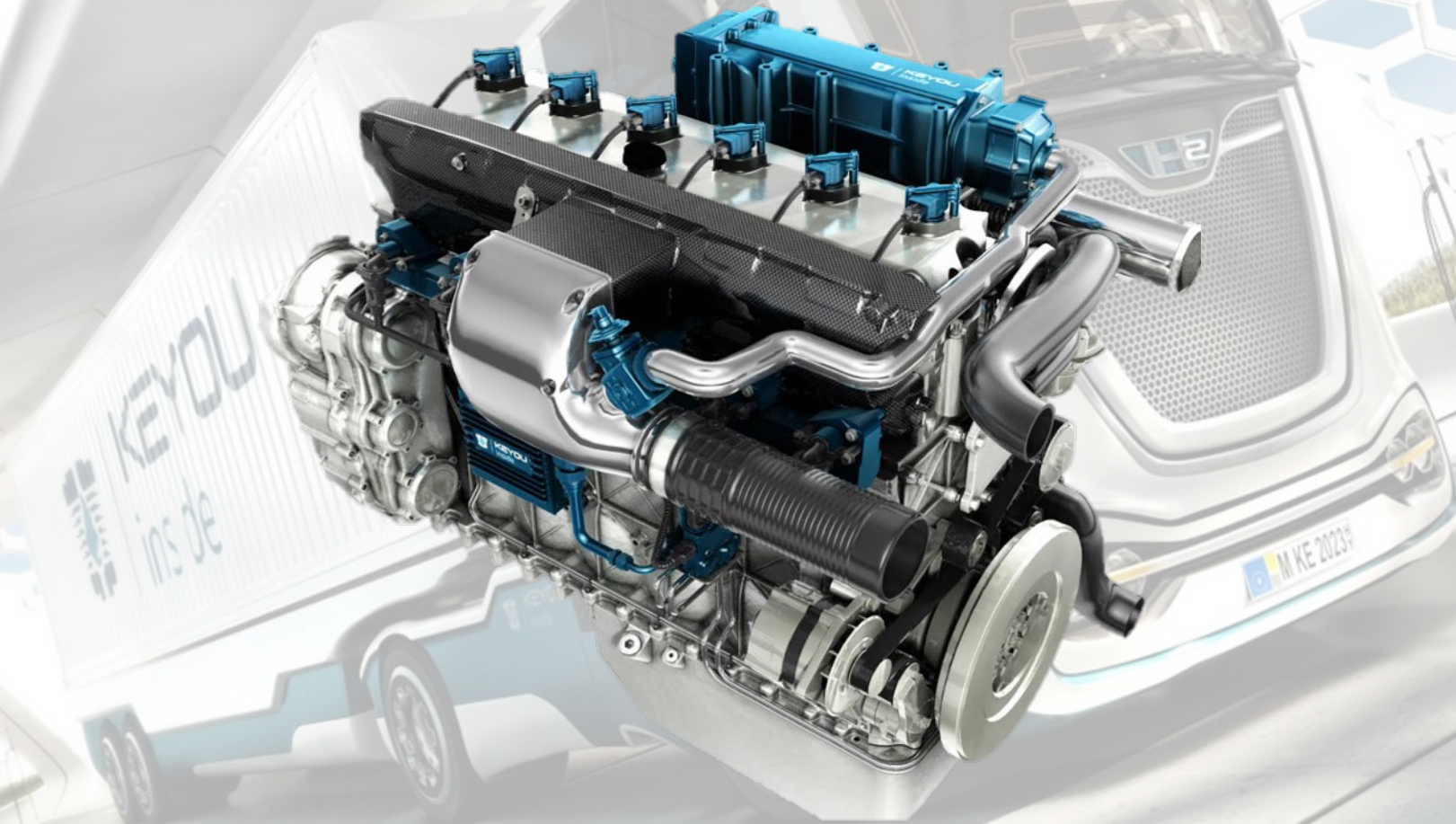


KEYOU 06 2020

KEYOU

## The Most Effective Technology to comply with CO<sub>2</sub>-Legislation: The New Generation of Hydrogen Internal Combustion Engines





**VITAL CHALLENGE OF INDUSTRIE**  
**Competitive, Attractive, and Zero CO<sub>2</sub>**



# Strong Motivation Towards Clean Mobility



## Innovation pressure for emission-free driving

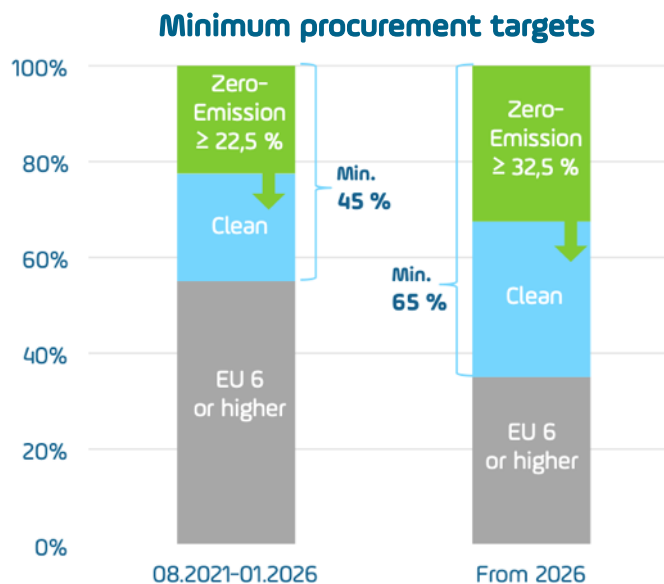
## EU regulation 2019/1242: new CO<sub>2</sub> targets for commercial vehicles

Statutory provisions on the reduction of average CO<sub>2</sub>-Emissionen of the manufacturer's fleets:

### CO<sub>2</sub> Goals EU:

- ▶ - 15 % CO<sub>2</sub> until 2025
- ▶ - 30 % CO<sub>2</sub> until 2030

## Clean-Vehicle-Directive (EU) 2019/1161



## CO<sub>2</sub> targets in other important automotive markets and regions



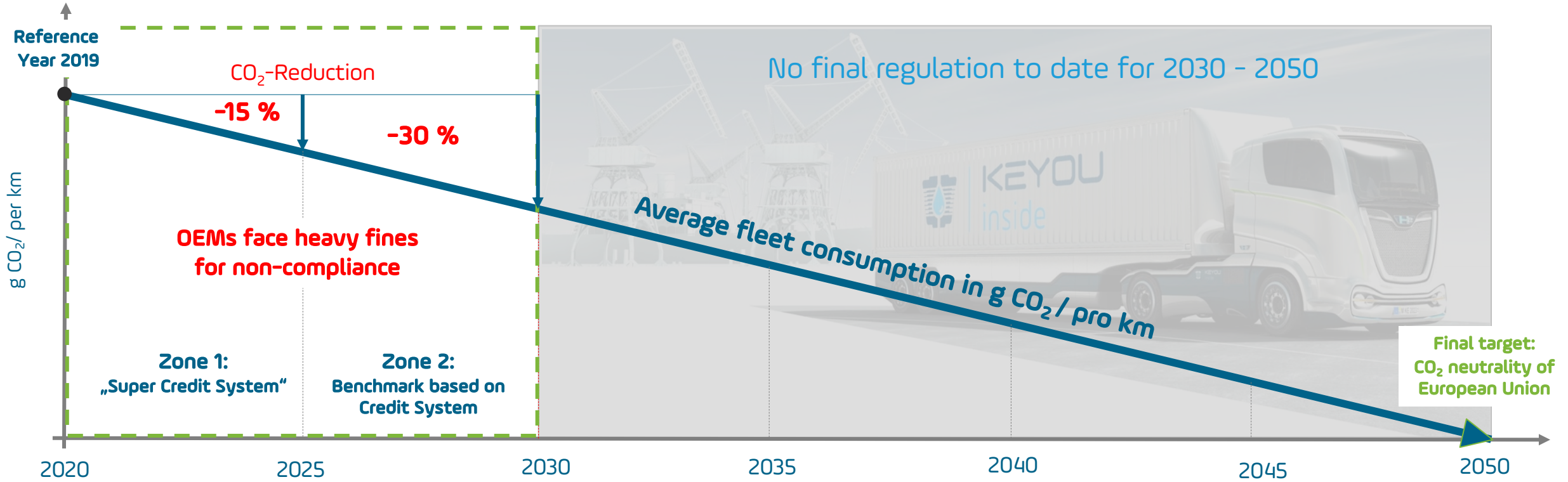
### CO<sub>2</sub> Goals - Average:

- ▶ Per Year: - 1,5 % to -2 % CO<sub>2</sub>
- ▶ 2030: - 10 % to -25 % CO<sub>2</sub>

There is a tremendous need for zero-emission technologies



# EU Route to Zero CO<sub>2</sub> Heavy Commercial Vehicles



**Engine and vehicle manufacturers must start developing zero-emission technologies today for the goals of tomorrow**

# Technology Wanted for Commercial Vehicles – how to Reach the Goals?



## Most effective CO<sub>2</sub>-Reduction-Technology: “Must-Haves”

- (1) Established mass production with high quality at low cost
- (2) Qualified and well trained personnel available - combustion engine is core competence)
- (3) Low risk in supply chain - independency from rare earths and valuable raw materials)
- (4) Highest customer benefit, attractive USP (TCO, range, refuelling time, etc.)
- (5) Profitable after-sales business



## Battery Electric Vehicles



## Fuel Cell Electric Vehicles



## Vehicles with H<sub>2</sub>-ICE



„zero emission heavy-duty vehicle means a heavy-duty vehicle without an internal combustion engine, or with an internal combustion engine that emits less than 1 g CO<sub>2</sub>/kWh as determined pursuant to Regulation (EC) No 595/2009 and its implementing measures, or which emits less than 1 g CO<sub>2</sub>/km“ (Directive (EU) 2019/1161) Article 4 (§5)

## Is there a **hidden Champion?**

# KEYOU Recognized the Potential for the H<sub>2</sub> Internal Combustion Engine (H<sub>2</sub> ICE) at an Early Stage The Window of Opportunity for the H<sub>2</sub> ICE Opened



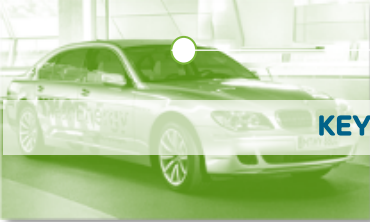
**Electromobility & Fuel Cell**  
as the right alternative technology over all vehicles

## Automotive Industry – Focused on Electric Mobility



## KEYOU – Focused on Hydrogen Combustion Engine

**BMW Hydrogen 7**



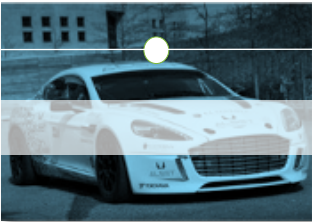
**2000 – 2011:**  
Production of 100 series vehicles  
Customer-use worldwide demonstration

**MAN Lion's City H<sub>2</sub>**



**2006 – 2014:**  
Production of 14 demo-fleet vehicles  
Service-lines operation in Berlin

**Aston Martin Rapide S H<sub>2</sub>**



**2013:**  
Construction of prototype car  
Finisher at 24h-Nürburgring race

**KEYOU**



**2015:**  
Foundation KEYOU

**Proof of Concept**



**2017:**  
Proof of Concept with  
DEUTZ TCG 7.8 H<sub>2</sub>

**First Customers**



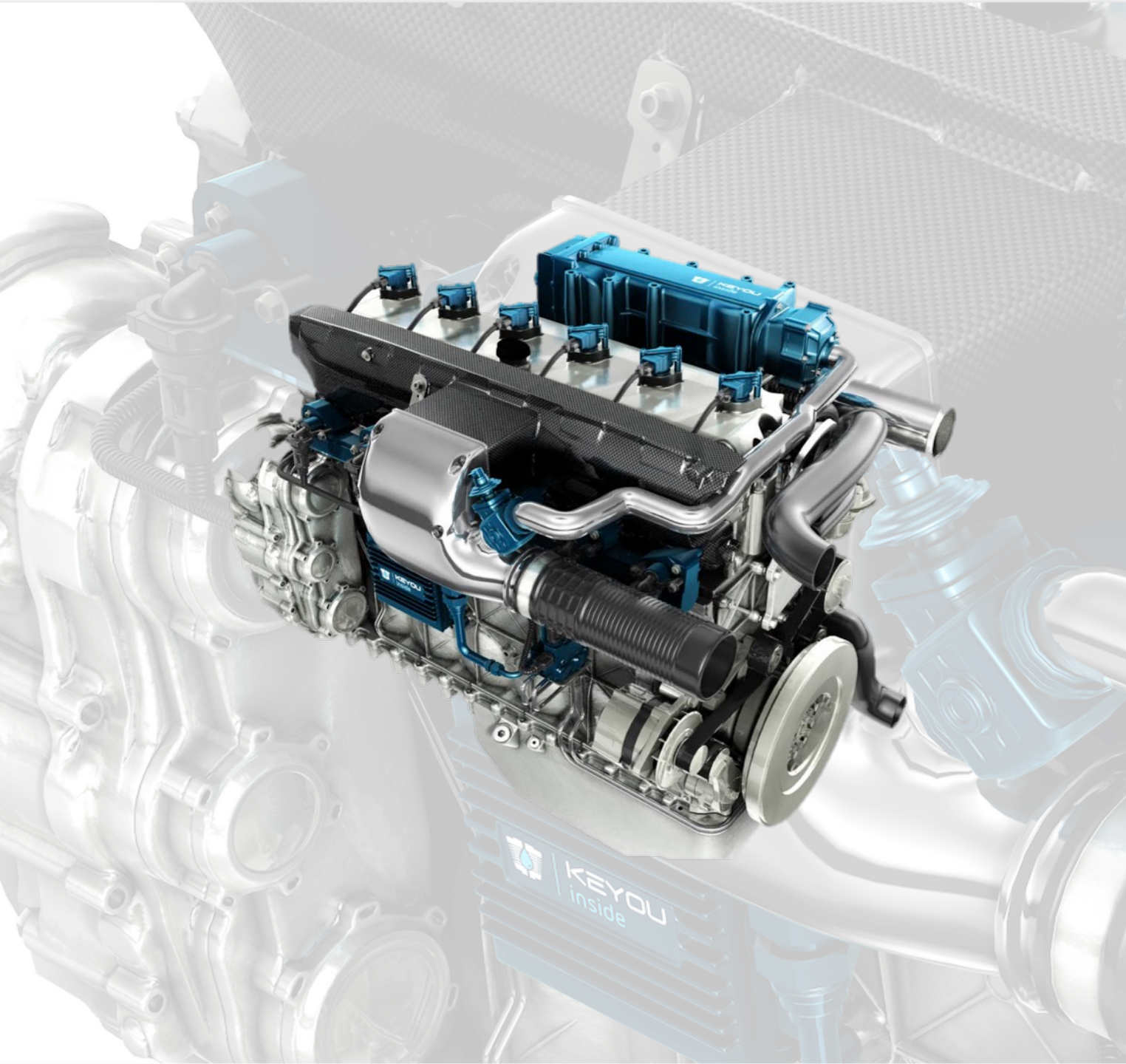
**2020:**  
Several engines and  
vehicles manufacturers

**KEYOU inside**



**2022:**  
First (prototype) vehicles  
with KEYOU-inside



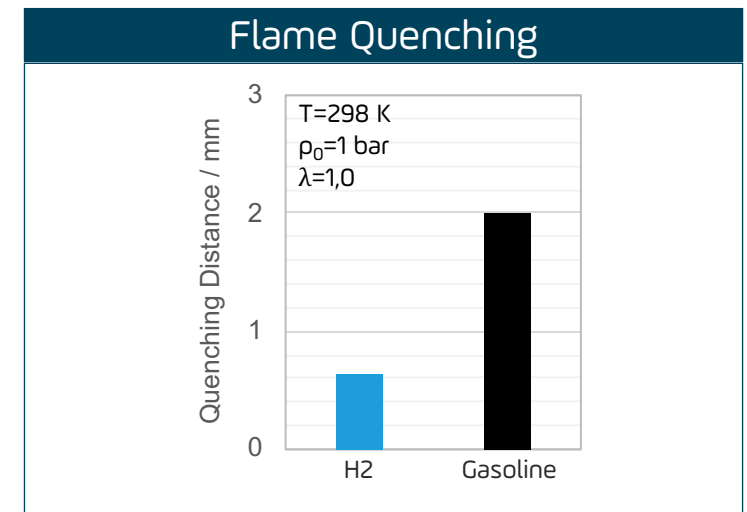
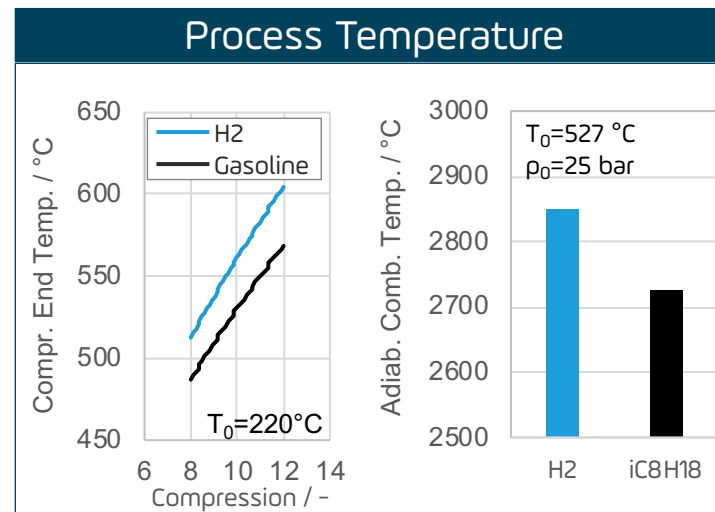
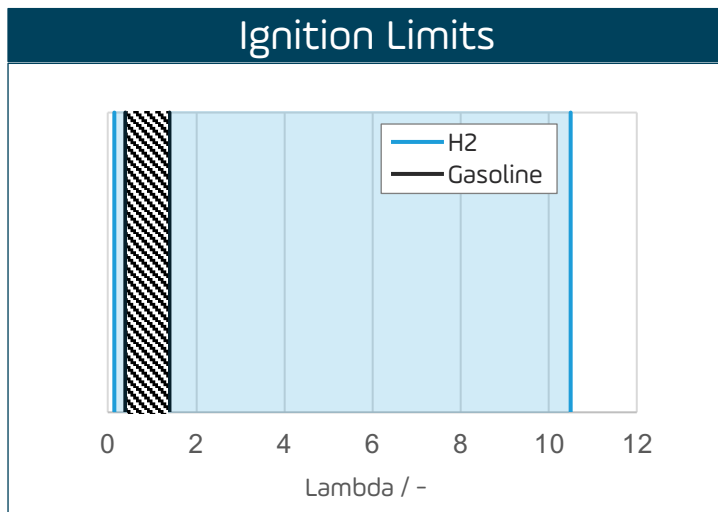
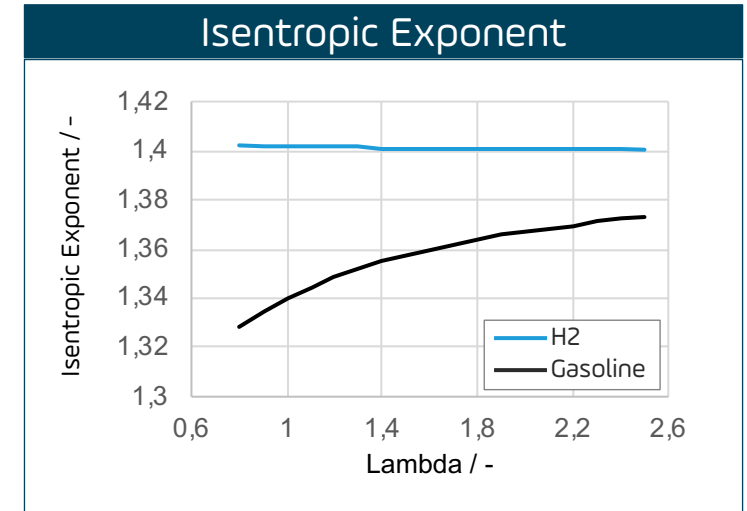
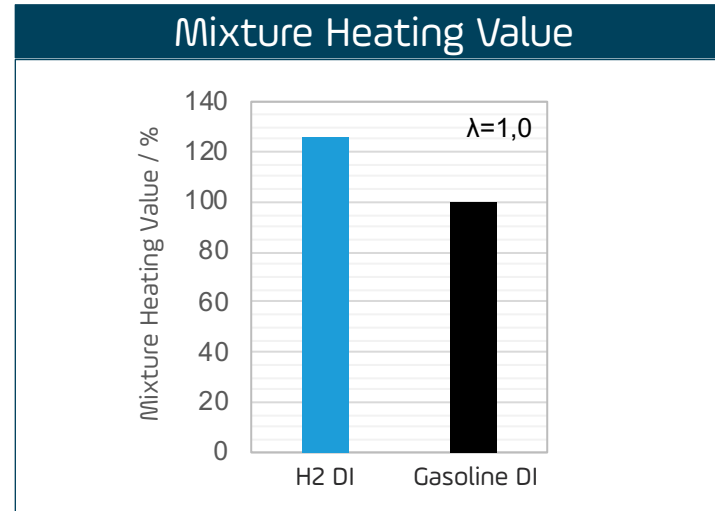
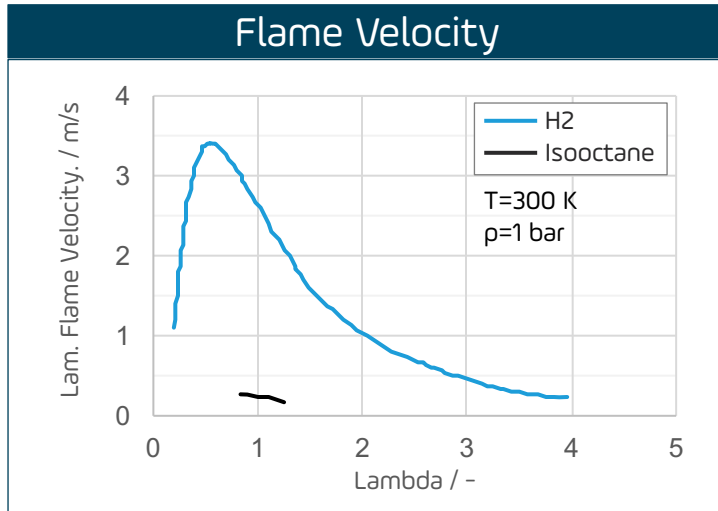


**INNOVATION**

**The new Generation of Hydrogen  
Combustion Engines**

# The Combustion Engine Shows Highest Potential with Hydrogen Fuel

## H<sub>2</sub> Combustion Process – Thermodynamic Characteristics





# Innovation Leap with the Right Concept



## Patented combustion process in a new H<sub>2</sub>-engine concept

- The first supercharged H<sub>2</sub>-engine world-wide with exhaust gas recirculation and H<sub>2</sub>-SCR
- Increased total efficiency
- Low consumption
- High specific power
- Low conversion efforts of base engine

## Previous H<sub>2</sub>-concepts in the past:

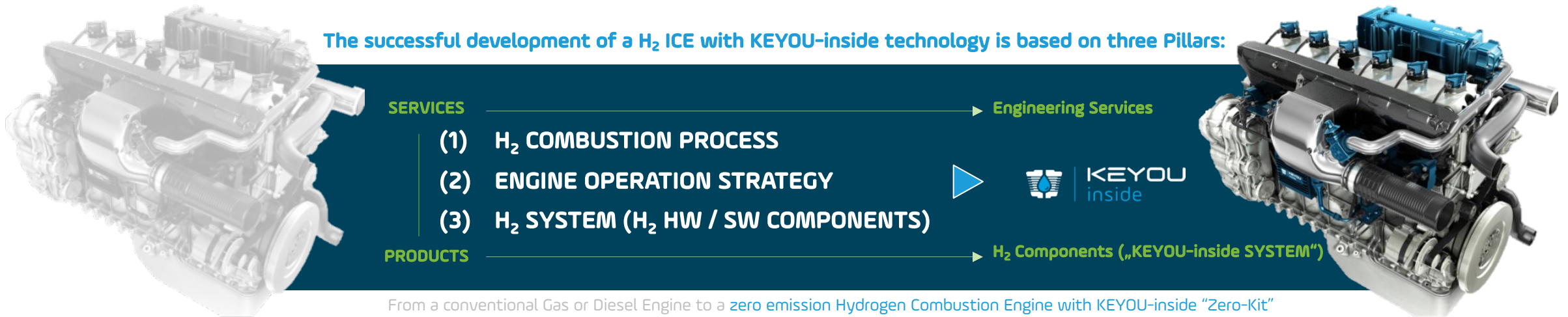
- Low efficiency
- High consumption
- Low specific power
- High conversion efforts of base engine



A new generation of combustion engines



**Result: A new generation of hydrogen combustion engines**



Manufacturer independent

All engine sizes & applications

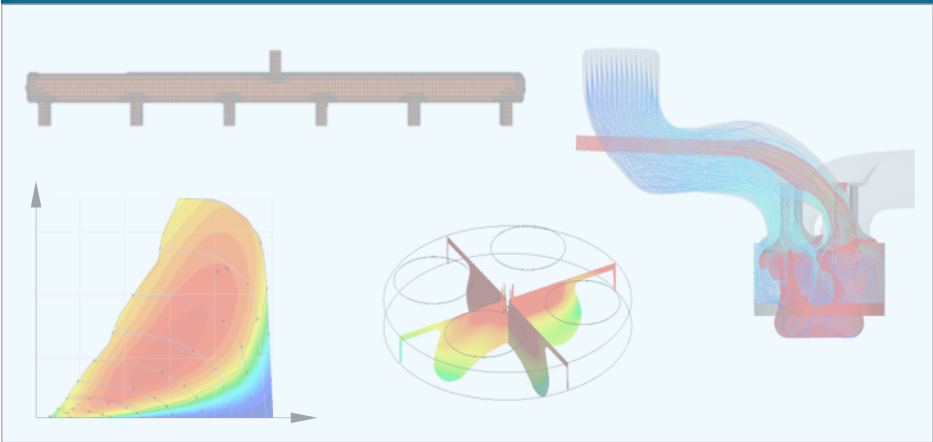
Low modification effort

Fast Integration

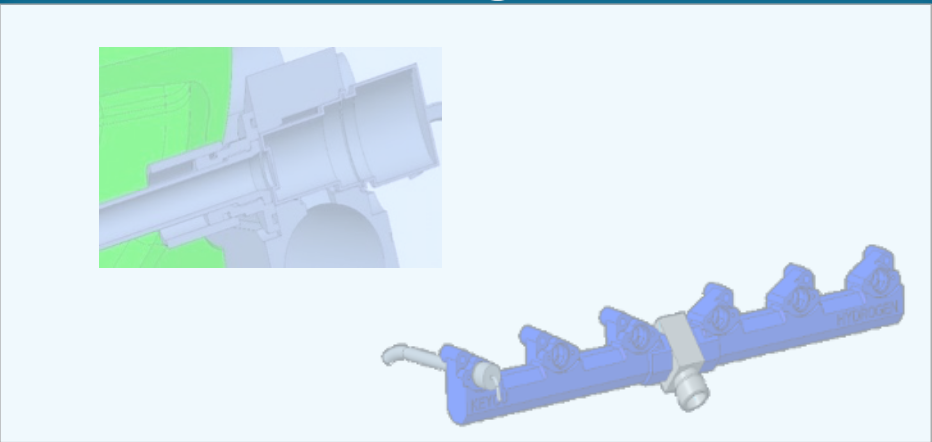
Market ready & validated technology

**OEMs can mass manufacture zero-emission hydrogen engines using its existing base engines as well as its mature processes, supply chains, and production infrastructure**

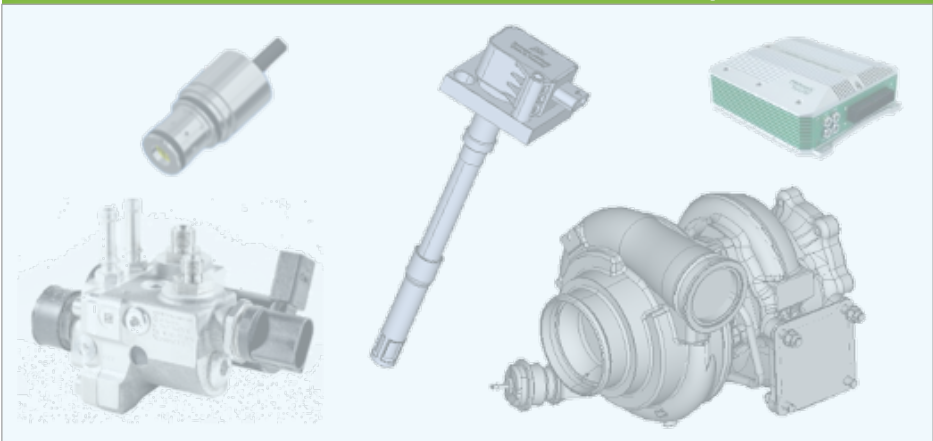
## 1D/3D CFD Simulation



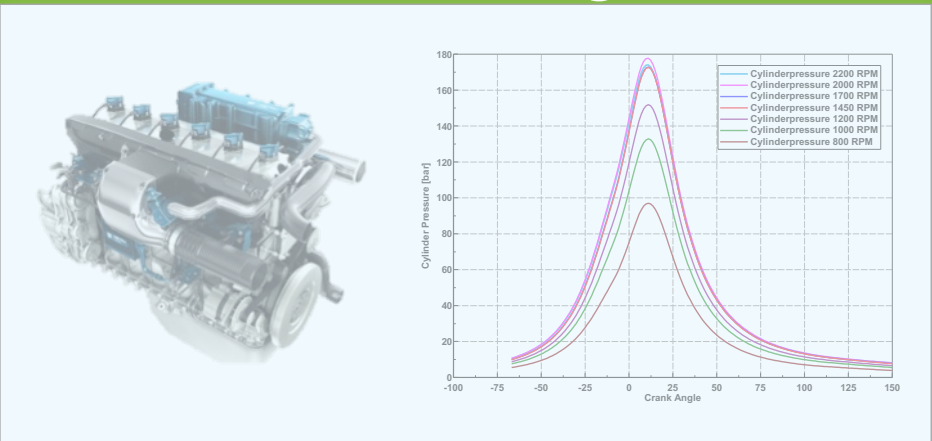
## Design



## Hardware & Software Development



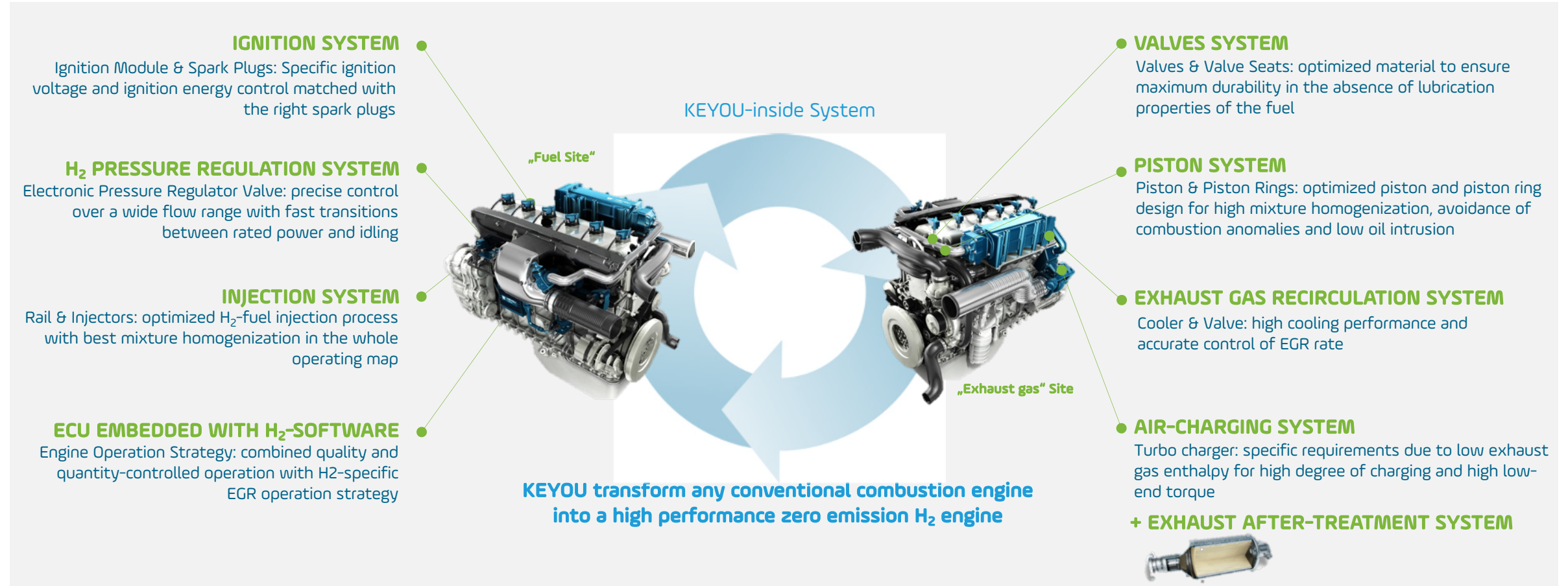
## Test Bench Investigations





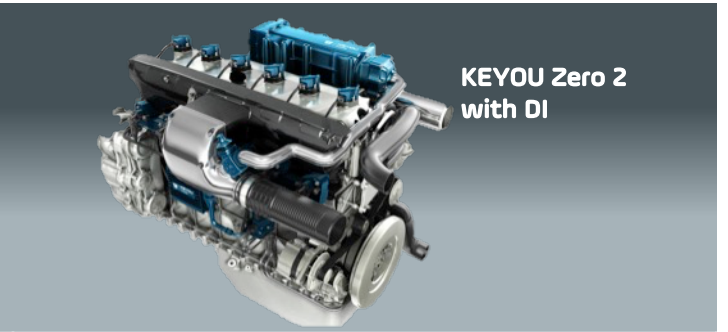
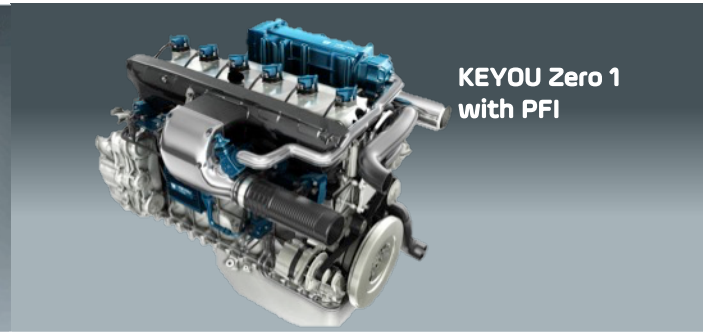
## Hydrogen in Combustion Engines Requires a Fine Tuned System

# The Combination of all H<sub>2</sub>-Components is Vital for Highest Performance



**High competitive advantage: KEYOU has the expertise how the specific H<sub>2</sub> components work best as a system - already today**

# Past H<sub>2</sub> ICE Concepts and Today's Technologies

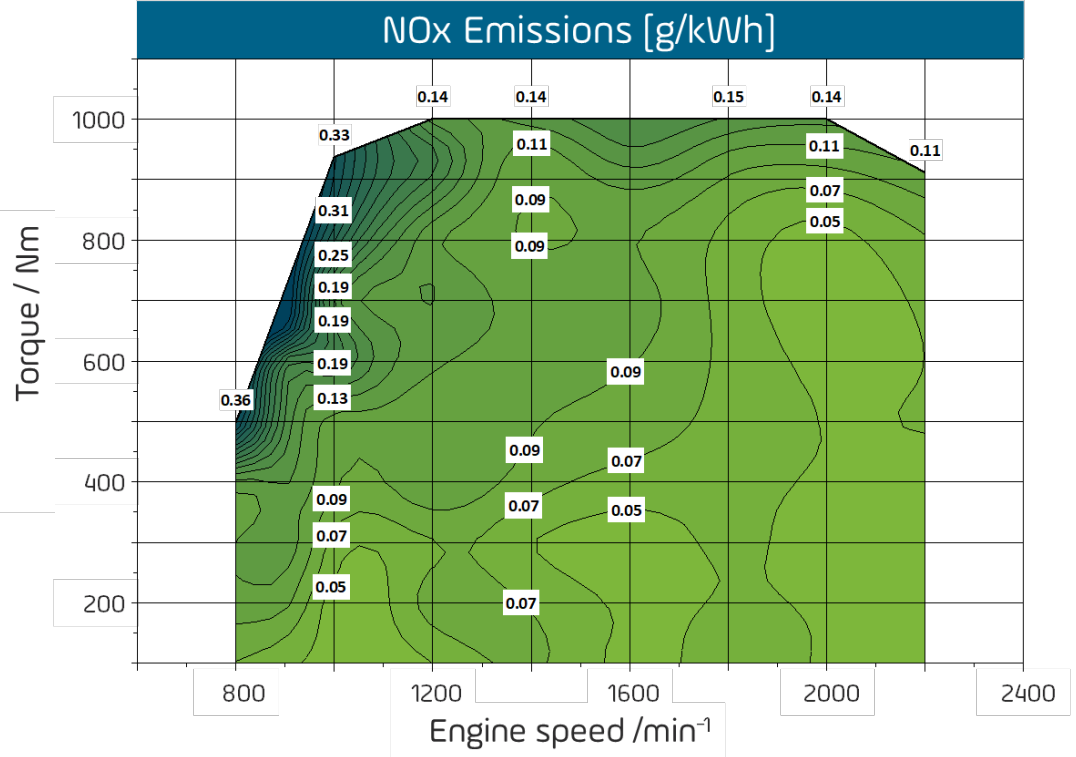
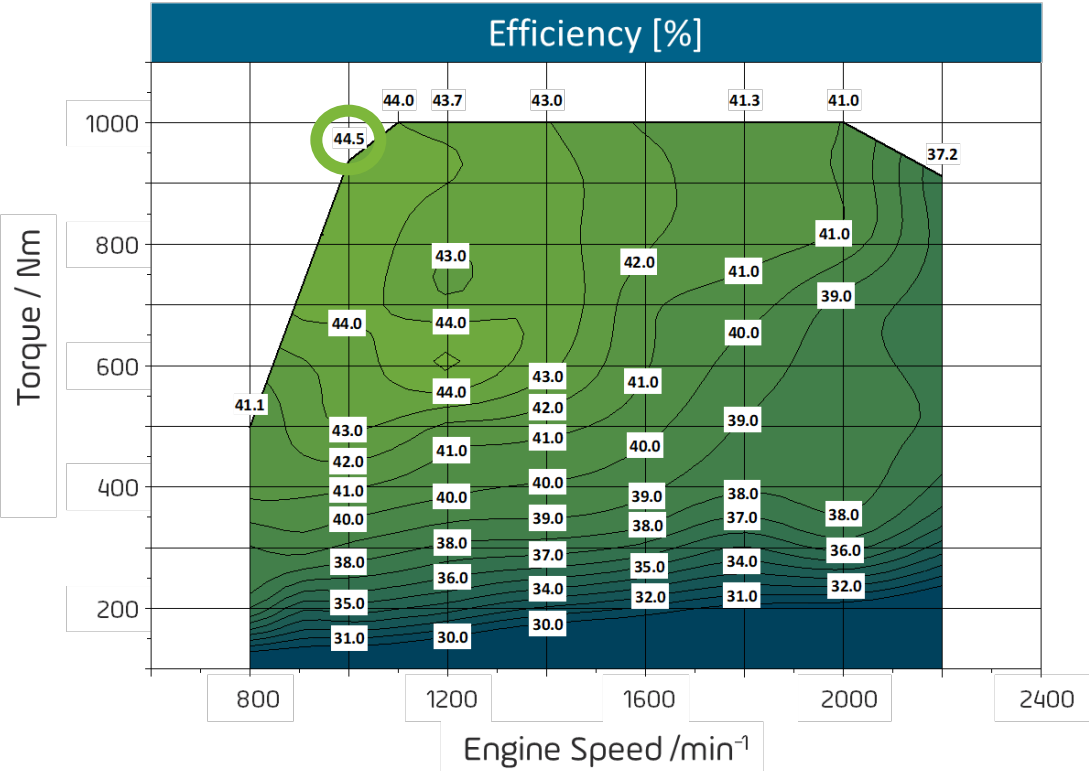


Engine	MAN H2876 UH01 (2006)	KEYOU H <sub>2</sub> -Technology with PFI	KEYOU H <sub>2</sub> -Technology with DI
Cylinders	6	6	6
Displacement	12,8 Litres	7,8 Litres	7,8 Litres
Charging	Naturally Aspirated	Turbo Charged	Turbo Charged
Power	<b>150 kW</b>	<b>210 kW</b>	<b>240 kW</b>
Torque	760 Nm	1.000 Nm	1.000 Nm
Combustion Concept	Stoichiometric	Lean	Lean
NOx Control	3 Way Catalyst	EGR + H <sub>2</sub> SCR	EGR + H <sub>2</sub> SCR
Consumption	<b>ca. 22 kg H<sub>2</sub> / 100 km</b>	<b>ca. 11 kg H<sub>2</sub> / 100 km</b>	<b>ca. 10 kg H<sub>2</sub> / 100 km</b>

More than double the Power/Displacement

Consumption reduced by > 50 %

# Successful Proof of Concept With KEYOU-inside H<sub>2</sub>-Technology



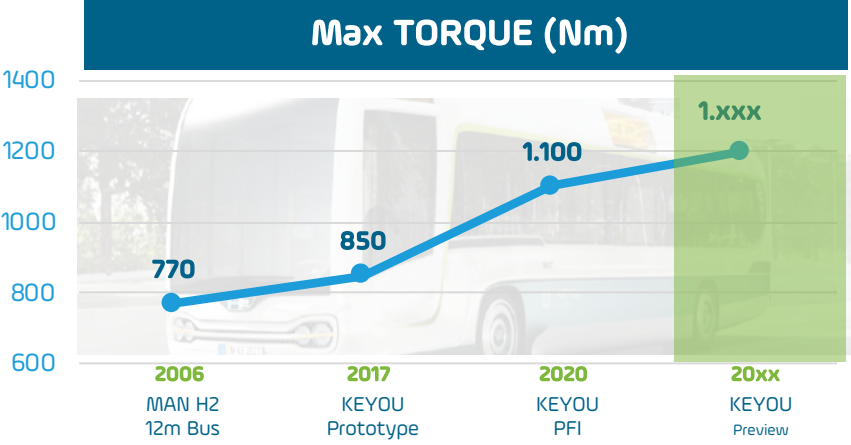
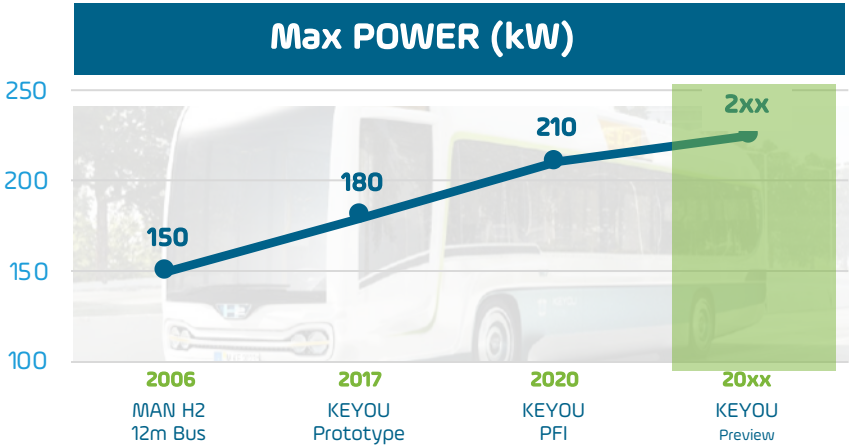
Hydrogen engines can significantly outperform diesel engines in terms of efficiency

▶ **44.5 % (today)**

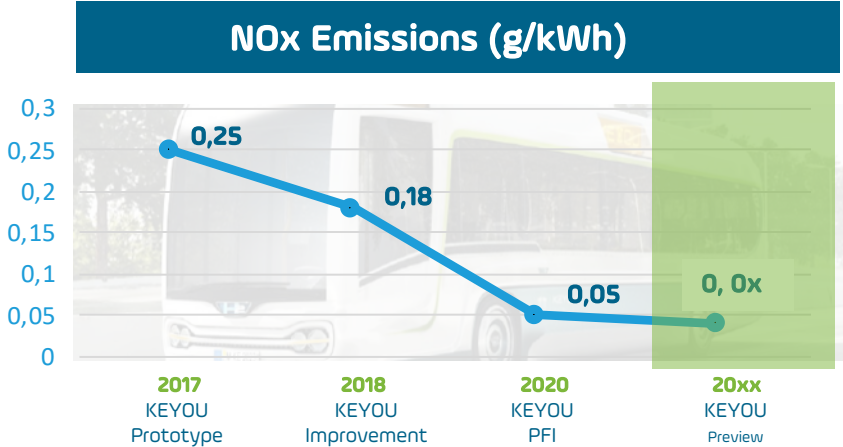
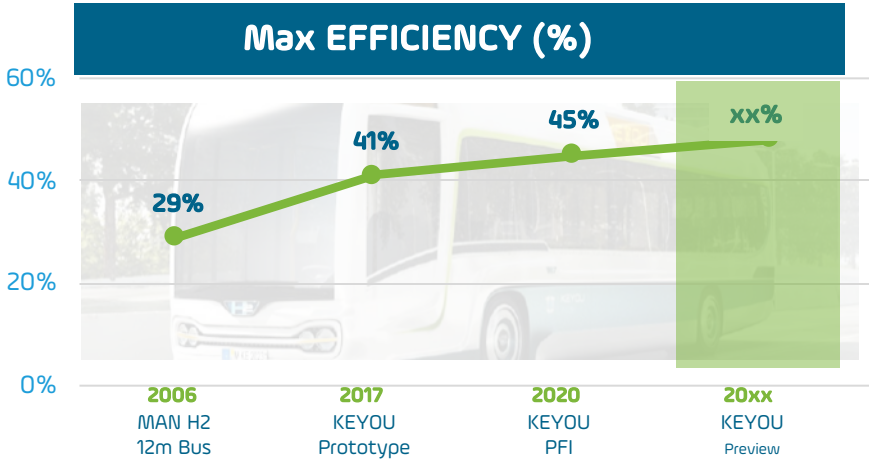
Even without exhaust aftertreatment, the strictest emission regulations are already undercut by 50 - 75 % today



# Continuous Improvement of the Most Important KPIs



Example 12m Bus:  
DEUTZ TCG 7.8 H<sub>2</sub> with  
KEYOU-inside

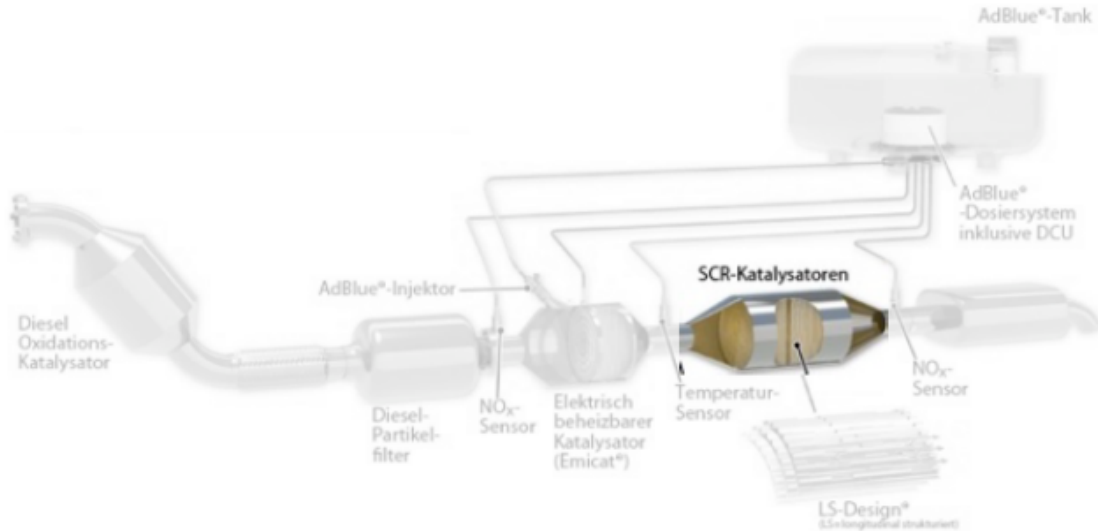
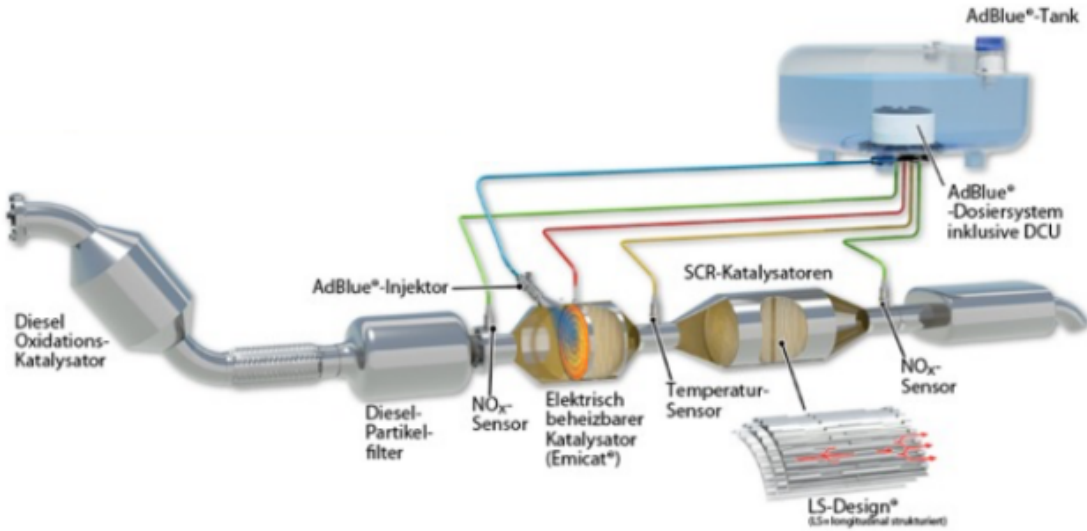


# Many Conventional Components are no Longer Required in a H<sub>2</sub> Engine



## DIESEL

## H<sub>2</sub> ICE



Less components mean considerable cost savings for the end product, the H<sub>2</sub> Engine

# Tank-to-Wheel Analysis of Vehicles with a Hydrogen Engine (12m Bus)



Bus 12m	Diesel Engine Euro VI	H <sub>2</sub> -Engine with KEYOU-inside
CO <sub>2</sub> [g/kWh]	1.000	0,08
	Regulatory Limits	
NO <sub>x</sub> [g/kWh]	0,46	0,046
PM* [g/kWh]	0,01	0,002
HC** [g/kWh]	0,16	0,01
CO [g/kWh]	4	0,01

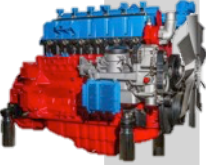



EU Definition of ZERO EMISSION: < 1 g CO<sub>2</sub>/kWh

\* Particulate Matter  
 \*\* Volatile organic substances such as hydrocarbons

**Modern H<sub>2</sub> engines meet EU standard for zero-emission commercial vehicles by 100%.**



# Engine Development Projects

Engine Development	OEM Customer	Maturity Goal	Timeline	Status	
	<p><b>TCG 7.8 H<sub>2</sub> PFI</b></p>	<p><b>DEUTZ</b></p>	<p>Pre-series – Approval for the operation of different pilot vehicles</p>	<p><b>30 months</b> Start Q3 2019</p>	<p>✓ <b>Development ongoing</b></p>
	<p><b>13,5 L PFI</b></p>	<p><b>European Manufacturer</b></p>	<p>Pre-series – Approval for the operation of different pilot vehicles</p>	<p><b>30 months</b> Start Q1 2019</p>	<p>✓ <b>Development ongoing</b></p>
	<p><b>15 L PFI</b></p>	<p><b>European Manufacturer</b></p>	<p>Concept validation on engine test bench</p>	<p><b>24 months</b> Start Q1 2020</p>	<p>✓ <b>Development ongoing</b></p>
	<p><b>13 L DI</b></p>	<p><b>Asian Manufacturer</b></p>	<p>Concept validation on engine test bench</p>	<p><b>36 months</b> Start tbd.</p>	<p>✓ <b>In Preparation</b></p>

# Conversion Systems in Development for all Displacement Classes

## Heavy-Duty Engines for Buses and Trucks



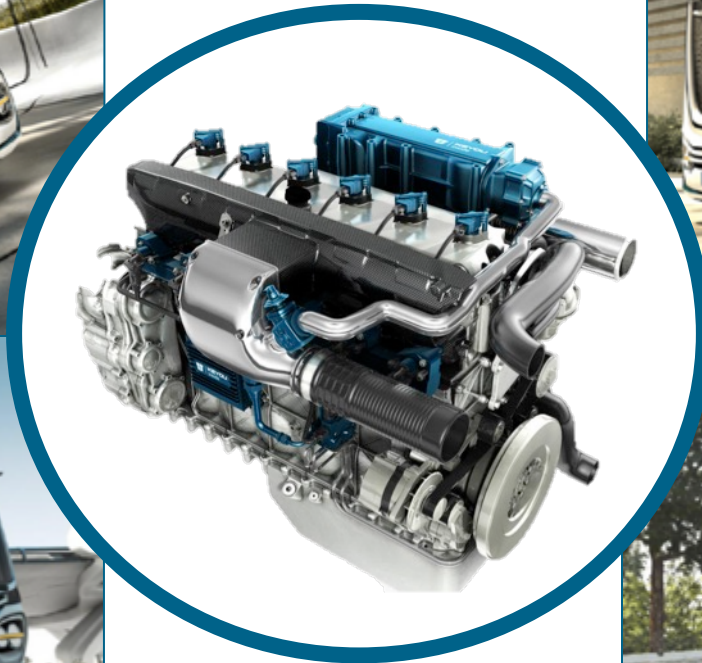
KEYOU-SYSTEM KIT	VERSION	INJECTION System	ENGINE Displacement CLASS
A	A.1	PFI	4 - 6 L
	A.2		7 - 9 L
B	B.1	DI	10 - 13 L
	B.2		
	B.3	PFI	14 - 16 L
	B.4	DI	

Market entrance in heavy-duty vehicles – passenger cars will follow





- defined Projects -



- Illustrations -



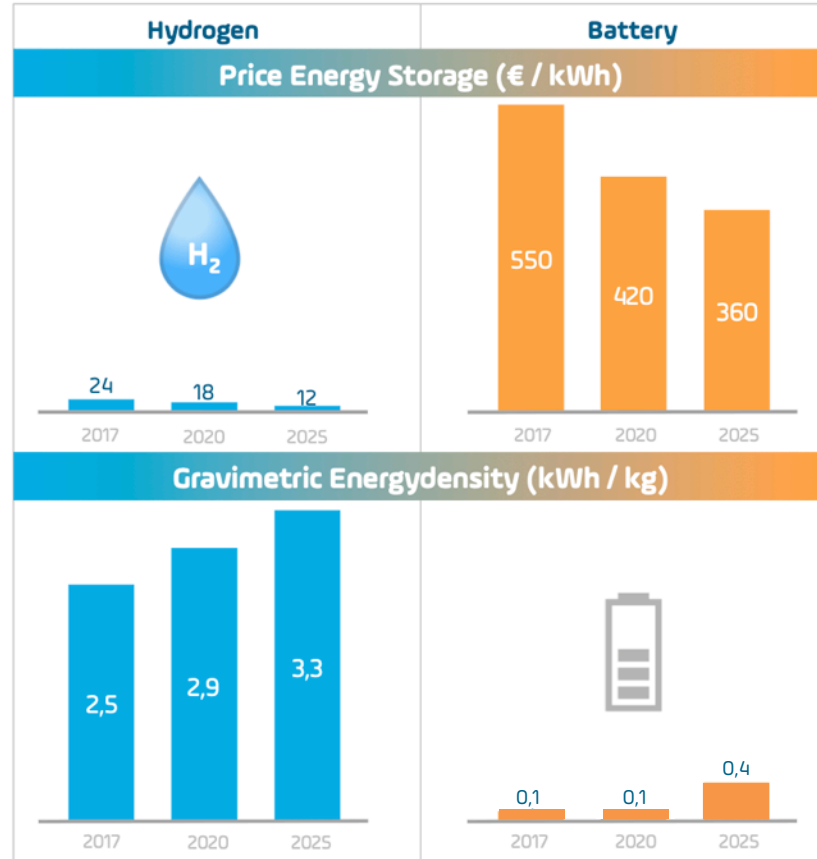


## COMPARISON

### Alternative Propulsion Systems



# Hydrogen – More Efficient than Batteries will ever be



Hydrogen Storage vs. Commercial Vehicles Battery

**H<sub>2</sub> > 20 x higher Energy Density**

**H<sub>2</sub> > 20 x lower Cost**

Sources:

- Battery Storage: Manufacturer's specifications, Fraunhofer Institut ISI: Gesamt-Roadmap Energiespeicher für die Elektromobilität 2030 / IKT für Elektromobilität, Abschlussbericht, gefördert durch Bundesministerium für Wirtschaft und Energie
- Battery-Storage: Manufacturer's specifications / Market Research (i.e. specification given by Akasol, Daimler)
- Hydrogen Storage: Manufacturer's specifications, Fraunhofer ISI, Fraunhofer IML, PTV Group: Teilstudie „Brennstoffzellen-Lkw: kritische Entwicklungshemmnisse, Forschungsbedarf und Marktpotential“

**The customer value of a vehicle will be defined by its energy storage potential**

# Energy Storage Density Beats Electric Powertrain Efficiency

HYDROGEN



Powertrain  
- Efficiency -

BATTERY



2x better

HYDROGEN



Storage System  
- Energy Density -  
(Gravimetric)

BATTERY



20x better

Mathematics

$$20 / 2 \triangleright H_2 = 10x \text{ better}$$

Transfer: 10x more range for vehicles with hydrogen engine

# Comparison in Range: E-Truck vs H<sub>2</sub> Truck With KEYOU-inside Technology

## Energy Storage is Decisive Parameter for the Range



High Energy Li-Ion Batteries



Assumptions: E-Truck – gravimetric energy density 100 Wh/kg, efficiency of battery propulsion twice as ICE, consumption 88kWh/100km

### Assumption: same weight of energy storage unit (ca. 420 kg)




Hydrogen Storage Tank (350 bar high pressure tank)



Hydrogen tank and KEYOU-inside Technology (350 bar) – gravimetric energy density 2530 Wh/kg, Tank size: 30 kg H<sub>2</sub>, consumption 6,8 kg H<sub>2</sub> / 100 km

# Hydrogen Engine Compared with Hydrogen Fuel Cell – Both Strong in Refuelling Time and Range, but: H<sub>2</sub> Engine Vehicles Offer Higher Value to End-users

FUEL CELL		H <sub>2</sub> ENGINE	
	<input checked="" type="checkbox"/>	<b>Range</b>	<input checked="" type="checkbox"/>
<small>Source: Nikola</small>	<input checked="" type="checkbox"/>	<b>Refuelling time</b>	<input checked="" type="checkbox"/>
Variations:			
<b>Cost (TCO)</b>	<input checked="" type="checkbox"/>	→	≈ Diesel equivalent
<b>Pureness of Hydrogen (99,999 %)</b>	<input checked="" type="checkbox"/>	→	98 %
<b>High cooling demand</b>	<input checked="" type="checkbox"/>	→	No
<b>Time to market</b>	<input checked="" type="checkbox"/>	→	Short
<b>Service Life</b>	<input checked="" type="checkbox"/>	→	≈ Diesel equivalent

The H<sub>2</sub> engine is more than a bridge technology, it's the solution the market needs



# The H<sub>2</sub> Engine – Most Attractive TCO for Fleetoperators



Assumptions:  
 Lifecycle: 1.000.000 km  
 (100.000 km / year)  
 H<sub>2</sub>-Price: 5 €/kg

Comparison: Reference Diesel

	Diesel	Battery 500	Fuel Cell	H <sub>2</sub> -ICE
<b>Purchasing Price</b>	80.000 €	x 8.6 times	x 7.5 times	x 2.6 times
<b>TCO</b>	822.000 €	x 1.7 times	x 2.3 times	≈ Diesel

Assumptions:  
 incl. Battery-/Fuel-Cell exchange; battery (Vehicle Lifespan: Fraunhofer institute, Lifecycle: KFA Kraftfahrbundesamt Germany); Fuel cost assumptions: Diesel: 1,16 €/L – AdBlue: 40 Ct/L – Battery: 19 Ct/kWh (Storage: 100 Wh/kg; Storage costs: 500 €/kWh) – Hydrogen: 5 €/kg;; Toll EU VI: 0,187 EUR/km; Price for H2ICE = Potential price small series, high cost reduction potential for high volume production

**The hydrogen engine – very strong in heavy-duty**



## SUMMARY

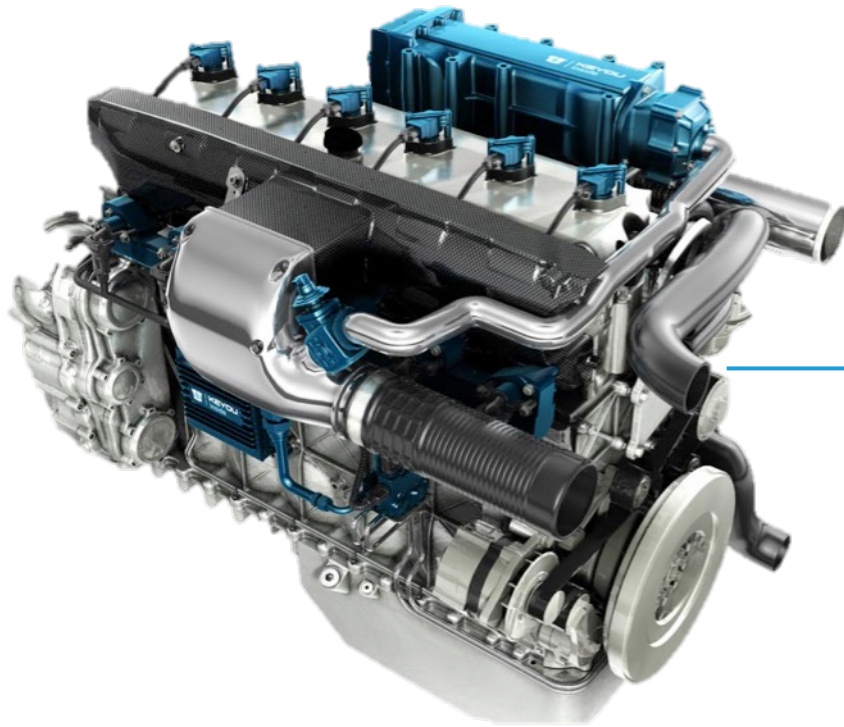
The New Generation of  
Hydrogen Internal Combustion Engines

# The H<sub>2</sub> Engine with KEYOU-inside: The Right Product at the Right Time

	Zero Emission Drive Technologies according to EU Legislation			
	DIESEL	ELECTRIC	FUEL CELL	H <sub>2</sub> ICE
Costs	✓	✗	✗	—
Driving Ranges	✓	✗	✓	✓
Payload	✓	✗	—	✓
Reliability	✓	—	—	✓
Service Life	✓	—	✗	✓
Climate Protection	✗	—	✓	✓
Air Pollution Control	—	✓	✓	✓

**Cleanest & most cost-efficient zero-emission drivetrain technology – benefitting OEMs, suppliers, and end-customers alike**

# The First Zero-Emission Drive Technology that beats Diesel



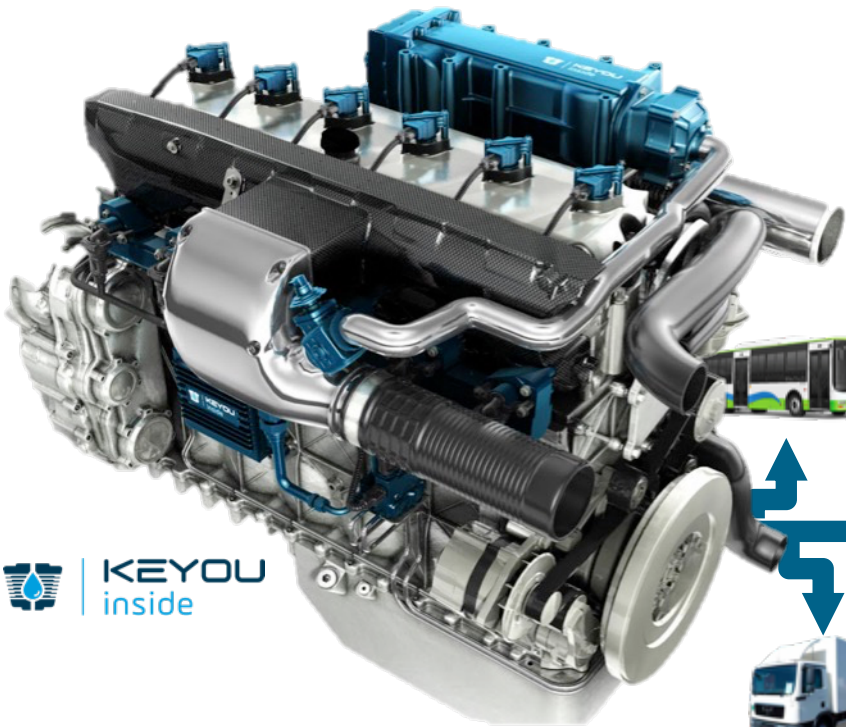
- High availability (> 95 %)
- Accustomed range
- Attractive TCO for end-customer
- Lower degree of H<sub>2</sub> purity required than for fuel cells
- High suitability for everyday use
- Best CO<sub>2</sub> balance in life cycle analysis
- Short refuelling times
- Lower production costs than diesel engines
- Overall economic advantage: securing technological leadership & prosperity

**KEYOU** today is already accepted **market leader** in the field of H<sub>2</sub> engines

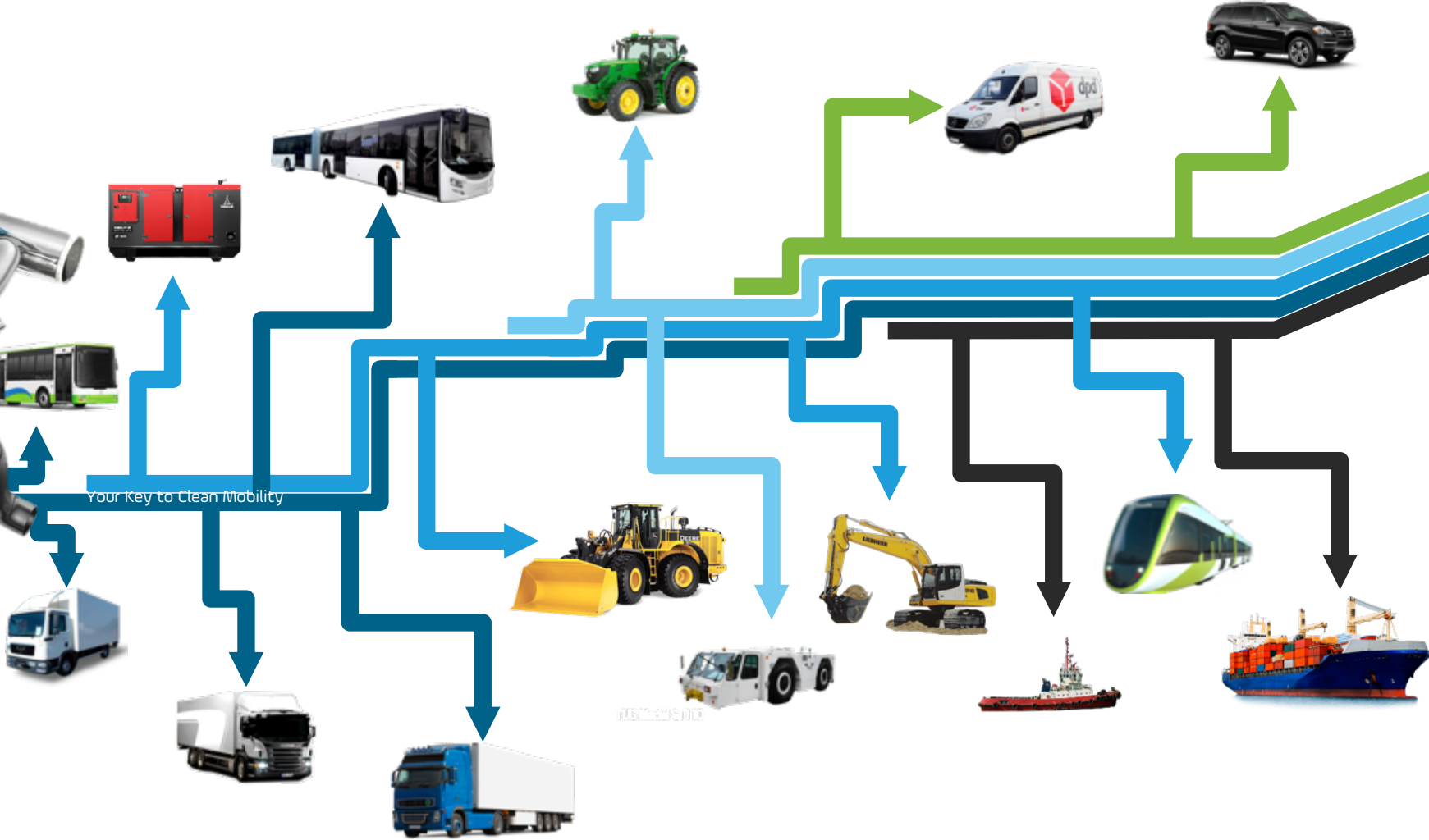


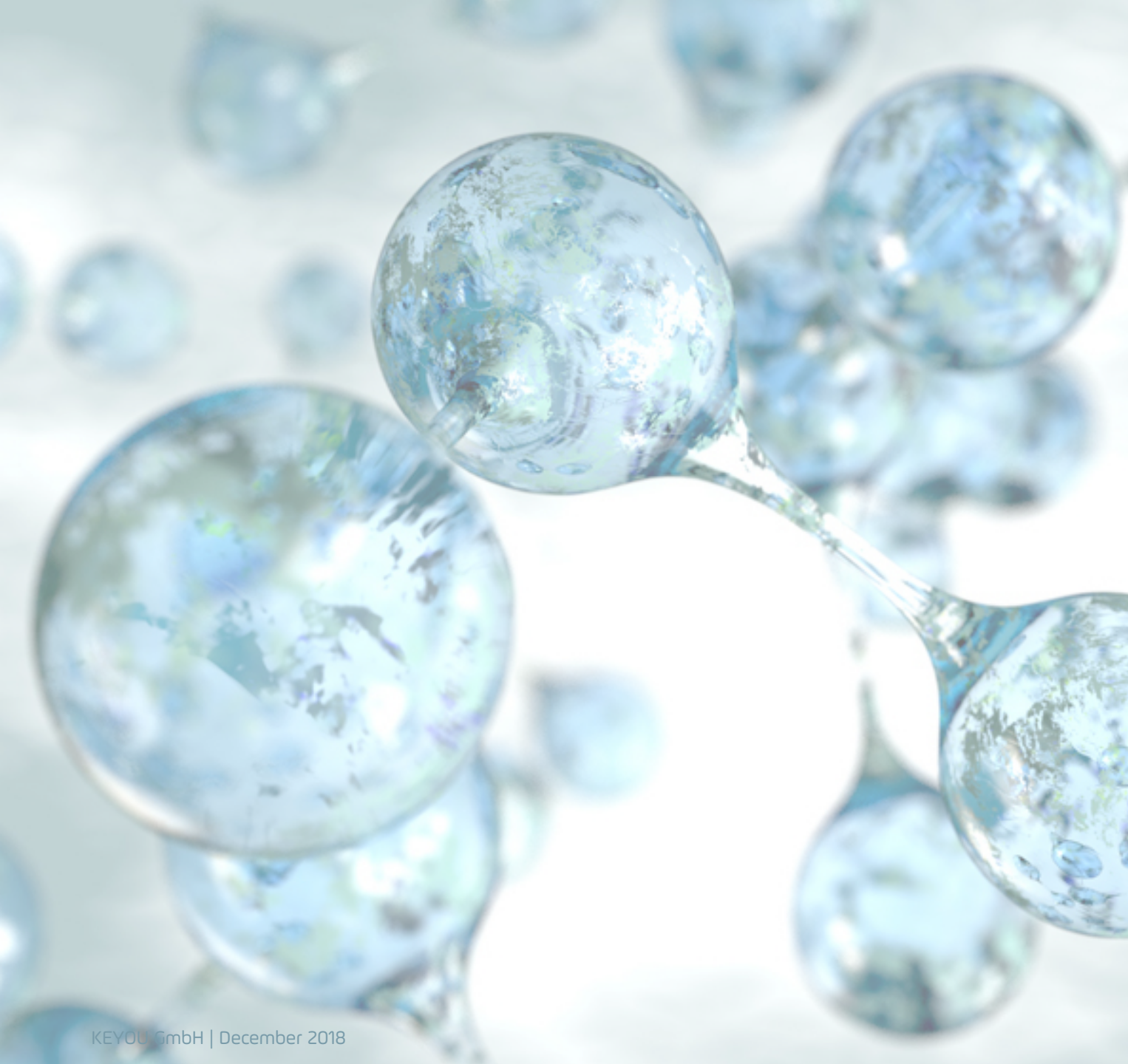
# Moving From Heavy Duty-Vehicles to the Mass Market – the Scalable KEYOU Technology Platform

## “The KEYOU-World of Clean Mobility” – Future Use Cases



Your Key to Clean Mobility





**KEYOU**

**Short Profile**

## KEYOU – What we do



- Development of **Hydrogen Combustion Engines & Components** that emit no CO<sub>2</sub> and other air pollutants
- Thus, **enabling customer OEMs** a fast-track to zero-emission vehicles in series production
- At present inner-city **buses & distribution trucks** as initial applications
- Due to the **technologies' high scalability** it is also applicable to stationary (genset/CHP) as well as **maritime applications** or in the **train sector**.



KEYOU  
inside





## KEYOU – Who we are



- **Fast growing high-tech start-up with automotive experienced management and engineering team**
  - 35 employees today
  - Coordinating institutes and engineering partners of about 40 external engineers
- **20 years team experience in hydrogen engine, hydrogen fuel cell, hydrogen storage and safety system development**
- **Track record of development and building of prototypes and pre-series vehicles in different companies**
  - 2 generations of MAN 12m city bus with hydrogen combustion engine
  - 3 generations of BMW 7 series passenger cars with hydrogen combustion engine
  - 5 kW PEM Fuel Cell APU for BMW passenger car propelled with hydrogen combustion engine
  - Aston-Martin Rapide prototype for 24h-race at Nürburgring



# KEYOU – What we Offer



- **Engineering service** to evolve conventional engines to zero-emission hydrogen derivatives
  - **KEYOU-inside technology**
    - Engine concept
    - Combustion process and operating strategy (software and application)
    - Components for engines and vehicles
      - E.g. Injection, ignition, controlling, charging, exhaust
      - H<sub>2</sub>-storage, safety, controlling
  - **Hydrogen Infrastructure**
    - Hydrogen engine test benches (exclusive partner)
    - Hydrogen component test benches (exclusive partner)
    - Access to on-road test track (in preparation)
- **Enabling customer OEMs a fast-track to zero-emission vehicles in series production**

# An Experienced Founding Team with Huge Expertise in Hydrogen Technologies

## The KEYOU Team - Complementary Expertise and Highly Experienced



### MANAGEMENT



**ALVARO SOUSA**  
CTO, Co-Founder

8 years BMW R&D Germany / USA  
University Lecturer: Clean-Vehicle Technologies



**THOMAS KORN**  
CEO, Co-Founder

13 years BMW R&D Germany / USA  
4 years Start-Up experience



**JÜRGEN NADLER**  
CMO

20 years Business Consulting  
(u.a. BMW, Siemens, Telekom)



**Dr. ZHIHE LI**  
VP China

30 years industry  
(MTU, DEUTZ, MAN)



**IVO PIMENTEL**  
H2, Co-Founder

7 years Start-up experience  
e.g. CEO Renewable Energy Co)



**PEDRO BRAVO**  
BD & Sales

15 years Sales & Business  
Development



**WERNER PRÜMM**  
Development

30 years R&D (MAN)



**RALF SOERMANN**  
Finance

7 years banking, M&A, PE  
(e.g. P. Hartmann AG, Charleston Holding )



**PIERRE STEFFEN**  
Strategy

30 years industry  
(e.g. Airbus, Siemens)

### ADVISORY BOARD



**Prof. Dr. Manuel Aguiar**

Socially committed top manager  
and academic researcher



**Dr. Ulrich Bez**

Automotive Engineer and Visionary  
C-Level Porsche, Aston Martin

**Starting 1<sup>st</sup> of July**

Experienced Automotive Expert  
Ex-C-Level OEM



**Prof. Dr. Jörg Zürn**

Business personality with  
34 years in the Daimler Group



**KEYOU TEAM**  
20 years team experience in hydrogen engine, hydrogen fuel cell, hydrogen storage and safety system development  
Track record of development and building of prototypes and pre-series vehicles in different companies

- 2 generations of MAN 12m city bus with hydrogen combustion engine
- 3 generations of BMW 7 series passenger cars with hydrogen combustion engine
- 5 kW PEM Fuel Cell APU for BMW passenger car propelled with hydrogen combustion engine
- Aston-Martin Rapide prototype for 24h-race at Nürburgring

**ADVISORY BOARD**  
KEYOU-Advisory Board: Business Angels & Visionaries

- Former Chairmen and active Managers enrich the KEYOU-Family with Know-how, Network and Experience
- Board members were working at C-Level in different automotive companies
- Former C- Level at Porsche & Aston Martin
- Former C-Level at Daimler / Mitsubishi Fuso

# Traction – KEYOU as a Well-known Brand and Leading H<sub>2</sub>-Expert in the Automotive Industry

## Great Public Interest in KEYOU and H<sub>2</sub> Engine Technology



### Press Releases

Logos include: Bayerischer Rundfunk, NEWS EUROPE, Transport FOCUS, AI 汽车制造业, MTZ, Müttinger Zeitung, Brennstoffzellen Zwei, SWR2, Frankfurter Allgemeine Zeitung für Deutschland, Automobilwoche, OMNIBUS, Deal Advisors, Springer Professional, lastauto omnibus, Handelsblatt, busplaner, OMNIBUSREVUE, KFZ anzeiger, BUSFahrer, LOGISTRA, GRÜNDERSZENE, busblickpunkt.

### Awards

Awards include: Green Product Award Winner 2017, #SET100 CERTIFIED, NEXT ECONOMY AWARD, TOP 3 Technology 2018, busplaner Innovation des Jahres 2018 (2. Platz), Automobilwoche START UP of the Week, GERMAN INNOVATION AWARD '18 WINNER.

### KEYOU as Speaker

Events include: VDV Die Verkehrsunternehmen, AUTOCONTACT'18, Automobilwoche KONGRESS 27, AACHENER KOLLOQUIUM AACHEN COLLOQUIUM, engineexpo, 2. INTERNATIONALE FEV-KONFERENZ ZERO CO<sub>2</sub> MOBILITY, BUS2BUS Fachmesse und Kongress, ENERGI KONTOR Norra Småland, FKFS, NEW MOBILITY WORLD, IAA 13. Internationale MTZ-Fachtagung, 12. TAGUNG GASFAHRZEUGE 24. - 25. OKTOBER 2017, Internationales Wiener Motorensymposium, Heavy-Duty-, On- und Off-Highway-Motoren 2018.





**Green  
Product  
Award**

Winner  
2017



**NEXT  
ECONOMY  
AWARD**

**TOP 3**  
Technology 2018



**GERMAN  
INNO  
VATION  
AWARD '18  
WINNER**



Wasserstoffbus

KEYOU

KEYOU-inside Wasserstoffmotor

**busplaner**  
Technik · ÖPNV · Mobilien

**hussverlag**

Federal Ministry  
for Economic Affairs  
and Energy

**WORLD  
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**#SET100  
CERTIFIED**

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of the SET Award 2020

**Start Up  
Energy Transition**  
Global Innovation Platform



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