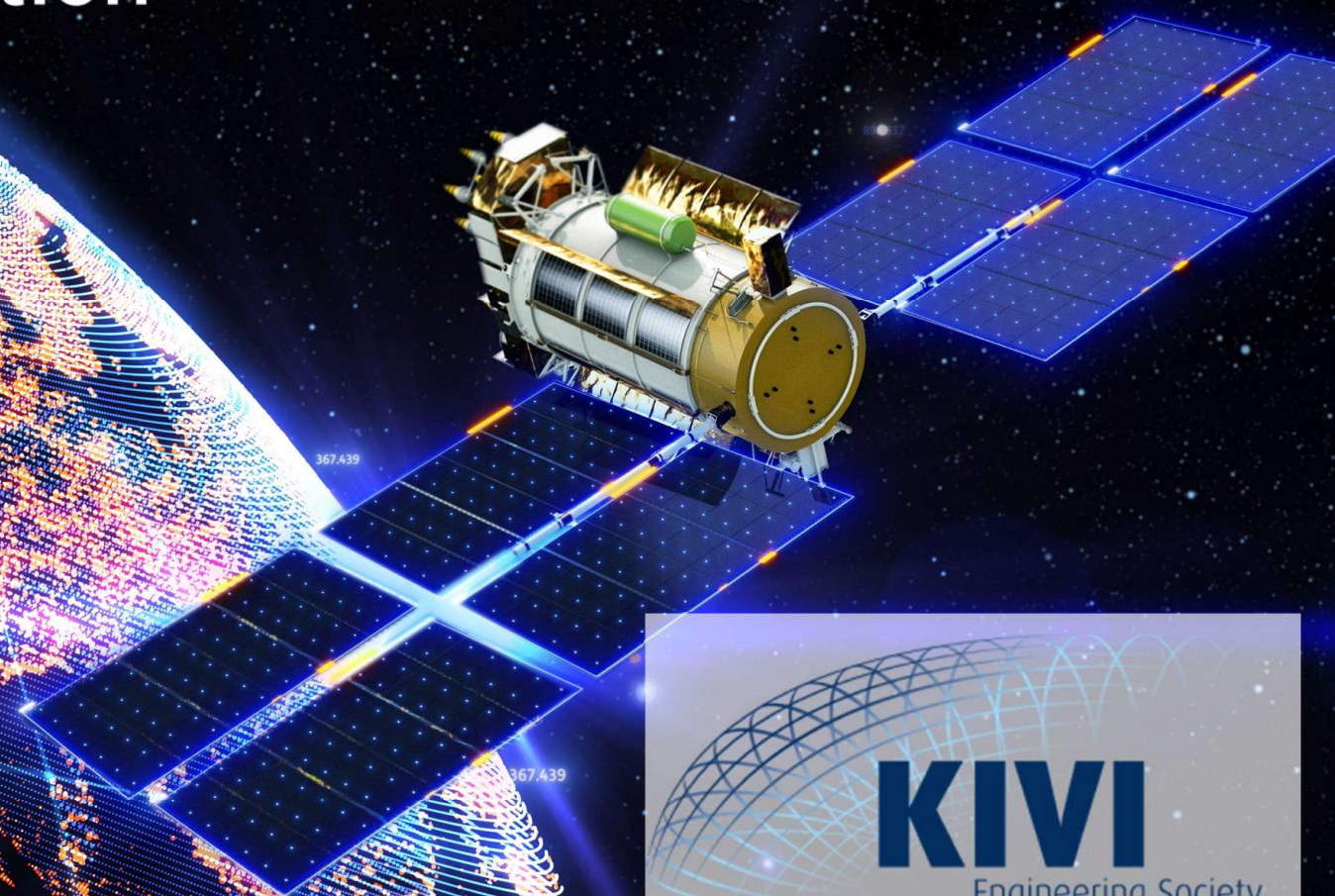


TNO innovation
for life



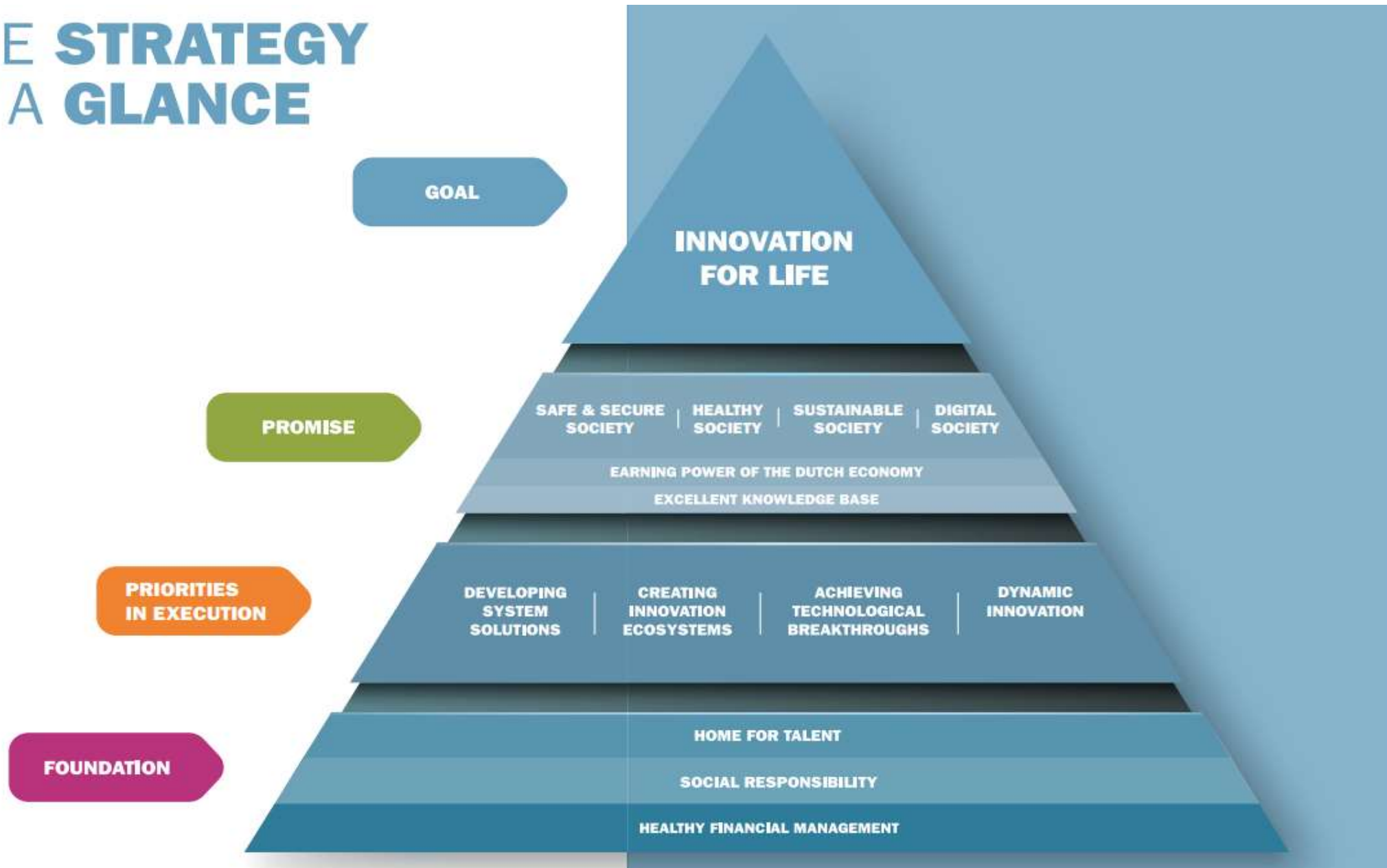
Ruim 90 jaar aan innovatie



01 Missie

Wij creëren impactvolle innovaties voor duurzaam welzijn en welvaart van de samenleving.

THE STRATEGY AT A GLANCE



01 Leading innovator

Om zo veel mogelijk impact te creëren, concentreren we ons op gebieden waarin we echt uitblinken en vooroplopen.





Meer focus & dynamisch
portfoliomanagement

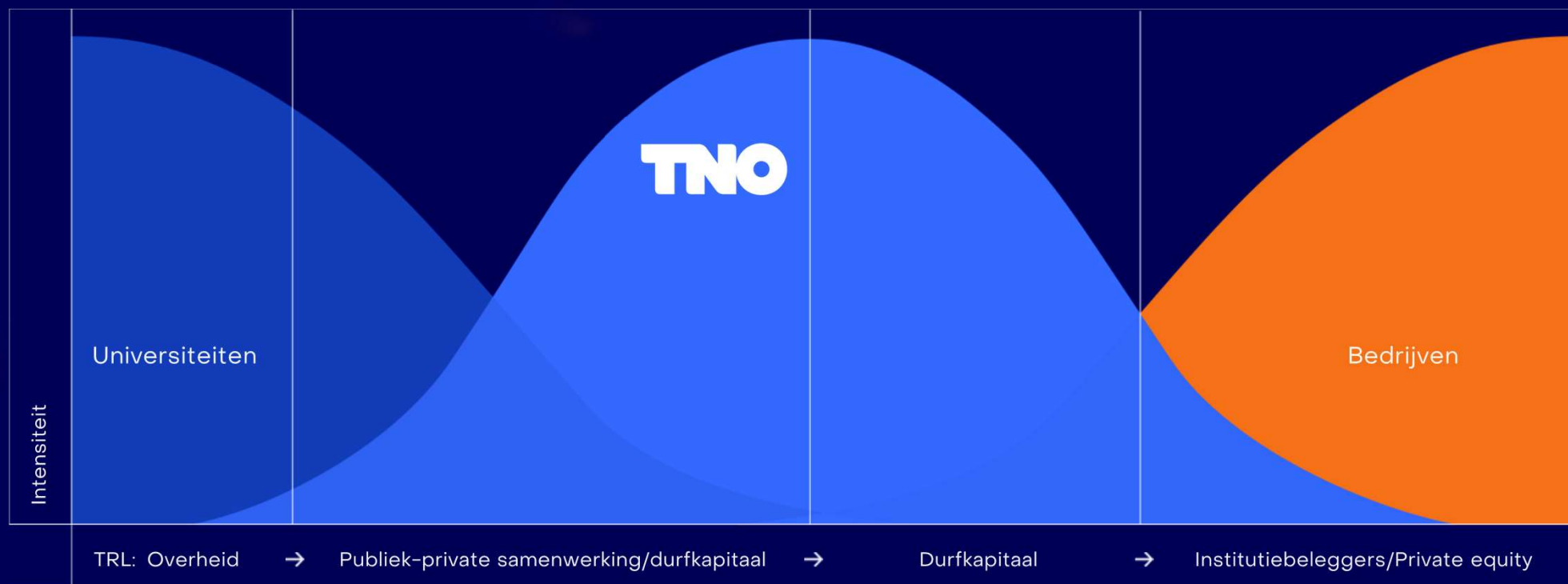


Meer impact
door valorisatie

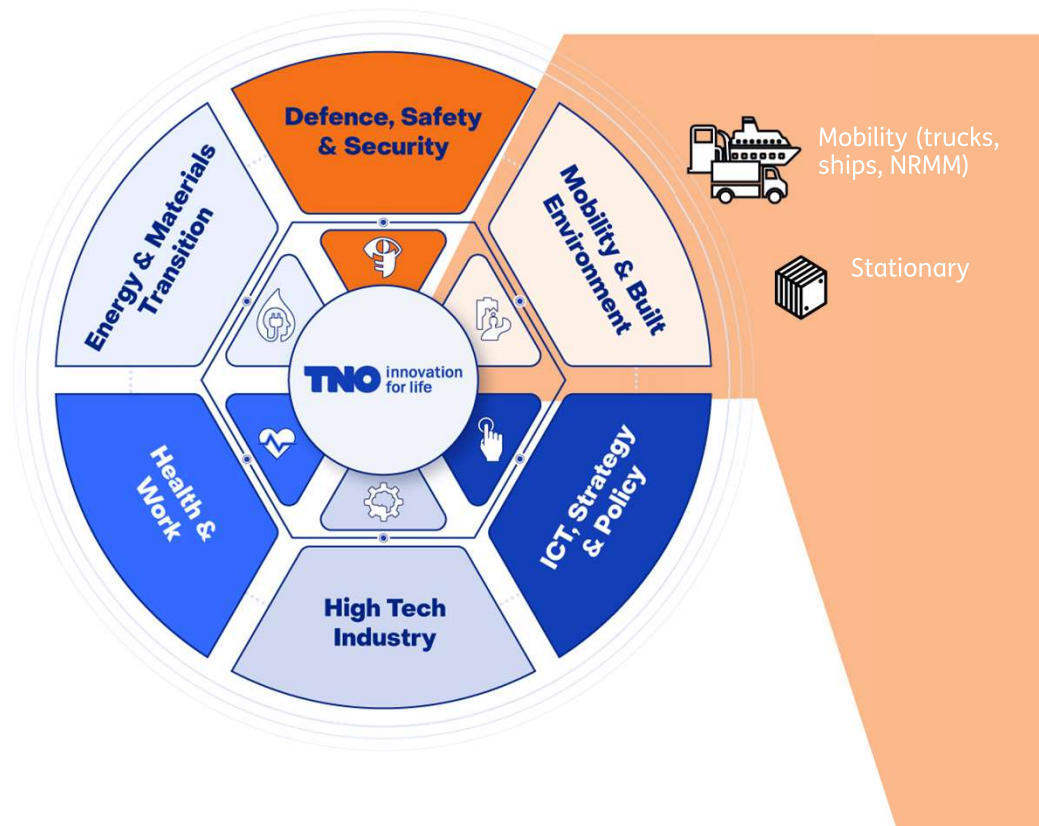


Meer klant-
& marktgericht

Voor een succesvolle innovatieketen zijn soepele transitie tussen TRL-niveaus cruciaal.



TNO Powertrains



Innovation Center Sustainable Powertrains (ICSP)



- Development projects for battery-electric, hydrogen/ Methanol combustion and Hybrid powertrains
- Validation of existing and new powertrains in the mobility, maritime, and stationary sectors
- Testing and application of alternative fuels (H₂, methanol).
- Energy storage: Battery (weight, environment, and performance) Alternative fuels (e.g., H₂: under pressure or chemically bound)

Sustainable Internal Combustion Engines for transport

Hydrogen and methanol

Seykens, X.L.J. (Xander) | TNO Powertrain, Helmond



Sustainable Mobility

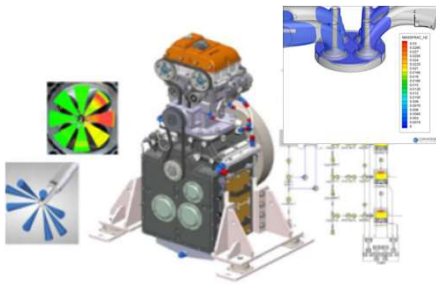
Focus Area

- Sustainable Combustion Engines
- Optimal Batteries
- Modular Energy Management System (MEMS)
- Innovation Centre for Sustainable Powertrains



The power of TNO: from idea toward application

Engine/Combustion design and development



- CR, piston shape verification
- Fueling & Ignition system, incl. spark plug heat range
- Airpath definition - power range
- Functional safety - installation requirements, misfire & knock detection, involvement classification society
- Supplier selection, incl. software

Integration on multi-cylinder platform



- Hardware integration
- Software integration
- Calibration
- Functional and Performance testing
- Start of (in-field) durability testing

Real-life demonstration



- Showcasing feasibility and potential by development of demonstrators
 - Road
 - Non-road
- Real-world performance verification

Verification and Certification



- Technical Service for Dutch Type Approval Authority
 - HD ROAD: EURO III, IV, V, VI
 - NRM : STAGE III, IV, V
- IMO via marine classification
- ISO 17025 accredited since 1994
- ISO 14001 accredited since 2004

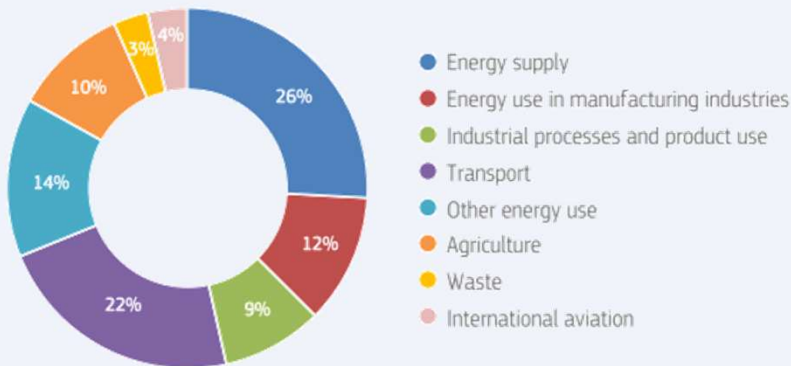
CO2 emissions Internal Combustion Engines running on sustainable fuels are significant source of CO2 emissions in EU

Sources of CO2 emissions in EU

- 22% of CO2 emissions in EU originate from the **transport sector**
- Transport sector dominated by internal combustion engines running on **fossil fuels**

Figure 2:

EU-27 greenhouse gas emissions by sector 2019 (in % of total emissions)¹⁶.

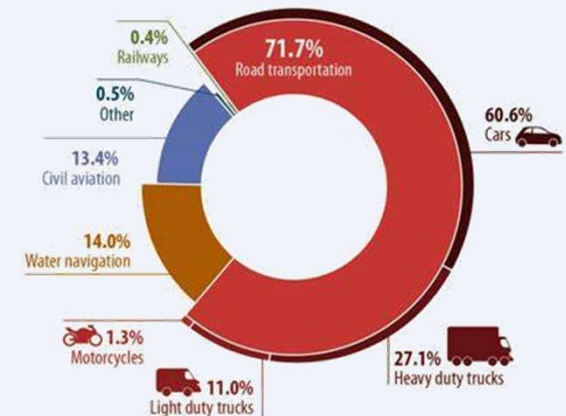


Greenhouse gas emissions by sector in the EU 27 – to illustrate the sectors we need to rapidly decarbonise

Source – *European Commission*, 2019

TRANSPORT EMISSIONS IN THE EU

Greenhouse gas emissions breakdown by transport mode (2019)



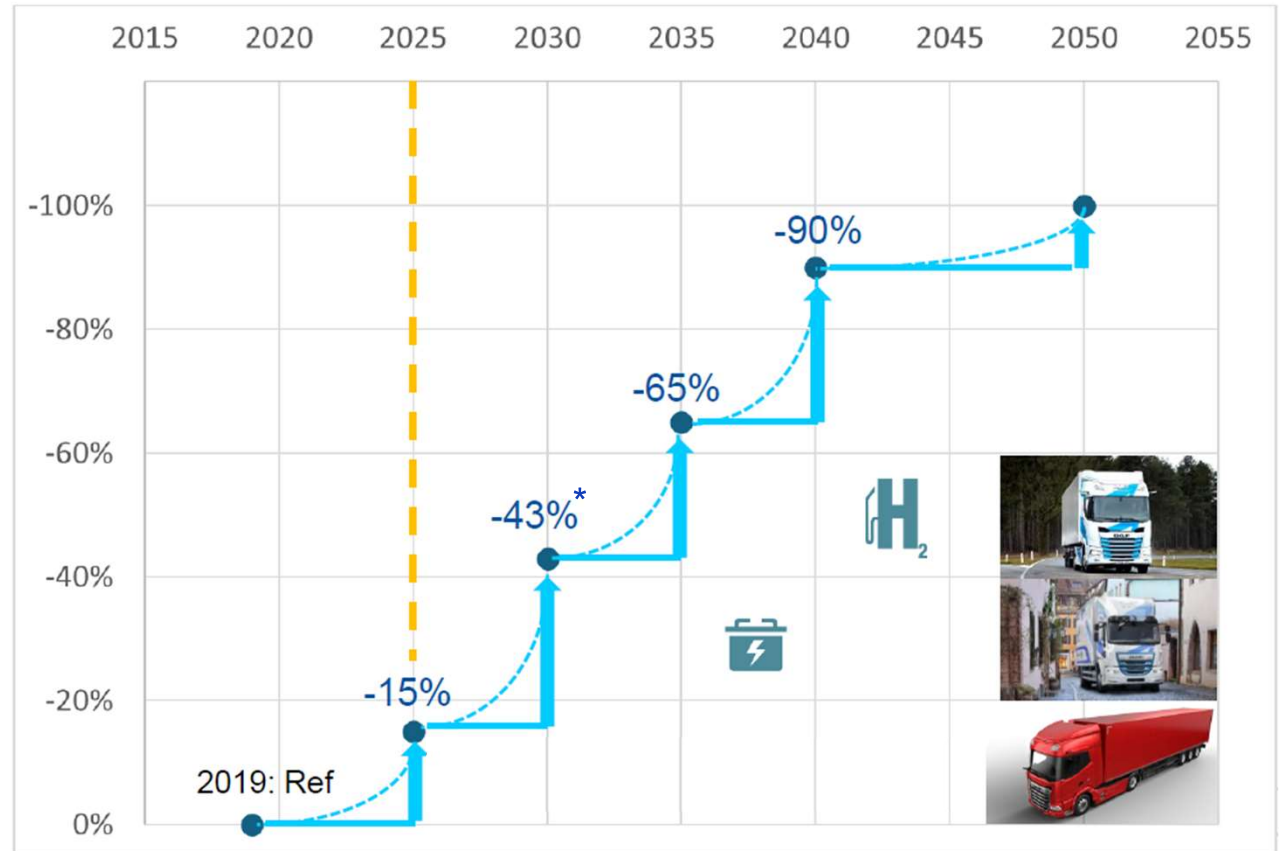
Source: European Environment Agency (2022)



EU Heavy Duty Truck CO2 legislation

- CO2 reduction targets using 2019 as reference
- Fleet-wide average targets
- **Tank-to-wheel** CO2 emissions
 - Battery-electric
 - Hydrogen
 - Fuel Cell
 - ICE
- Note: no bio-fuels or E-fuels!
- Zero Emission Vehicle (ZEV):
 $CO_2 < 3gr/ton.km$
- Note: ICE-ban not part of the discussion in Heavy Duty Truck

CO2 reductie target



* 45% when fleet includes busses

Decarbonizing road transport

Electrified powertrain

Battery-Electric



Zero Emission

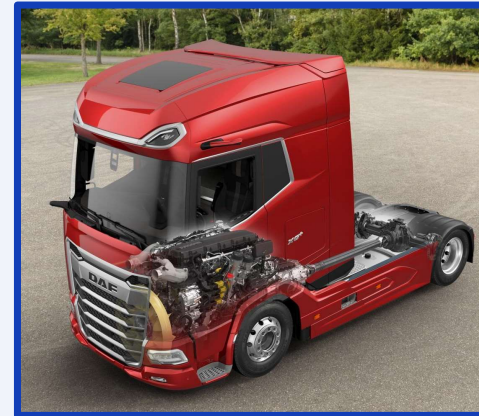
Fuel Cell-Electric



Zero Emission

CO2-neutral ICE

Bio-fuel / E-fuel



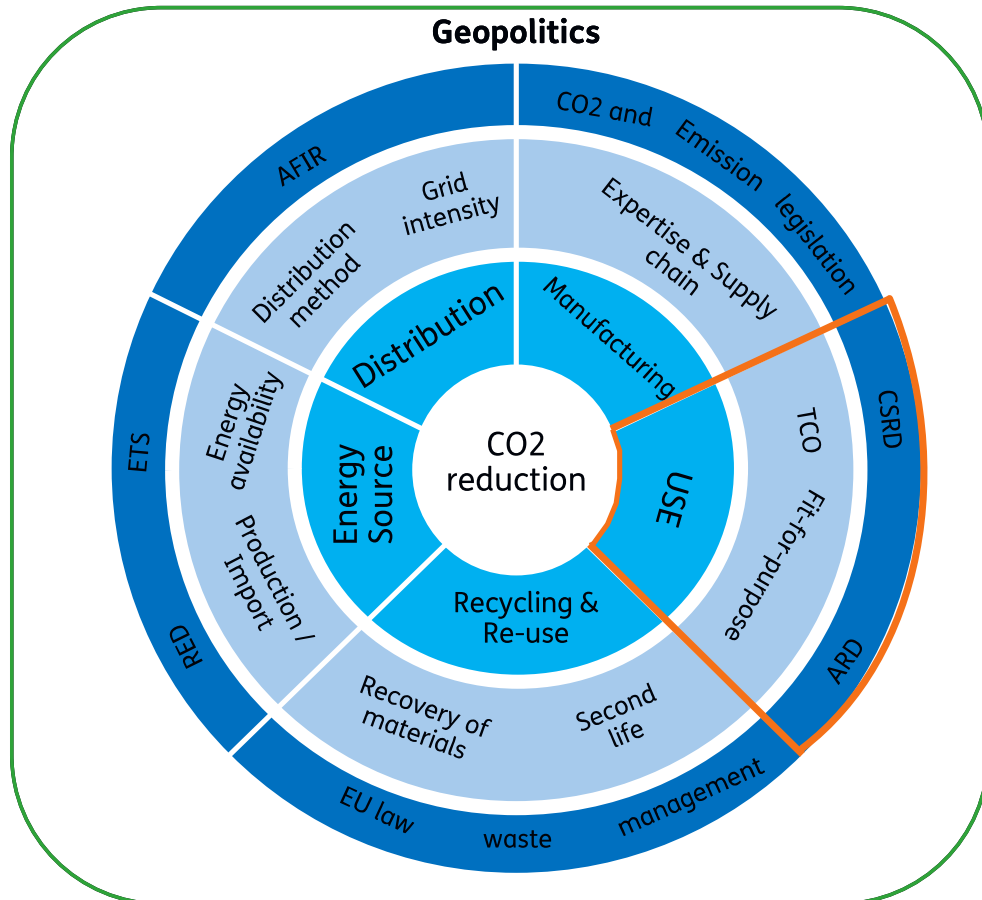
NOT Zero Emission

Hydrogen ICE



Zero Emission

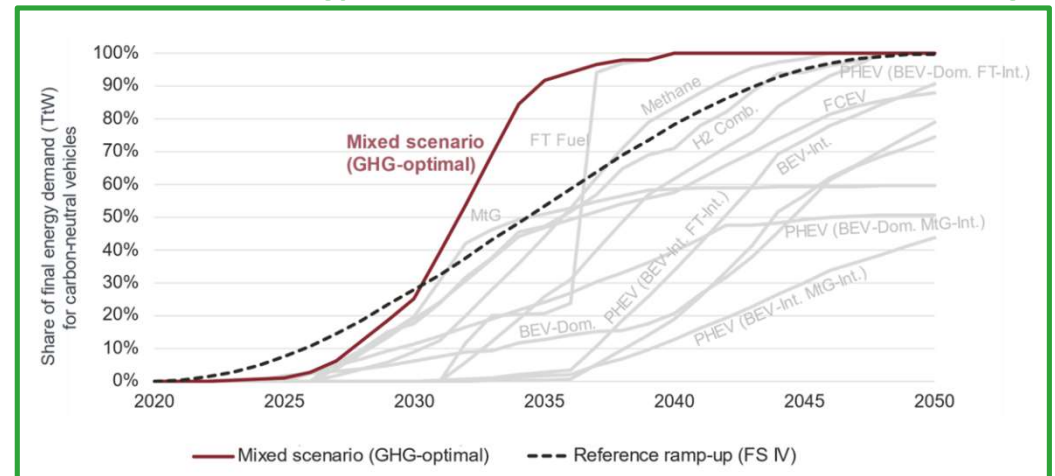
Decarbonization depends on many factors



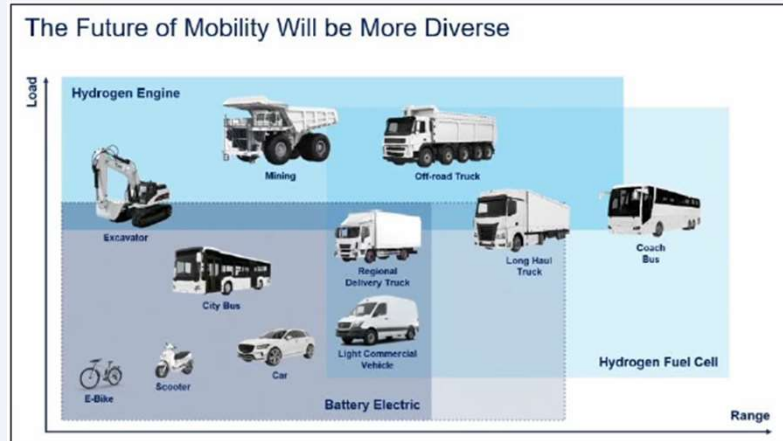
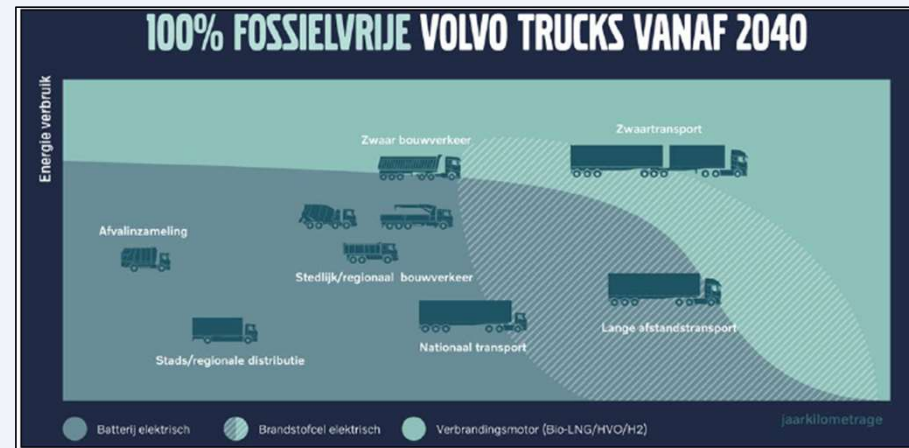
- BEV is superior in aspect efficiency in USE

“Electric when you can”

- Multi-technology scenario needed to meet climate targets



Industry view on Zero Emission Truck application



The right powertrain for the right application

- BEV and H2-ICE on opposite sides regarding load vs range with FCEV in between
- Mixed technologies in Long Haul Truck: BEV, FCEV and H2-ICE
- Hydrogen upscaling starting from national transport and heavy vocational (construction) vehicles

Sustainable Internal Combustion Engines

Fuels

- Hydrogen
- Methanol
- Bio-fuels / E-fuels

Engines

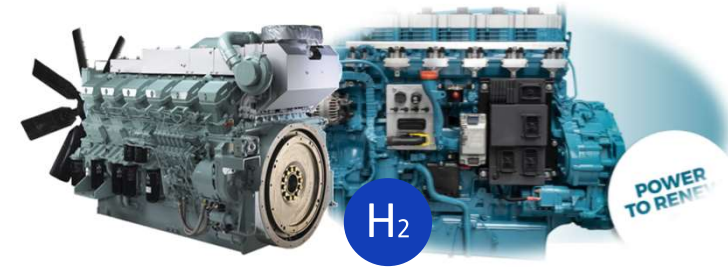
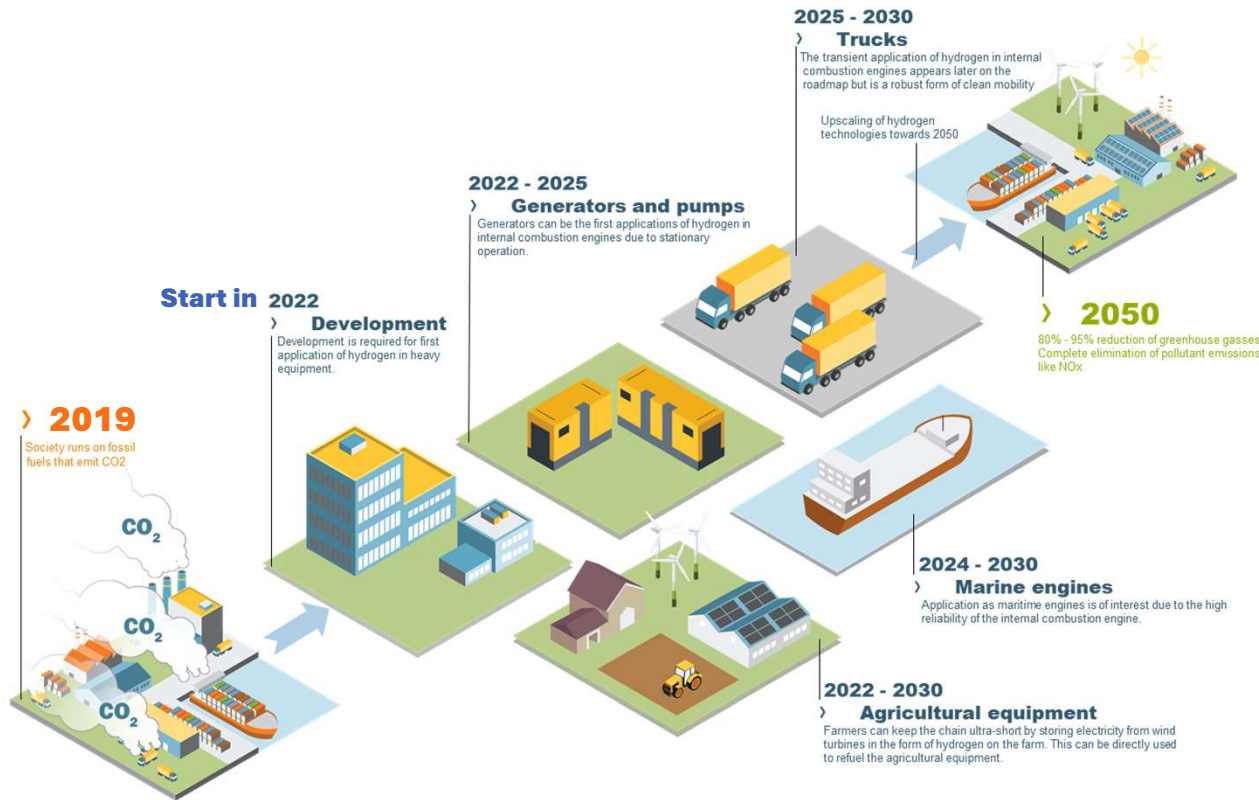
- High-speed engines up to 1.4 MW with and without aftertreatment

Applications

- Heavy-Duty Truck
- Stationary power generation
- Construction equipment
- Inland water way and near coast shipping



Hydrogen-ICE: Accelerating the energy transition



Aspect	Score
CO2 reduction	100%
Costs	Low
Efficiency potential	≥ diesel
Robustness	High
Tolerance to H2 quality	High
Independency	Strong


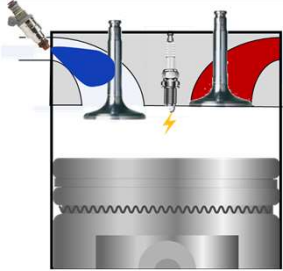
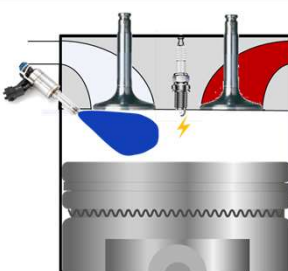
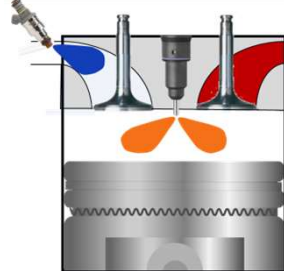
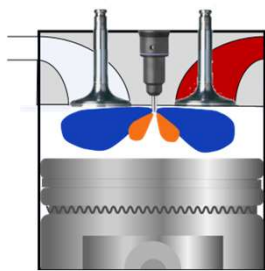








H2-ICE

Relevant H2-ICE concepts having different characteristics, challenges and application benefits

H2

Diesel

What is H2-ICE?: multiple H2-ICE concepts exist


	<p>PFI SI</p> 	<p>LP-DI SI</p> 	<p>Conv. DF CI</p> 	<p>HPDI CI</p> 
Fuel type	100% hydrogen		Hydrogen + Diesel (<< 90% H2 energy share)	Hydrogen + ignition liquid (~97% H2 energy share)
Fuel injection type	Port Injection	Direct Injection, max. ~50 bar	Port Injection Hydrogen DI diesel	Direct Injection, max. > 250 bar
H2 ignition	Spark plug		Compression	"Liquid spark" (Ignition liquid)
Benefit / potential	(Ultra-)low engine-out NOx		Retrofit	High performing
Challenges	NOx reduction during transients Occurrence unstable combustion	Occurrence unstable combustion NOx reduction during transients	Two storage tanks Low hydrogen share	Need for 2 nd fuel (2 tanks, CO ₂) HP compressor for full range
Application	1. Stationary power  * 2. NRMM / Inland waterway  3. Truck 	1. Truck 	1. Retrofit solution Truck  NRMM / inland waterway 	1. Truck  2. Construction equipment 

Green Transport Delta – Hydrogen

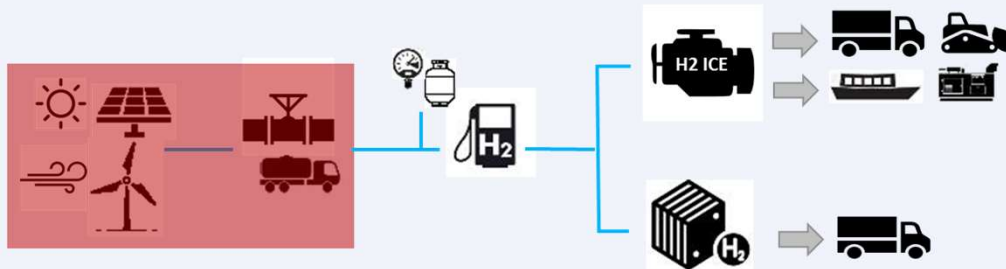
Goal: Develop a strong hydrogen ecosystem in the Netherlands

Lead partner 

 19  17



Green Transport Delta Waterstof



€ 37 Million

 1 Sept 2021
31 Aug 2025

 Website [link](#)

"Within GTD-H we are developing hydrogen combustion engines, hydrogen fuel cells and next-generation technology for hydrogen refueling infrastructure"
- Freek de Bruijn, project leader at RAI Automotive Industry NL

Supported by:

The project was carried out with a grant from the R&D Mobility Sectors scheme of the Ministry of Economic Affairs and Climate, implemented by Rijksdienst voor Ondernemend Nederland.

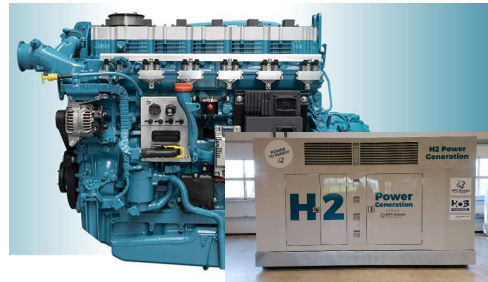
H2 (re-)fuelling technology and prototype engines for various sectors

Fuel system & Infra



- High pressure H2 fuel systems
- Next generation re-fuelling technology

Stationary Power Generation



- Prototype engine realized
- Integration of engine into genset
- Field-testing started, SOP in 2025

Inland Waterway



- Prototype engine realized
- Integration of engine into vessel foreseen

Heavy Duty Truck



- Performance potential quantified on all relevant H2-ICE concepts
- Prototype engine realized

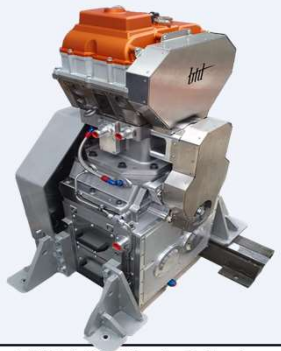
PFI SI & HPDI: different strengths and challenges

Cost efficient solution (no EAS)

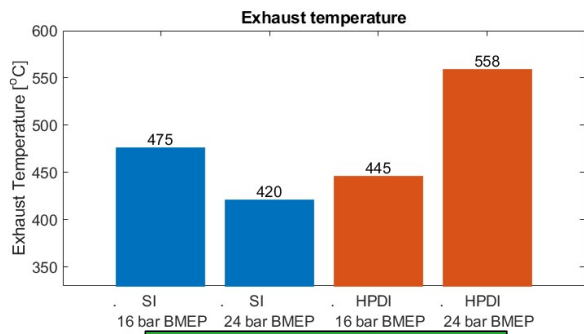
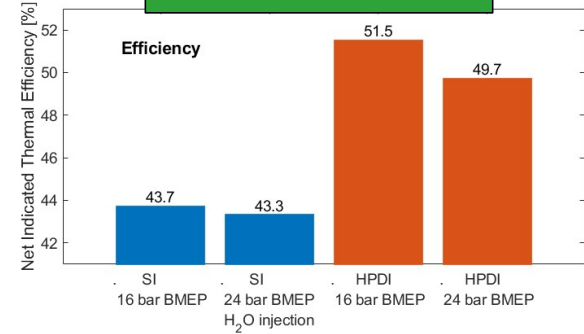
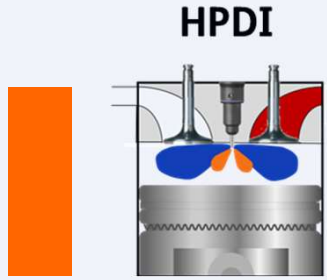
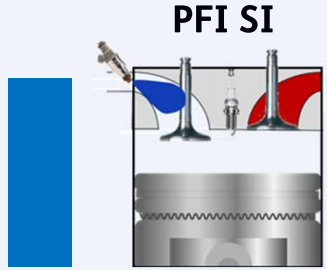
Competition with Fuel Cell efficiency

HPDI Highest efficiency

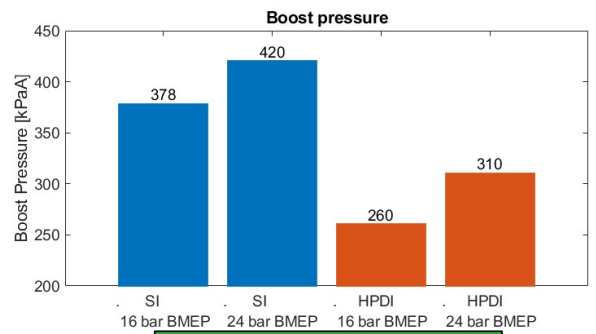
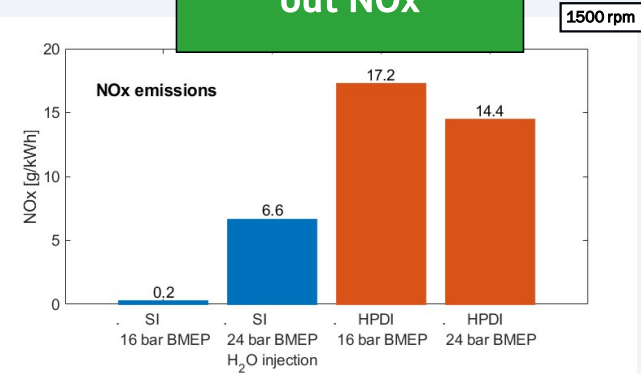
SI lowest engine-out NOx



TNO 1.8L Single-Cylinder Engine (SCE) research platform




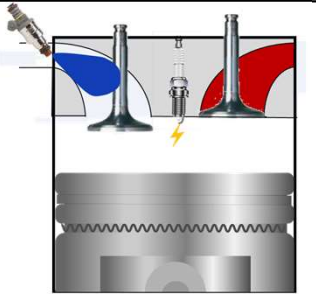

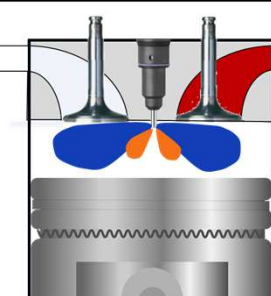
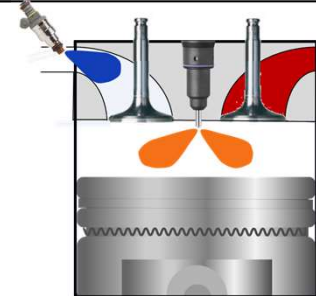
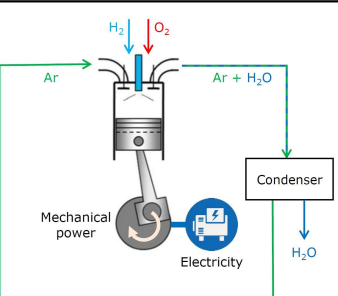
Sufficient temperature for aftertreatment



HPDI Fastest dynamic response

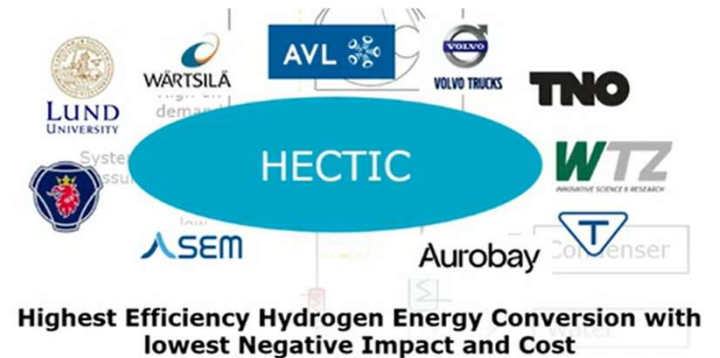
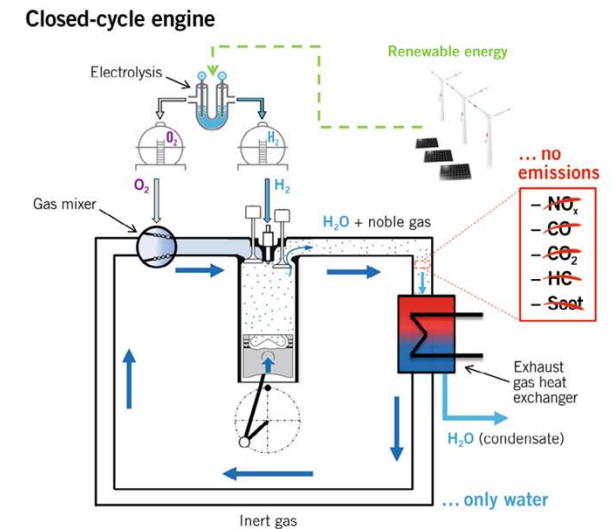
1500 rpm

H2-ICE concepts: development outlook

	<p style="text-align: center;">PFI SI</p> 	<p style="text-align: center;">LP-DI SI</p> 	<p style="text-align: center;">Conv. DF CI</p> 	<p style="text-align: center;">HPDI CI</p> 	<p style="text-align: center;">Argon Power Cycle</p> 
<p>Benefit</p>	<p style="text-align: center;">(Ultra-)low engine-out NOx</p>		<p style="text-align: center;">retrofit</p>	<p style="text-align: center;">High performing</p>	<p style="text-align: center;">Ultra-high efficient</p>
<p>Challenges</p>	<p>Transient NOx reduction Occurrence unstable combustion</p>	<p>Occurrence unstable combustion Transient NOx reduction</p>	<p>Two storage tanks Low hydrogen share</p>	<p>Need for 2nd fuel (2 tanks, CO₂) HP compressor for full range</p>	<p>Thermal loading H₂O/Argon separation</p>
<p>Development outlook</p>	<ul style="list-style-type: none"> • Improving dynamic response while reducing transient engine-out NOx to minimize need for aftertreatment • Negative NOx emissions with use of aftertreatment (NOx in exhaust < NOx in ambient air) 			<ul style="list-style-type: none"> • Elimination of pilot fuel (elimination of any CO₂ and second tank) 	<ul style="list-style-type: none"> • Development of ultra-high efficient Argon Power Cycle

Closed-cycle engine concept (Argon Power Cycle)

- **Argon Power Cycle Concept:**
 - Intake charge consists of argon premixed with O_2
 - High-pressure direct injection of H_2 near TDC enables mixing-controlled combustion
 - Exhaust composition: primarily H_2O and Ar (with O_2 present under lean conditions)
 - A condenser is used to remove water vapor from the exhaust stream
- **Benefits:**
 - Emission free regarding all GHG's and regulated local pollutant emissions
 - High BTE potential, approx. 60%
 - No aftertreatment
 - Unlike SOFC, dynamic operation is well possible
- **Applications:**
 - Stationary power generation (data centers, energy hub)
 - Long term: heavy duty transport



Hydrogen in heavy duty road transport

- EU Legislative framework in place, including H2
 - EU CO2 legislation: H2-ICE Vehicle = Zero Emission Vehicle (ZEV)
 - Infrastructure: EU AFIR, NL “Subsidieregeling Waterstof in Mobiliteit”
 - Euro 7: Includes hydrogen
 - ADR: Includes H2-ICE
 - ZE-Zones NL: H2-ICE Vehicles are allowed to enter ZE-Zones
- Stagnant H2-ICE developments by OEMs
 - Awaiting availability of H2 at competitive pricing
 - H2 upscaling expected post 2030 for HD truck
 - Non road sector: early adapters, but low volume
- Recent push for H2 in HD Truck sector

<https://www.daimlertruck.com/en/newsroom/stories/europes-biggest-opportunity-the-smallest-element>



CTO Daimler Truck: Hydrogen is “Europe’s biggest opportunity” and must act now on hydrogen trucks (June 23rd 2025)

PFI SI



hydrogen | building a greener future | jcb.com

JCB

Start of production 2023

LP-DI SI



MAN expands its zero-emission portfolio | mantruckandbus.com

MAN

Start of production 2025

HPDI™ CI



Volvo to launch hydrogen-powered trucks | volvo Trucks.com

VOLVO TRUCKS

Demo vehicles in 2025
Start of production “before 2030”

Sustainable Internal Combustion Engines

Fuels

- Hydrogen
- **Methanol**
- Bio-fuels / E-fuels

Engines

- High-speed engines up to 1.4 MW with and without aftertreatment

Applications

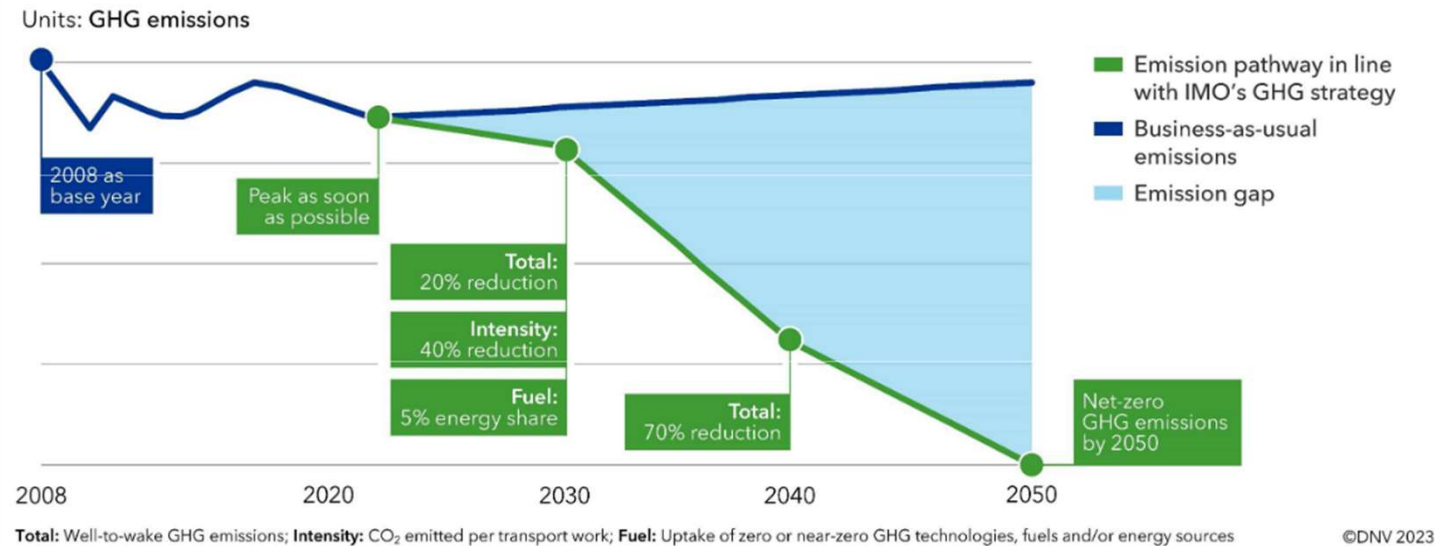
- Heavy-Duty Truck
- Stationary power generation
- Construction equipment
- **Inland water way and near coast shipping**



Maritime applications: focus on GHG reduction

- **IMO 2023 GHG strategy:**
 - guidelines for policy
 - “levels of ambition”
 - No penalties
- **New Net-zero framework**
 - In development (2025)
 - Ships > 5000 GT
 - GHG Intensity standards
 - CO2 pricing
 - Credits & Penalties (shipowner)
 - Implementation: 2027 – 2028
- **STAGE V applications (e.g. IWW)**
 - Indirect drivers for CO2 reduction
 - EU: ETS, RED III, CSRD

Strengthened IMO strategy on GHG reductions



Expanding and strengthening of MARITIME capabilities

Generic



Specification:

- 6 transient test cells
- Climate-Altitude Chamber
- Single-cylinder research platforms
- Liquid and Gaseous fuels
- High pressure H₂
 - 50 kg/h @ 400 bar
 - Up to 3 tube trailers
- Aligned with fundamental research setups at TU/e

Maritime test cell including aftertreatment machine room




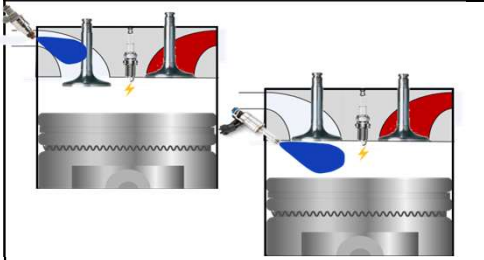
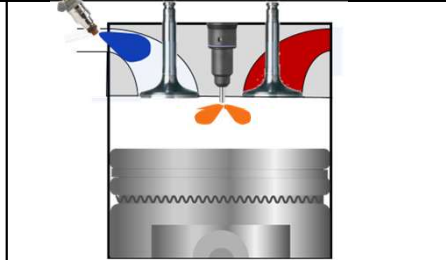
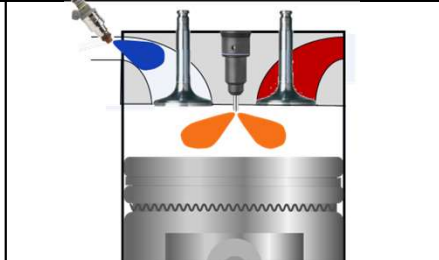

Specification:

- Power up to 1.4 MW
 - Hydrogen, Methanol, etc.
 - Machine room for aftertreatment (below the engine test cell)
 - Stationary & Transient
- Engine and aftertreatment system and control development
 - Functional verification
 - Calibration optimization and performance validation (power & emissions)
 - Measurements as input to emissions certification

simcat 

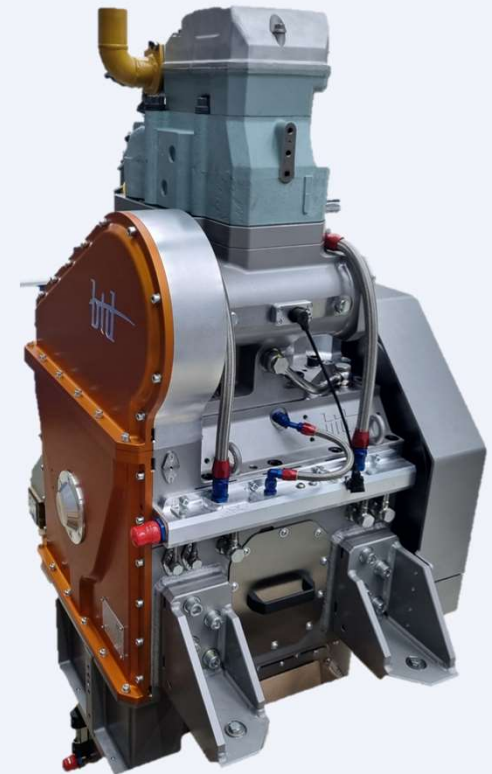
Supported by TNO's
control-oriented
aftertreatment models
& model-based controls

Methanol-ICE concepts

	SI (PFI or LP-DI) 	RCCI CI 	Conv. DF CI 	HPDI CI 
Fuel type	100% hydrogen	MeOH + Diesel ($< 90\%$ H ₂ energy share)	MeOH + Diesel ($< 90\%$ H ₂ energy share)	MeOH + ignition liquid ($\sim 97\%$ H ₂ energy share)
Fuel injection type	Port Injection or Direct Injection, max. ~ 50 bar	Port Injection MeOH, DI diesel	Port Injection MeOH, DI diesel	Direct Injection, max. > 250 bar
H ₂ ignition	Spark plug	Compression / Mixture reactivity	Compression	Ignition liquid

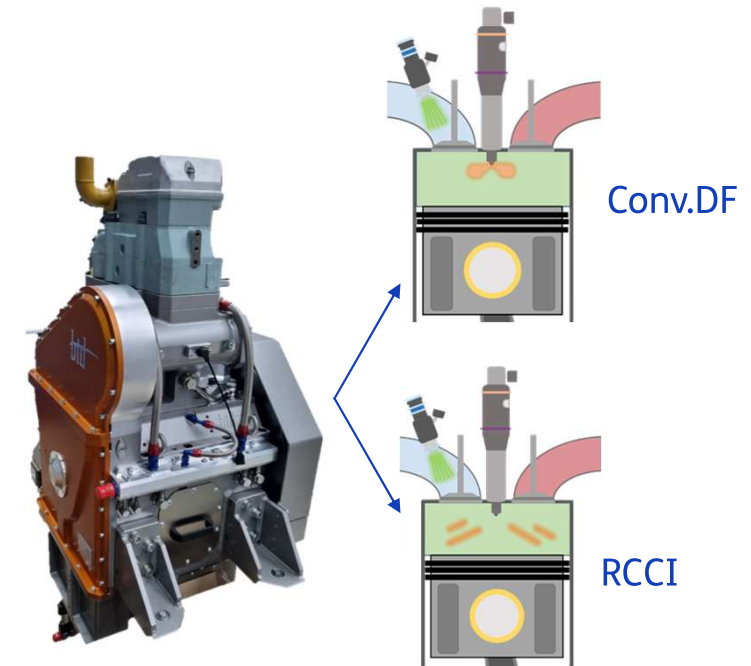
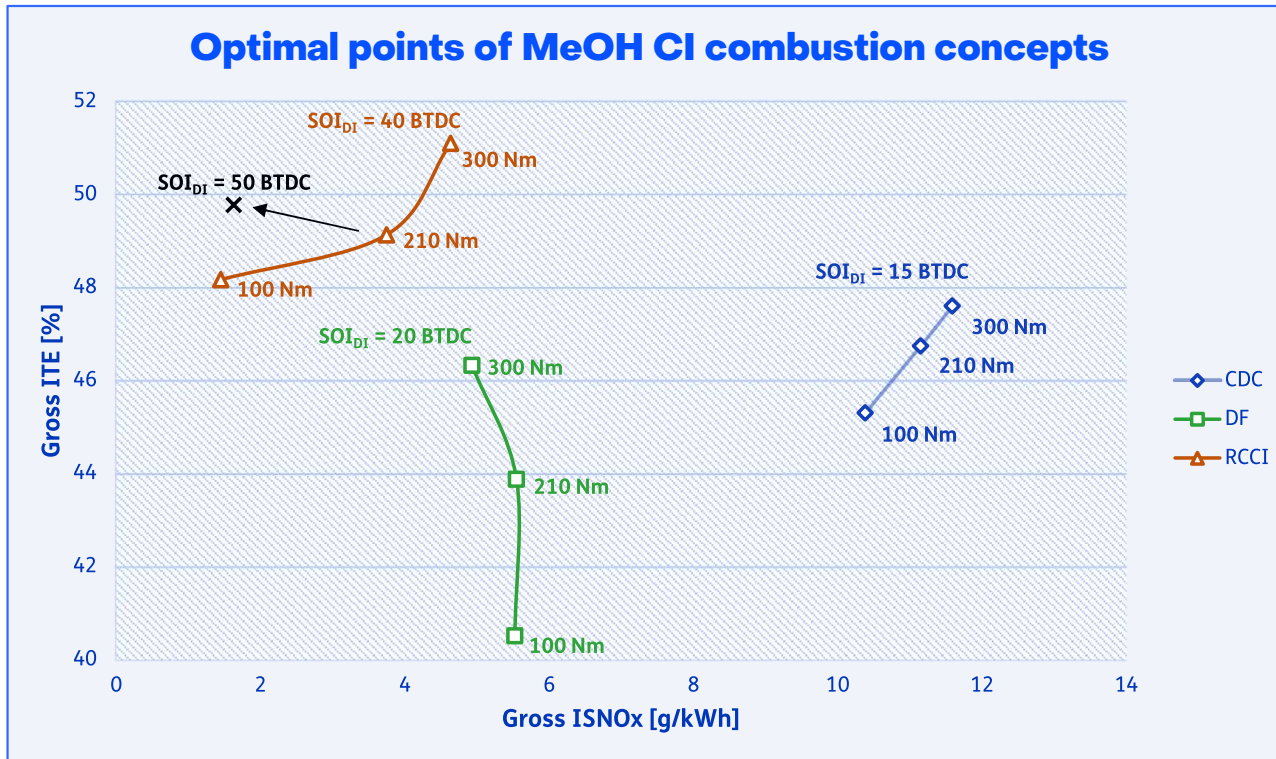
Single-Cylinder Engine research platform for Maritime

Swept volume	4.0 L
Compression Ratio	SI: ≤ 11.5 , CI: ≤ 14.5
Charging system	External compressor, max. boost pressure 4.5 barA, intake throttle
EGR system	High pressure, cooled EGR
Max. p_{cyl}	140 bar
Charge Temperature Conditioning	Variable charge temperature [15 – 70 °C] Port Water injection



Dual fuel versus RCCI with MeOH

- Experiments performed on TNO SCE 4.0L with CR = 14
- RCCI outperforms DF: further optimization possible with DI timing (X)
- Conventional diesel combustion included as benchmark





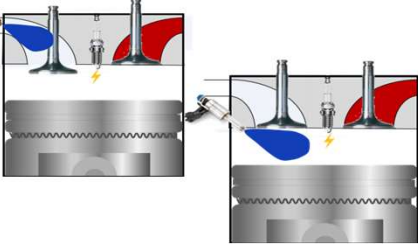
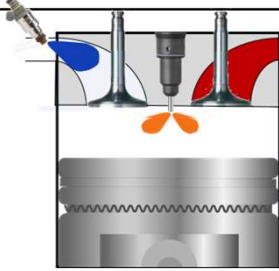
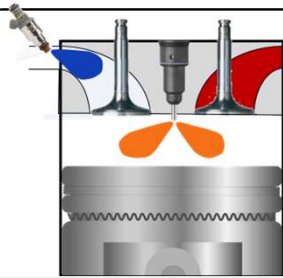
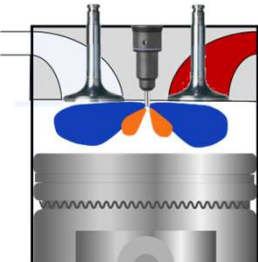
KPI	DF	CDC	RCCI	HPDI
Efficiency	↓	0	↑	0/↑
NOx	↓	0	↓↓	0
THC	> 50 g/kWh	0	> 20 g/kWh	0

To be confirmed

THC sources:

- Premixed MeOH in crevices
- Too lean local mixture

Methanol-ICE concepts

	SI (PFI or LP-DI)	RCCI CI	Conv. DF CI	HPDI CI
				
Fuel type	100% hydrogen	MeOH + Diesel ($< 90\%$ H ₂ energy share)	MeOH + Diesel ($< 90\%$ H ₂ energy share)	MeOH + ignition liquid ($\sim 97\%$ H ₂ energy share)
Fuel injection type	Port Injection or Direct Injection, max. ~ 50 bar	Port Injection MeOH, DI diesel	Port Injection MeOH, DI diesel	Direct Injection, max. > 250 bar
H ₂ ignition	Spark plug	Compression / Mixture reactivity	Compression	Ignition liquid
Hydrocarbon emissions	High Three-Way-Catalyst (TWC)	High Oxidation Catalyst	Low	Low
NO _x	Moderate Three-Way-Catalyst (TWC)	Low No deNO _x catalyst?	High SCR catalyst	High SCR catalyst
Efficiency	Lower than diesel	Better than diesel	Diesel-like	Diesel-like
Application	1. Sea-going (IMO)	1. Sea-going (IMO) 2. Inland waterway (STAGE V)	1. Inland waterway (STAGE V) 2. Sea-going (IMO)	1. Inland waterway (STAGE V) 2. Sea-going (IMO)

Research on MeOH-ICE for maritime

- Complete quantification of emission footprint various MeOH-ICE concept
 - Part of on-goingwork, e.g. Maritime Masterpan Projects (MMP)
- Research on effective application of Oxidation Catalyst for conversion of unburnt methanol emissions
- Research on feasibility of SCR deNOx technology for MeOH-ICE

The route to sustainable HD transport

[+]

Zero emission



Thank You

**Hydrogen Engine Ignites
the Future**