Internal combustion engines are proven robust technology in road and non-road applications. Established industry (design & optimize, manufacture, service & maintenance, re-cycling). Tolerant on hydrogen fuel quality. Also in NG/H2 combinations. Internal combustion engine concepts without aftertreatment don’t need precious or rare metals.

Application of hydrogen in ICE enables accelerating the transition towards a sustainable society and provides an interim solution for many applications for as long as alternative (electrified) powertrains are not available or possible.
WHY USING H2 IN INTERNAL COMBUSTION ENGINES?

POTENTIAL FOR HIGH EFFICIENCY & ULTRA-LOW EMISSIONS

NOx

Efficiency

Unstable combustion (knock)

Air-Excess ratio $\lambda$ [-]

BMEP [bar]

1 2 3 4

Efficiency [%]

NOx limit EURO VI & STAGE V

No aftertreatment required

H$_2$ $\rightarrow$ $\lambda=1$

TWC

Diesel

DPF

SCR

H$_2$ $\rightarrow$ $\lambda>>1$

H$_2$

23 March 2020
## FEASIBLE HYDROGEN COMBUSTION CONCEPTS

<table>
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<th>Diesel</th>
<th>SI $\lambda=1 + \text{EAS}$</th>
<th>SI $\lambda &gt;&gt; 1$ zonder EAS</th>
<th>Dual Fuel + EAS</th>
<th>H2/Argon</th>
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### CO2 Reduction
- Diesel: 100%
- SI $\lambda=1 + \text{EAS}$: 100%
- SI $\lambda >> 1$ zonder EAS: 30 – 60%
- Dual Fuel + EAS: 100%
- H2/Argon: >60%

### Aftertreatment
- Diesel: DPF + SCR
- SI $\lambda=1 + \text{EAS}$: None
- SI $\lambda >> 1$ zonder EAS: None
- Dual Fuel + EAS: DPF + SCR
- H2/Argon: None

### Euro/kW
- Diesel: 
- SI $\lambda=1 + \text{EAS}$: 
- SI $\lambda >> 1$ zonder EAS: 
- Dual Fuel + EAS: 
- H2/Argon: ?

### Thermal Loading
- Diesel: 
- SI $\lambda=1 + \text{EAS}$: 
- SI $\lambda >> 1$ zonder EAS: 
- Dual Fuel + EAS: 
- H2/Argon: 

---

The diagram shows the efficiency and CO2 reduction for different concepts along with the impact of EGR. The bars represent the percentage of efficiency and CO2 reduction, with the blue bars indicating the data with EGR and the green bars without EGR.
High potential for sustainable HD applications

**APPLICATION HYDROGEN INTERNAL COMBUSTION ENGINE**

- **High efficiency**
- **0 Emissions**
- **Proven technology**
- **Reduced power density**

**H2-ICE**

- **H2/air-ICE**
  - H2 → Diesel → DPF → SCR
  - H2 → λ=1 → TWC
  - H2 → λ>>1

- **H2/air-ICE + battery: range extender hybrid truck & tractor**
  - <100 kW
  - 100 - 300kW

- **H2/Argon-ICE for stationary power generation with local H2 generation**
  - >300kW

**2020 - 2025**

- H2/air-ICE + battery: range extender hybrid truck & tractor

**2025 - 2030**

- H2/Argon-ICE for stationary power generation with local H2 generation

**>2030**

- H2/air-ICE + battery: range extender hybrid truck & tractor
THANK YOU FOR YOUR TIME

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