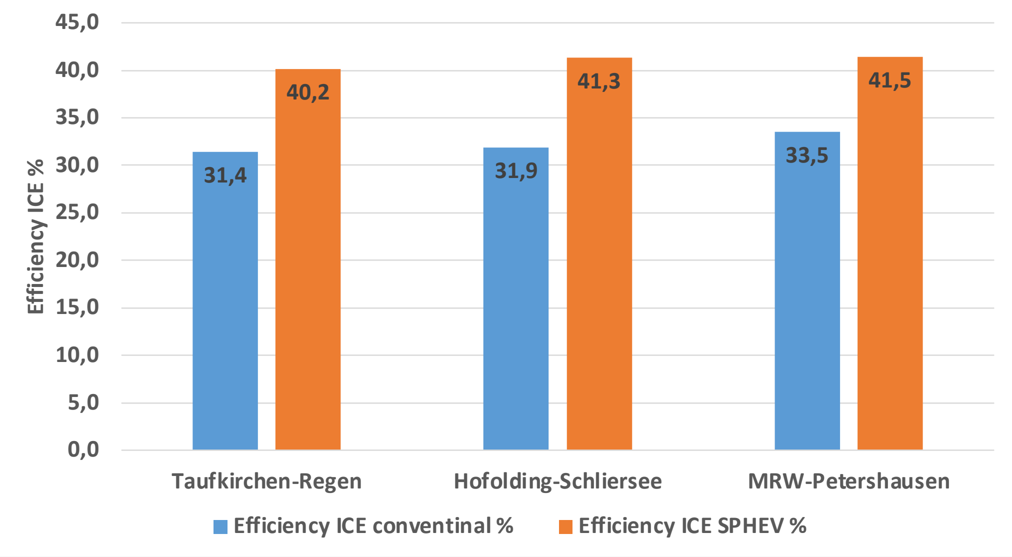
Average ICE & e-motor efficiency

Ø Efficiency with conventional ICE:
32.36 %

⇓ Phlegmatization
Hybridization

Ø Efficiency with phlegmatized ICE:
40.86 %

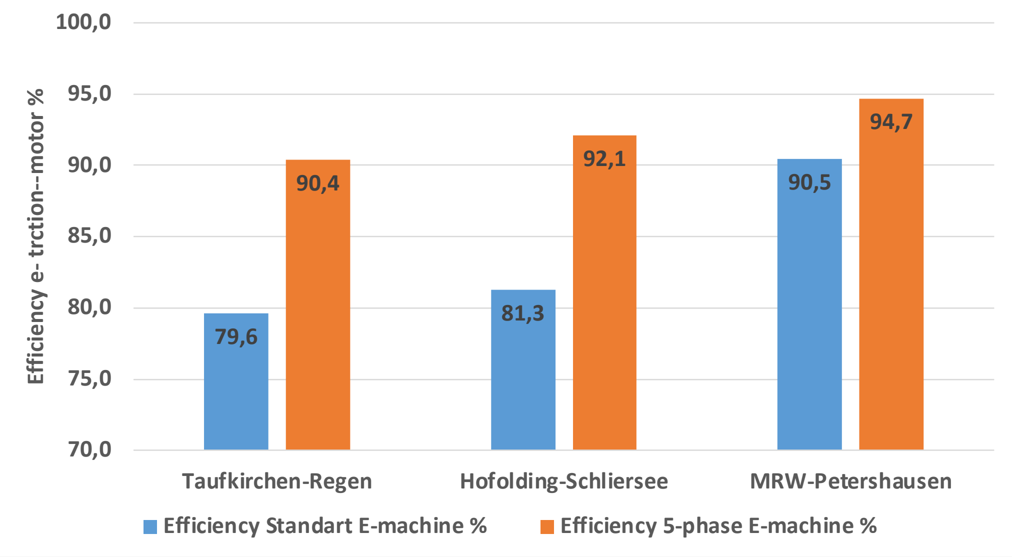
Low-load, low-efficiency operation is **entirely avoided**.



Ø Efficiency with conventional e-motor:
84,8 %

⇓ Innovative 5 phase design

Ø Efficiency with innovative e-motor:
92,7 %



Vielen Dank für Ihre Aufmerksamkeit !