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H₂IQ

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The #H2IQ Hour

Today's Topic:

Overview of Hydrogen Internal Combustion Engine (H2ICE) Technologies

This presentation is part of the monthly H2IQ hour to highlight hydrogen and fuel cell research, development, and demonstration (RD&D) activities including projects funded by U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office (HFTO) within the Office of Energy Efficiency and Renewable Energy (EERE).

This webinar is being recorded and will be available on the [H2IQ webinar archives](#).

Technical Issues:

- If you experience technical issues, please check your audio settings under the “Audio” tab.
- If you continue experiencing issues, direct message the host, Cassie Osvatics

Questions?

- There will be a Q&A session at the end of the presentation
- To submit a question, please type it into the Q&A box; **do not** add questions to the Chat



The #H2IQ Hour Q&A

Please type your questions
into the Q&A Box

Open the Q&A panel

To open the Q&A panel, click Panel options (Windows)
or More options (Mac)  and select **Q&A**

Q&A

All (0)

Select a question and then type your answer here, There's a 256-character limit.

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Energy &
Homeland Security

Is there a place for H₂ internal combustion engines?



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Principal Investigator and Senior R&D Engineer

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Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525

**H2ICE development and demonstration programs are gaining momentum**

“Over 130 OEMs are interested in, planning or running H2 engine R&D projects” (Bosch)

H2ICEs have both short-term and long-term potential

H2ICEs can provide for a smooth, continuous transition as H2 supply and infrastructure develops

H2ICEs may be the preferred long-term technology solution for some applications

Several OEMs have series production plans as early as 2023

There is geographical disparity in H2ICE activities and know-how → activity centered in Europe and Asia

Early market introduction is prioritized → efficiency is secondary

Second generation H2ICEs will be developed with focus on performance and emissions (DI, optimized config., etc.)

R&D can have both a near-term and longer reaching impact

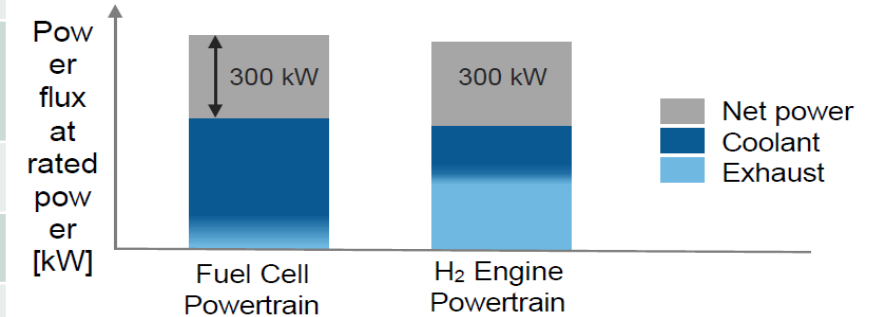
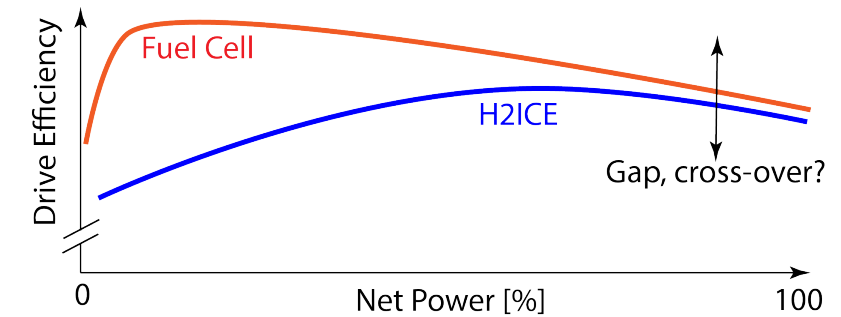
Retrofits

Current engine generational updates and near-term new engine releases

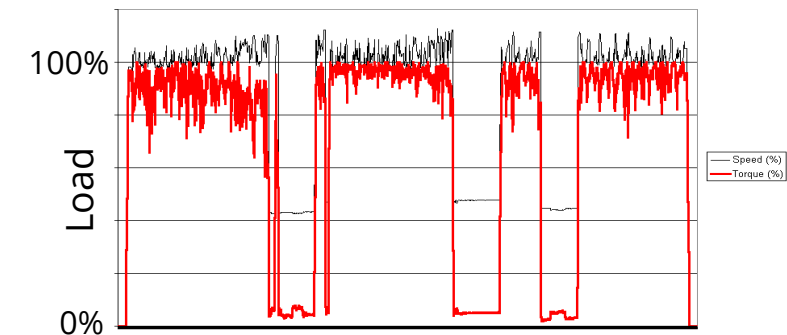
High-efficiency, low emission future generation engines



Characteristic	H2ICE	H2FC
Efficiency	Good: mid – high load	Excellent: low – mid load
Cooling needs	Intermediate	High, critical for stationary and slow-moving applications
Emissions	NOx (and minor CO ₂) Low with aftertreatment	None
Durability	High	Improving with new R&D
Robustness	High	Sensitive to vibration
Noble metal consumption	Low – intermediate (after-treatment)	High
Fuel purity	Tolerant to contaminants	High-purity H2 required
Fuel flexibility	Diesel/NG backup	Can be flexible, efficiency penalty
Upfront cost	Low	High
Cold start	No issues	Temperature conditioning
Resale value	Depending on infrastructure	Unclear



High-load duty-cycles:
US EPA cycle: excavator

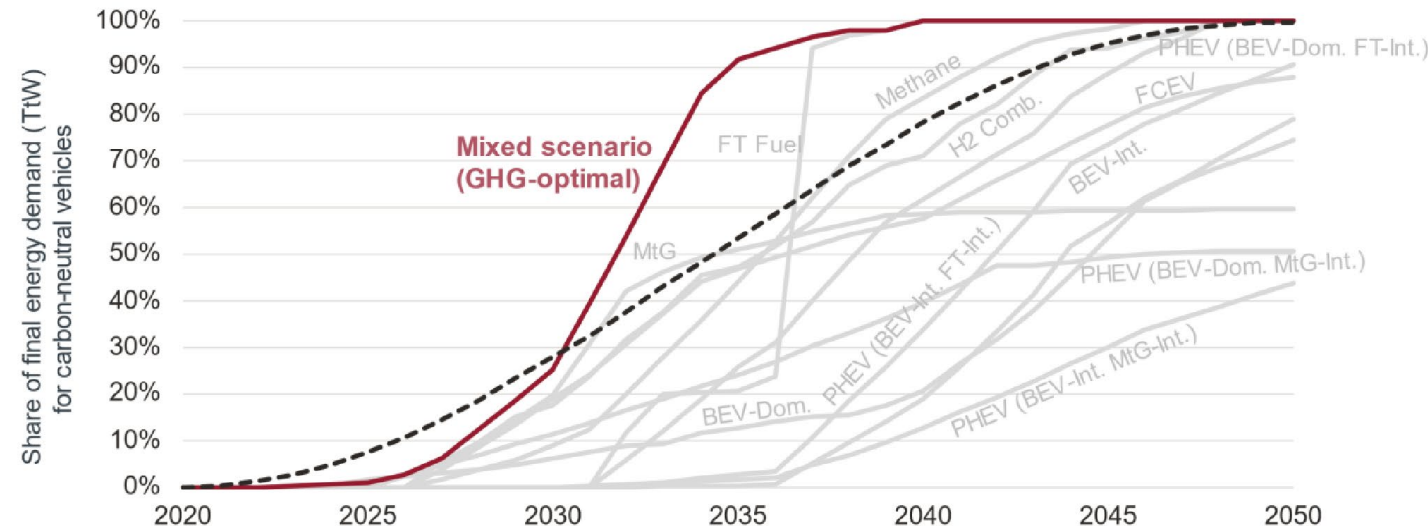


Single technology scenarios will delay decarbonization:

- Infrastructure limitations
- Production ramp-up
- Fleet replacement time
- Material availability and mining ramp-up
- Customer acceptance

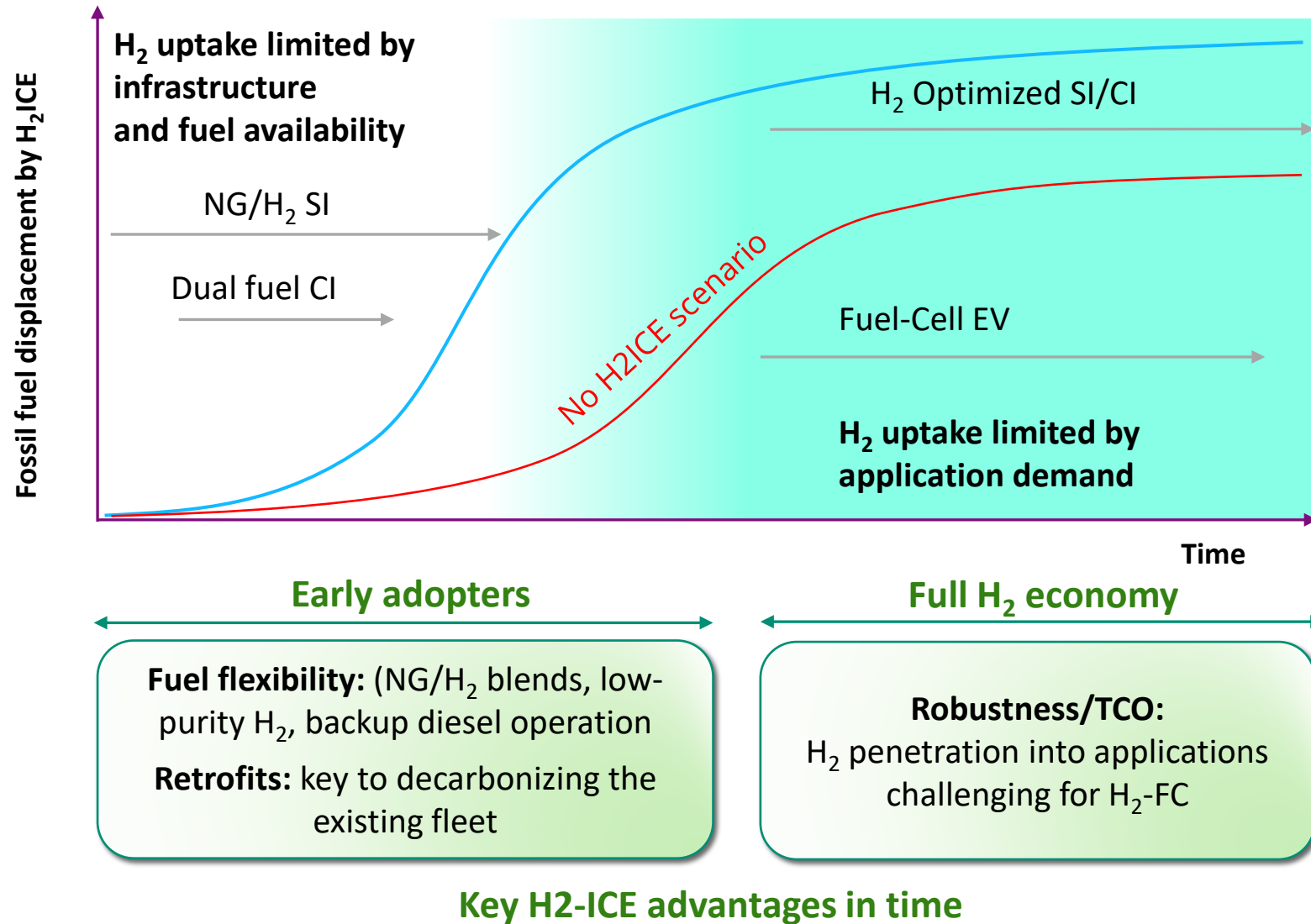
A technology-neutral mixed-scenario is likely the fastest, most cost-effective, and lowest risk path to carbon neutrality

Rate of decarbonization scenarios: Accounting for material/infrastructure limitations



BEV	Battery-Electric Vehicle	PHEV	Plug-In Hybrid Electric Veh.
FCEV	Fuel-Cell Electric Vehicle	Dom.	EU domestic sourcing
FT	Fischer-Tropsch	Int.	International sourcing
MtG	Methane to Gasoline		

Source: FVV Future Fuel Study IVb, Project Nr. 1452, Final Report, 2022;
https://www.fvv-net.de/fileadmin/Storys/Wie_schnell_geht_nachhaltig/FVV_H1313_1452_Future_Fuels_FVV_Fuel_Study_IVb_2022-12.pdf
 Accessed 01/09/2023



H₂ICEs provide for a smooth, continuous transition as H₂ supply and infrastructure develops and the existing fleet turns over



H2ICEs tend to have advantages in

- Very large vehicles
- Construction and agriculture applications with significant vibration and/or dust
- Applications with limited installation space
- Severe ambient conditions (cooling)
- Difficult H2 supply (remote)
- Stationary mechanical-drive applications
- Retrofits (rail, marine, CHP)

FCs are best for

- Lower power applications
- When noise or pollutant emissions are critical

Many believe H2ICEs have a significant long-term potential, and will be the preferred technology for some applications

Criterion		Power density	Technology maturity	System integration	Cost		
Application	Power					Other properties	Overall
Truck	<200 kW	O	-	O	O	- Emissions	-
	200-350 kW	+	-	O	+	- Emissions	-
	>350 kW	+	O	O	+	- Emissions	+
Ultra-duty vehicles	>350 kW	+	O	+	+		+
Bus, Coach	<250kW	-	-	-	O	- Emissions - On board power	-
Construction machinery		O	O	+	+	+ Dust/vibration	+
Agriculture	<200kW	O	O	+	+	+ Dust/vibration	+
Municipal vehicles	<250kW	O	-	O	O	- Emissions - On board power	-
Marine		O/+	-	-	O/+	- Emissions	O
BEV range extender		-	-	-	+	- Emissions	-
Mechanical drive		O	O	+	+		+



TCO studies for off-highway vehicles are rare, predict similar FC vs H2ICE TCO

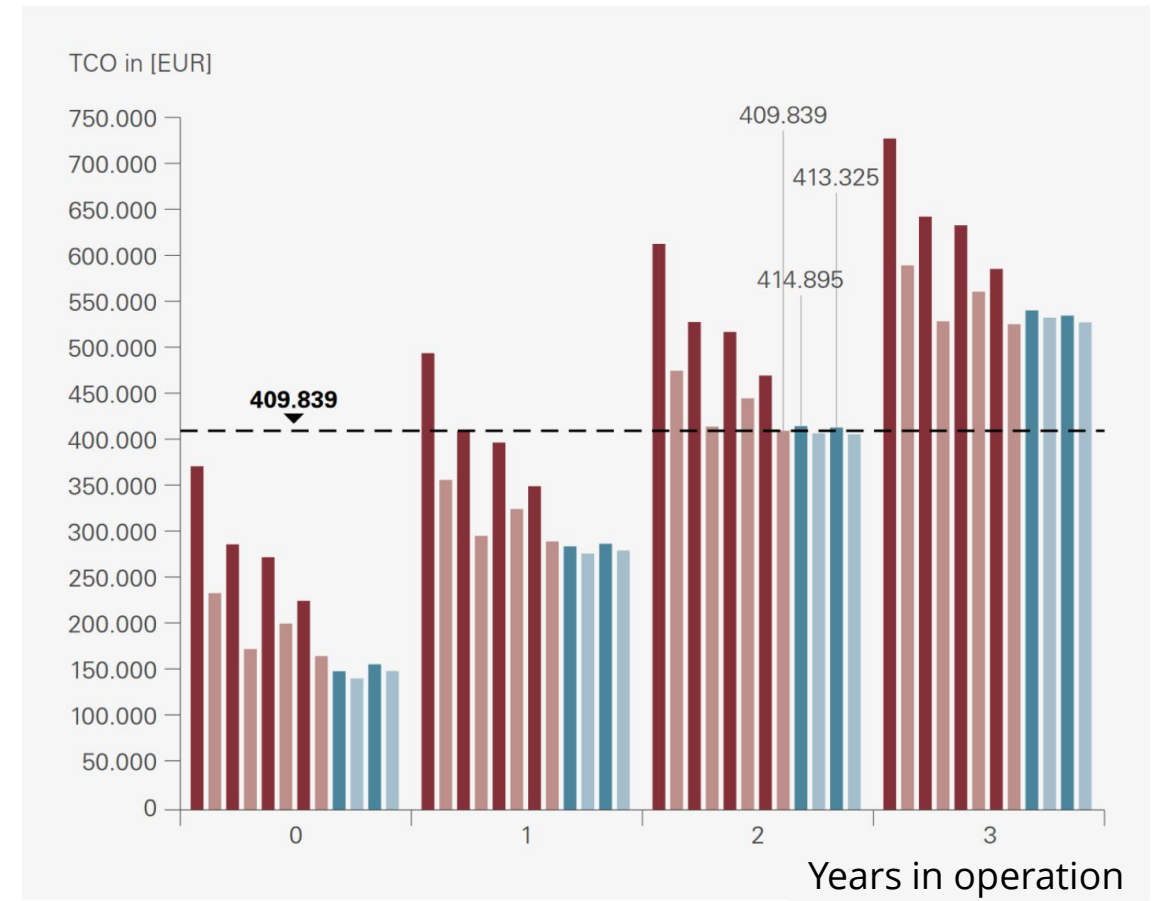
Heavy-Duty trucking 2025 technology and cost:

- FC acquisition pays off over time (efficiency advantage)
- Rate of investment return depends of fuel cost and cost of FC system

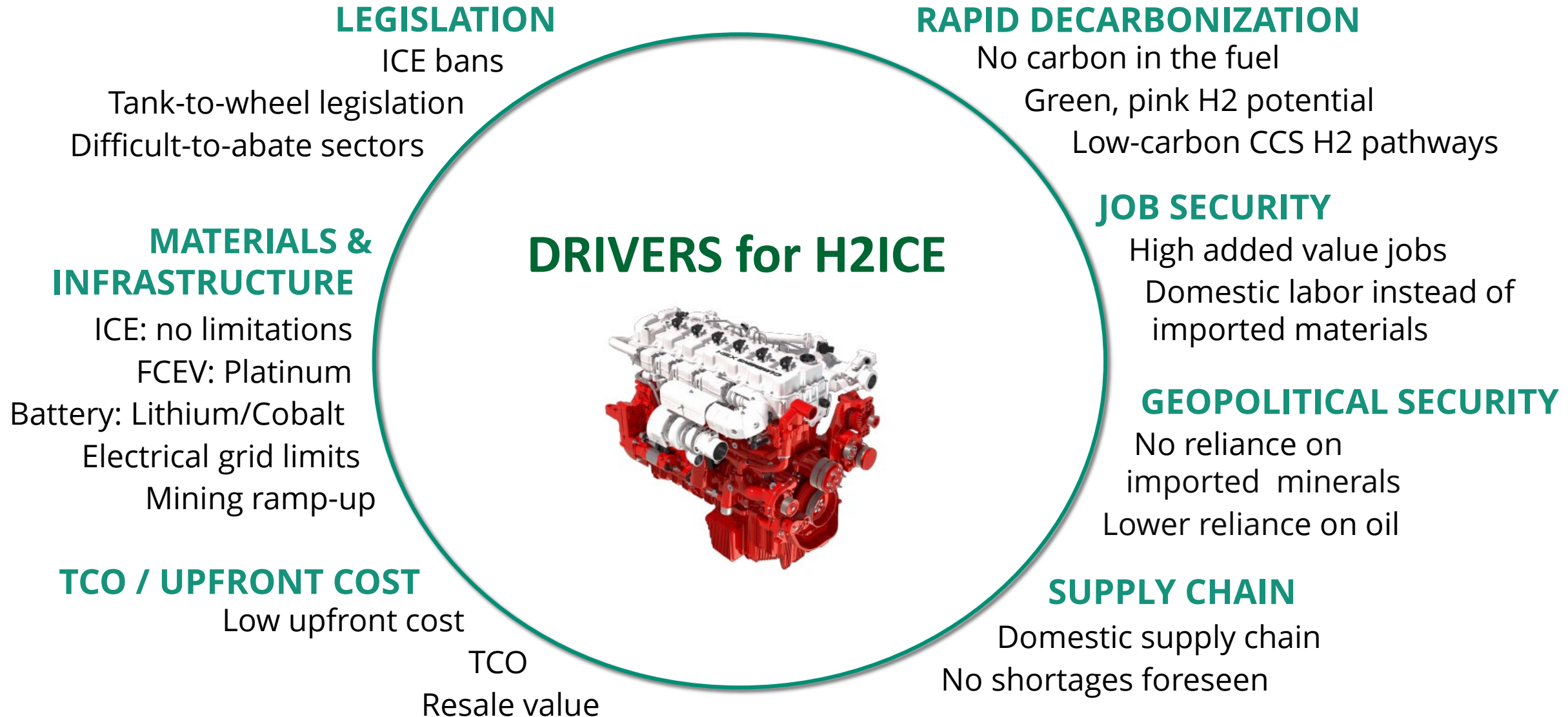
2030 technology and cost:

- FC upfront cost is comparable to H2ICE
- Fuel consumption gap becomes smaller as H2ICE becomes more efficient
- FC has a TCO advantage for on-road transportation (a close call in nearly all scenarios)

Cumulative TCO, 2025 technology/cost level
6 EUR/kg H₂ cost, H2ICE: 20% efficiency penalty

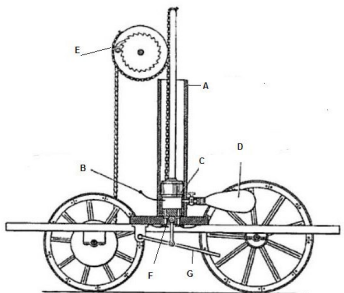


Red: FC cases/configurations; Blue: H2ICE configurations



H₂ICE HAS A LONG HISTORY, CURRENT R&D WAVE UNPRECEDENTED

1807: ICE invention (De Rivaz)
First engines run on H₂



1800 - 1970

Town-gas power generation

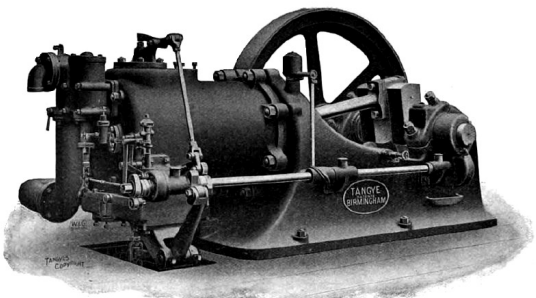


Fig. 51.—Tangye Horizontal Engine.

Tangye Ltd. 340hp engine, 1906
Source: VintageMachinery.com

No activity

1970-2000

MAN H₂ICE city-bus
Berlin, 14 units, 2006-09
4 units operated until
2015



BMW Gen 1 H₂ICE luxury sedan



BMW Gen 2 H₂ICE
100 units sold (2005-07)
uses DI tech.

GM-Opel
LD commercial
demonstrator



2000-2012

Japan NTSEL
R&D 2005-10
(injectors,
lab testing)

Dutch H₂-demo
project 2005-09



Ford H₂ program 2006-09
US-DOE research in natl. labs
BTE of 45.5% demonstrated

2012-2019

No activity

Tokyo city Uni.
Minibus demo, 2011-2013
~10,000 miles



Revived interest
in H₂ICE:

- Heavy-Duty
- Off-road
- Power gen



2020 - present

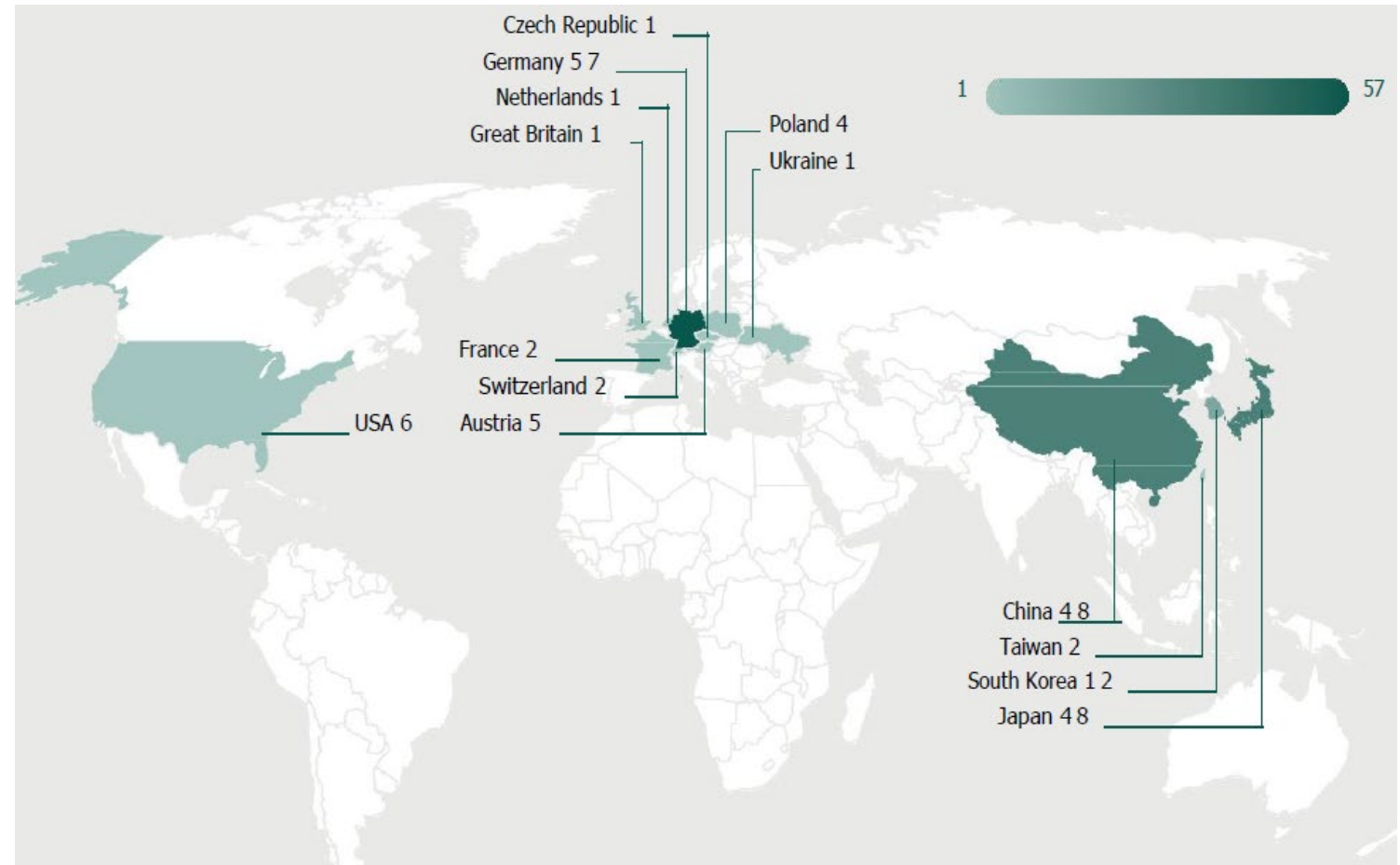


See also:

<https://allianz-wasserstoffmotor.de/en/home.html>
<https://www.swri.org/industries/hydrogen-powered-vehicles>
<https://www.h-ope-wg.com> & others

- Efforts concentrated in Germany/Austria and eastern Asia
- Peak activity from 2006-2012 and from 2015 onward
- Focus on fuel injection equipment and operating strategies with content pointing to a preference for DI approaches

Total active patents specific to H2ICE (2000 - 2020)



Source: www.now-gmbh.de/en/news/pressreleases/meta-study-published-on-the-topic-of-hydrogen-combustion-engines/

European Union

- Main legislation: "Fit for 55" and "European Green Deal"
- **Proposed legislation explicitly allows for H2ICE as zero-emissions tech.¹**
- "Tank-to-wheel" legislation may be re-assessed to "Life-Cycle" emissions by ~2025
- "Zero-emission" CO2 limits might be set at 1-4 g/kWh

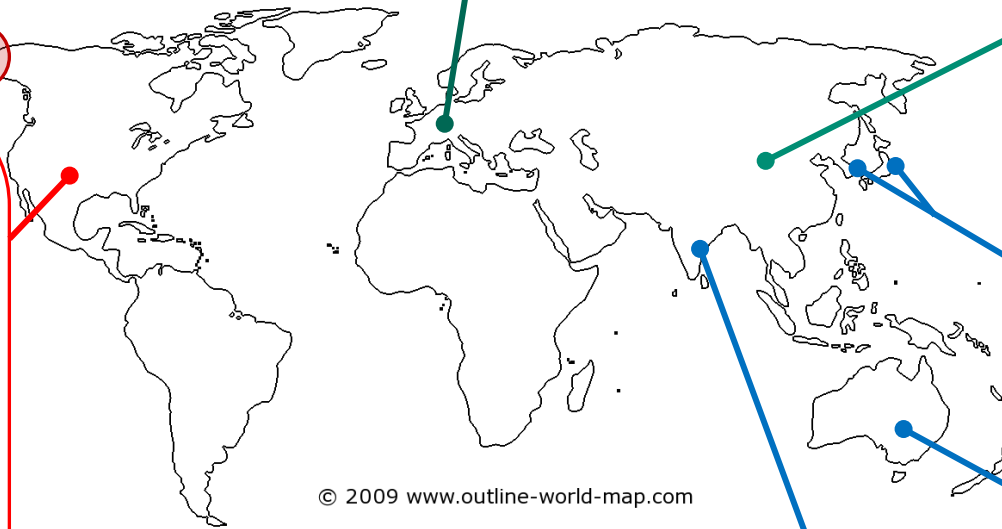
China

- **H2ICE listed on strategic level²**
Strategy lists R&D needs for advanced and alternative fuels
- Strategy promotes formulation of "urgently needed" standards

United States

Legislation does not promote a market for H2ICEs

- **Inflation Reduction Act**
\$2B: domestic production of HEV, PHEV, BEV and FCEV. H2ICEs excluded!
- **Infrastructure Investment and Jobs Act**
ZEV reqd. for some programs (e.g. Clean School Bus)
- **CARB Heavy Duty Emissions**
100% ZEVs by 2045
(ZEV: zero emission of any GHG or pollutant)



Japan and Korea

- Strategic shift from importing HC to importing H2
- No clarity on H2ICE role in transportation
- Encourages **H2ICE for power generation and marine**

India

- 2023 National Green H2 strategy focuses on production and industrial decarbonization
- Foresees H2FC and H2-derived liquid fuels for transportation, **H2/NH3 ICE for marine**

Australia

- Strategic efforts to become H₂ exporter (green and blue H₂)

¹EU Council, Inter-institutional File: 2021/0197(COD): Zero-emission vehicles: BEV, FCEV, other H2 powered vehicles.

² Ministry of Industry and Information Technology, Development and Reform Commission and the Ministry of Science and Technology: "Medium and Long-term Development Plan for the Automobile Industry", issued in 2017

PRODUCTION STATUS AND TIMELINES – ROAD TRANSPORT SERIES PRODUCTION ~2025



Keyou GmbH
develops H2ICE
conversion kit



Alliance for
hydrogen engine
(today, >60 partners)



H2 opposed-piston
ICE working group
(today, >17 partners)



Weichai HD truck
13L DI-H2ICE
41.8% BTE



Cummins 6.7L
H2ICE
concept truck



Numerous demonstrations planned
Injection hardware serial production

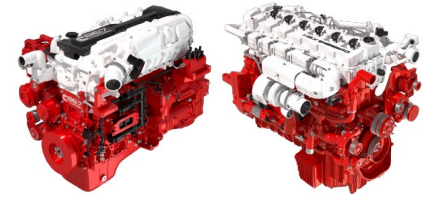
2022 Toyota Cross
H2ICE concept



Ashok Leyland (India)
H2ICE truck unveiled



MAN H2ICE HD
truck series
production



Cummins H2ICE
portfolio small series
production start

2017 - 2021

2022

2023

2024 - 2026

2027 - 2030



Toyota endurance
H2ICE race car



BorgWarner H2ICE
LDV demonstrator



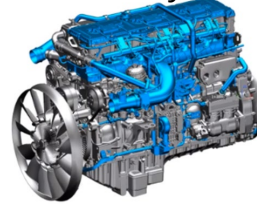
DAF HF H2-ICE demo
2022 truck innovation award

BorgWarner
H2-DI injector
series production

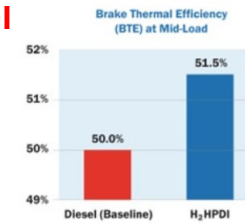
Westport H2 HPDI



Daimler DD15 PFI H2ICE
44.5% efficiency, 335kW



Scania 51.5% BTE
using HPDI



SWRI H2ICE
Class 8 demonstrator
<https://www.swri.org/industries/hydrogen-powered-vehicles>

Small-scale H2ICE
deployment in Europe
Light-duty, possibly HD

Keyou-Deutz 7.8L H2ICE,
44.5% BTE
Small series production



EURO7/CARB27
Legislation

PRODUCTION TIMELINES – OFF-ROAD – 2023 SMALL SERIES MARINE, STATIONARY - ~2025 COMMERCIALIZATION



Stationary ICE:

kits for <25% H2 co-fire by most OEMS
(long life-time of equipment)

JCB £100M investment
into H2ICE for 2023
small-series
production

JCB 448 4.8L. H2ICE, 70kW
PFI injection, diesel engine base



Small H2ICE vessel
demonstrations (Europe)



Full JCB H2ICE product line
including field re-fueller



100 JCB
H2ICEs
produced

JCB H2ICE
production
start

100% H2ICE CHP and
power-gen offered by most
OEMs

Rail H2ICE
commercialization
likely

2020 - 2021

2022

2023

2024 - 2026

2027 - 2030

Liebherr and Mahle
announce
collaboration for
heavy-duty H2ICE



Case New-Holland
H2-diesel dual-fuel
conversion kit



Jenbacher J416
100% H2 CHP ICE
40% electrical efficiency
93% total efficiency



Liebherr
H2-DI injectors



Liebherr 966
H2ICE, PFI, 13L

Start
Wabtec CRADA
H2ICE for rail

Liebherr
BAUMA 2022
award



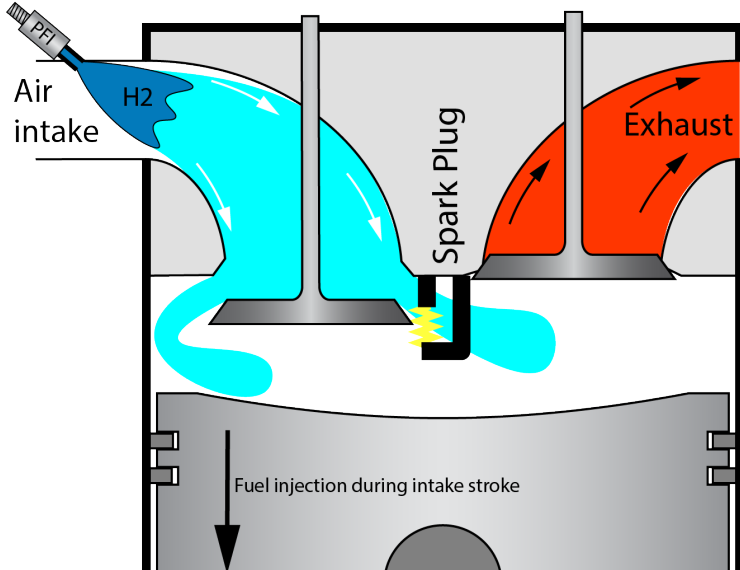
50ton H2ICE
excavator demo.



Wabtec CRADA
completed
(PFI and DI
technologies)

Asian marine OEMs
full 100% H2ICE
product line
(medium and large
4-stroke, 2-stroke)

Port-injection spark-ignition 3-10 bar injection pressure

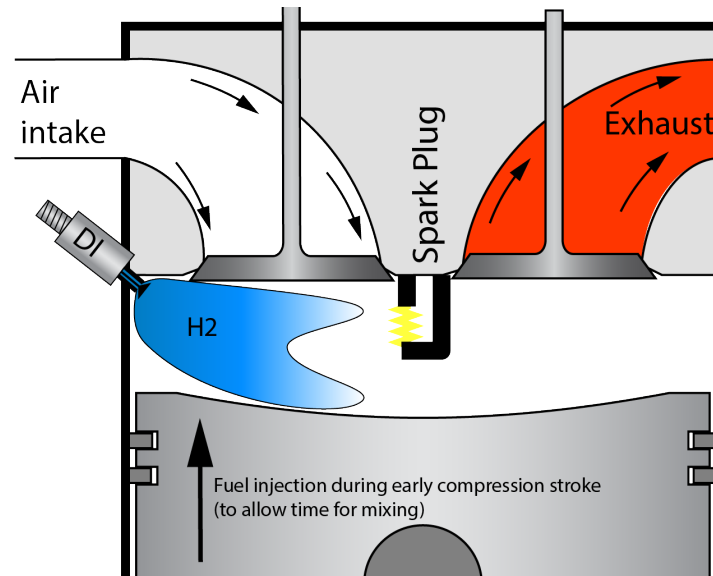


Key challenges: power density, abnormal combustion, efficiency

“Generation 1” H2ICE technology
~2025 market introduction, retrofits

- + Simplest system – minimal engine modification, low-cost fuel system
- + Typically low NOx emission
- + Simple to integrate with advanced ignition systems
- Loss of power density
- Efficiency
- Risks of back-fire into intake manifold, highly-prone to pre-ignition
- Poor transient response
- Extreme turbocharging requirements

Direct-injection spark-ignition 10-50 bar injection pressure

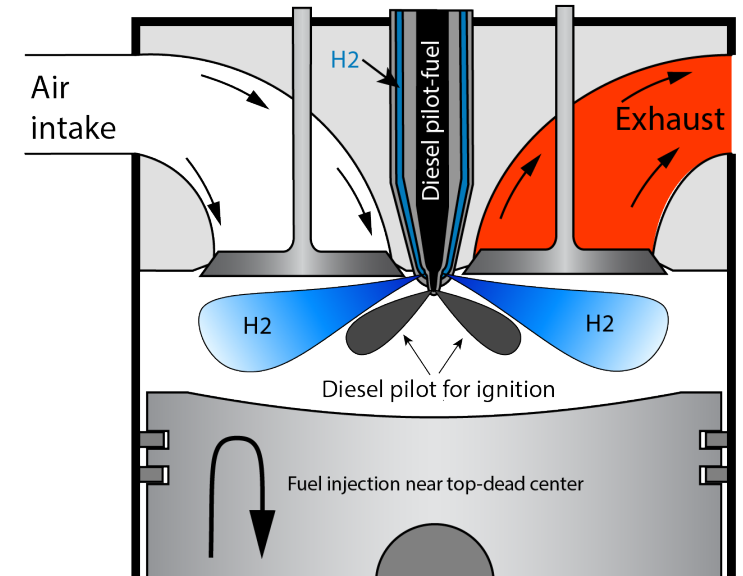


Key challenges: injection technology, abnormal combustion

“Generation 2” H2ICE technology
~2025-2030 market introduction

- + High power density, improved efficiency, transient response
- + Moderate engine modification required
- + No back-fire risk, reduced pre-ignition
- Somewhat higher NOx emission
- Residual pressure in “empty” tank
- Injection system with high durability required
- Development effort for optimization

High-pressure (100-600bar) direct-inj. Pilot-fuel or pre-chamber ignition



Key challenges: High-pressure pump, NOx, fuel compression energy

“Generation 2+” technology, best efficiency
Market readiness ~2025-2030

- + Best efficiency, power density, transient response
- + Reduced turbocharging req.,
- + Moderate engine modification required, reduced turbocharging
- + No back-fire risk, reduced pre-ignition
- Somewhat higher NOx emission
- Residual pressure in “empty” tank
- Injection system with high durability required
- Development effort for optimization

Current legislation –

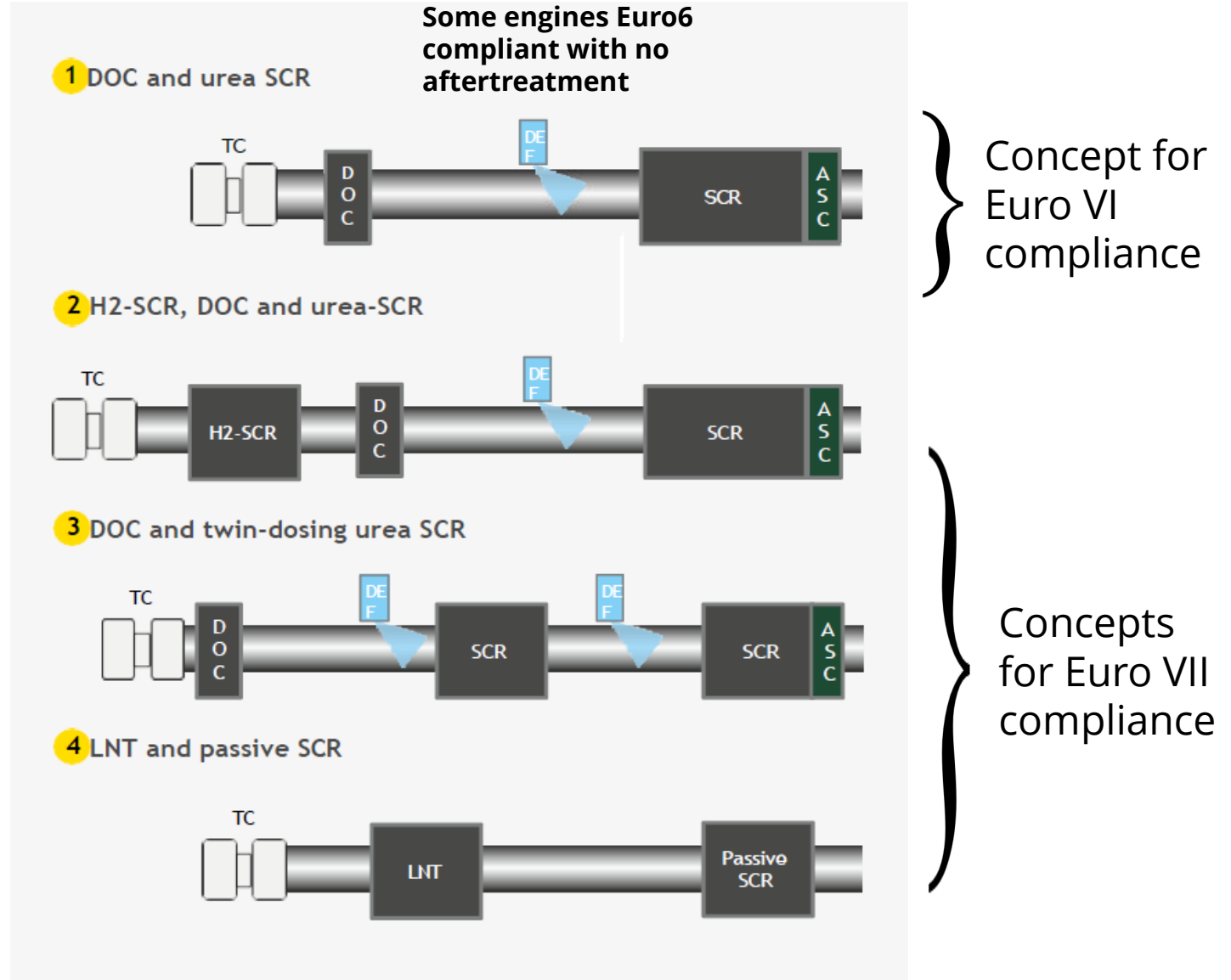
Option (1) series diesel aftertreatment is sufficient

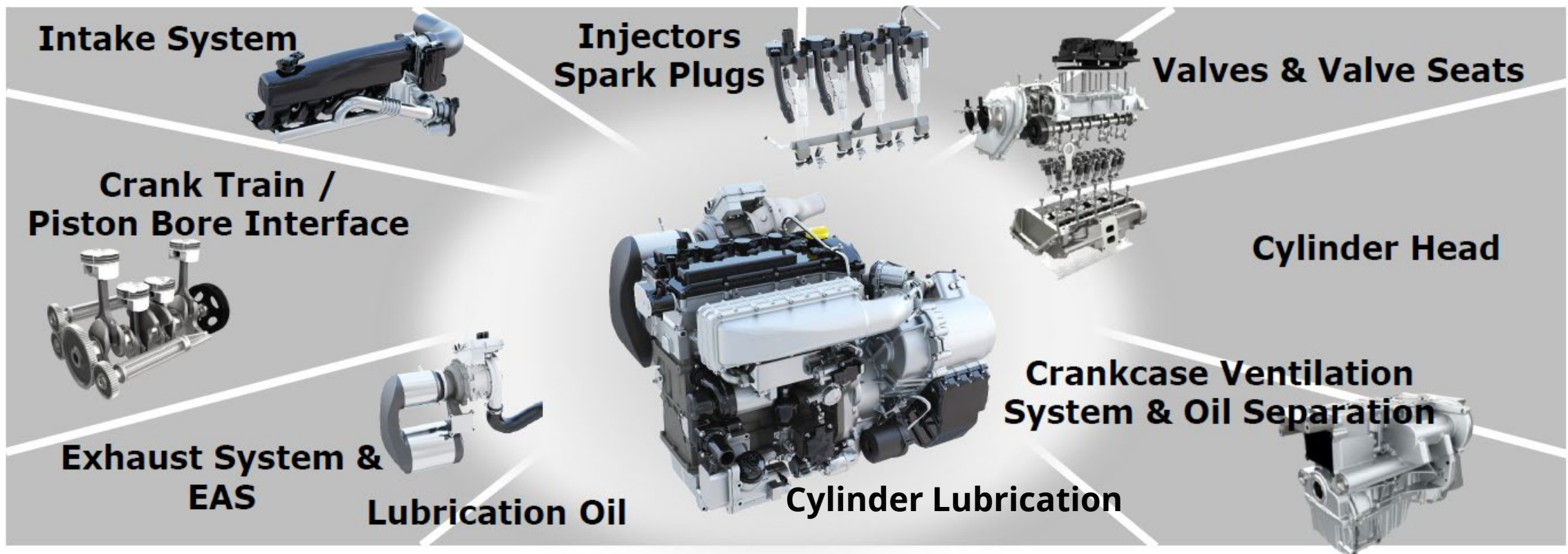
- 0.58g CO₂ / 1g NO_x emissions from DEF fluid
- Some engines compliant without aftertreatment (<0.1g/kWh in most op. points)

Future legislation (Euro VII, CARB27)

- Option (3) is ready
- (2) and (4) need further research
- **Challenges:**
 - CO₂ emission (3)
 - Potential N₂O emission (2)
 - Durability (1M miles)
 - Noble metal use for (4)

Advances in H₂ICE can reduce the need for complex aftertreatment and reduce the TCO





Graphic: courtesy of AVL

- Hardware upgrades are common with engine generation changes
- Technologies already in production are not static

Pre-competitive research opportunities:

- Material compatibility
- Injection system (durability, configuration)
- After-treatment (H₂-SCR, simplification, new catalysts)
- Lubrication
- Flame-wall interactions --> Oil consumption, durability

FUNDAMENTAL R&D GAPS SIGNIFICANT IMPACT ON PERFORMANCE AND COST

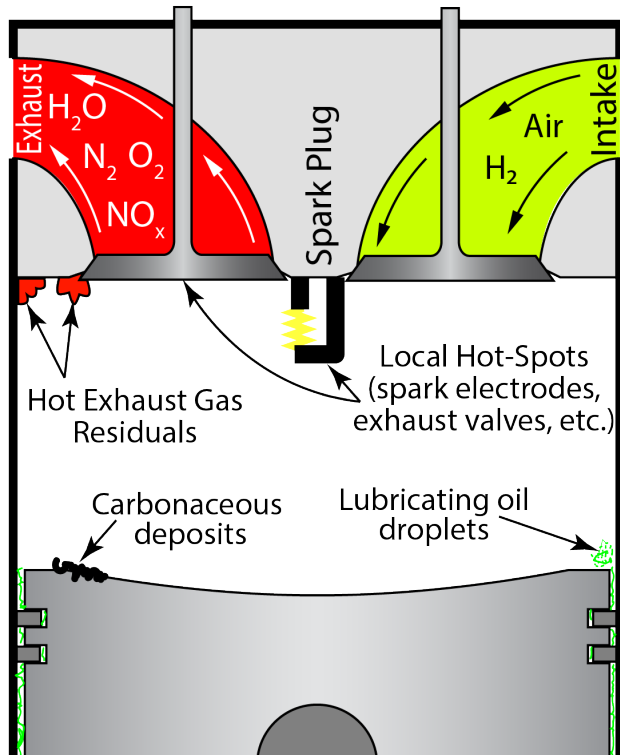


Current OEM perspective:

Urgent need to bring a H2ICE product on the market fast (PFI, modifying existing engines, efficiency is secondary)
Second generation H2ICE will be developed with focus on performance and emissions (DI, optimized configuration, etc.)

Understanding pre-ignition/knock mechanisms is key to successful mitigation

"Every engine is different"



Challenges

Preignition & knock:
mitigation and detection

Injection and mixing:
full optimization, NO_x mitigation

Flame/wall interactions
Heat-loss, material thermal stress

Predictive simulations of H2ICE
combustion process

Multi-fuel operation using single
hardware configuration

Reduced power density relative to
diesel counterparts, efficiency

NO_x emission in certain operating
points

Knowledge Gaps

Phenomenological understanding of
key pre-ignition mechanisms

In-cylinder mixing validation data
Predictive CFD modelling
Injector design guidelines

H₂ near-wall quenching/reactions
Accurate heat-loss models

Kinetics of H₂/NG/renew. diesel fuel
blends

Combustion strategies & controls

Strategies for increasing power
density & efficiency

Alternative NO_x mitigation strategies
(e.g. H₂O inj.)

Impact

Efficiency, range,
emissions, cost,
accelerated
development

Improvements to
existing products
through
component
retrofit



Retrospective Benefit-Cost Evaluation of U.S. DOE Vehicle Combustion Engine R&D Investments:

Impacts of a Cluster of Energy Technologies

May 2010

Prepared by:

Albert N. Link
Department of Economics
University of North Carolina at Greensboro
Greensboro, NC 27402

PAST RESEARCH IMPACT

- **Economic and health:** **\$931M invested** (1986-2007) yield a **\$70B** fuel and health effects cost **savings** (1995-2007) in the heavy-duty sector alone.
- **Environmental:** Reduced pollutants and CO₂.
- **Energy security:** Reduced dependence on imported oil.
- **Knowledge:**
 - A foundation for advancing more than a dozen high-impact technologies
 - Substantial patent linkage to later industry patents.

FUTURE H2ICE R&D IMPACT

- **Economic:** Increased rate of return on H₂ infrastructure investment, H₂ adoption in hard-to-abate sectors
- **Environmental:** Reduced CO₂ and pollutants.
- **Energy security:** Reduced reliance on imported minerals
- **Knowledge:** High-impact technologies rapidly adopted by industry
- **Job security and equity:** Upkeep of existing domestic manufacturing and supply chains with high added value



H2ICEs are a viable transition technology and, in certain sectors, a long-term solution

- Complementary strengths of H₂ICE and H₂FC will accelerate adoption of H₂ economy
- Robustness, short time-to-market, existing supply chain, low Pt requirements, and HD weight/packaging constraints can favor H₂ICEs
 - Power-generation w/CHP, off-road, certain vocational vehicles, potentially even long-haul trucking
- H₂ICE in small-series production by 2025 and full-scale by 2027-2030
- H₂ICE can match/exceed the efficiency of today's diesel engines
- Clear technology-neutral legislation needed to encourage development (zero-impact NOx and CO₂ emission targets)

Fundamental and applied R&D can improve new designs & technologies already in the market

- Unique H₂ properties require applied and fundamental research for optimization
 - Shorter time-to-market of improved units/components
 - Highest efficiency and lowest emissions
- Applied R&D to prove real-world performance and gain public confidence



Technical content contributors

OEMs

- Cummins Inc.
- Caterpillar Inc.
- Achates Power
- Volvo trucks
- MAN Energy Solutions
- Liebherr
- Toyota Motor Company
- Wartsila
- Daimler

Tier 1 suppliers and research centers

- Large Engine Competence Center
- AVL
- Bosch
- BorgWarner
- Mahle
- Woodward
- FVV – Association for combustion engines

Research Institutions

- Argonne National Laboratory
- Oak Ridge National Laboratory
- Southwest Research Institute
- Allianz Wasserstoffmotor – Hydrogen Engine Alliance
- Korea Advanced Institute of Science and Technology
- King Abdullah University of Science and Technology
- Chiba University
- IFP New Energy
- Technical University of Eindhoven
- University of Orleans
- Seoul National University
- Marquette University
- Indian Institute of Technology Kanpur
- State Key Laboratory of Engines, China
- STEMS, Italy
- University of Duisburg-Essen
- University of New South Wales

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• Sandia Center 8300 leadership team

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APPENDIX INDEX: SUMMARY SLIDES FOR MANY KEY H2ICE PLAYERS WORLDWIDE



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- 59. IFP New Energy
- 60. King-Abdullah University of Science and Technology
- 61. Technical University of Eindhoven
- 62. Seoul National University
- 63. Marquette University
- 64. Indian Institute of Technology Kanpur
- 65. State Key Laboratory of Engines, China
- 66. Prinoth/FPT snow groomer
- 67. Italian National Research Council
- 68. University of New South Wales
- 69. Chiba University
- 70. Korean Advanced Institute of Science and Technology
- 71. German Research Foundation – Research Unit 2687
- 72. Sandia National Laboratories

Legend:

Green: Directly contributed material;

Blue: Adapted from directly provided material

Orange: Composed of publicly available information



Cummins Hydrogen Internal Combustion Engines (ICE)

State of development

- Announced testing H2-ICE in July 2021
- Reached development goals for the B6.7H, near the goals for the X15H
- [Demonstrator vehicles](#), [MOU](#) with TATA in India, early adopter letters of intent ([on-road](#), [agro](#))

Advantages of H2ICE

- Mass production possible within the decade
- Initial cost, drop-in replacement, maintenance and supply chain
- Complementary with FC development
- Proven technology, multiplying decarbonization options

Investment barriers

- High R&D cost to deploy technology
- Confidence in market volume to sustain investment
- Risk of regional ICE bans

Market barriers

- Accessibility and cost of H2 fuel

Technical challenges:

- Abnormal combustion (pre-ignition, knock, backfire)
- Transient response and turbocharging
- Fuel system reliability

Areas where government support would help:

- Fundamental H2 combustion in general
- Understanding root causes and mitigation for abnormal combustion
- Design of engine components (piston rings, lubrication, crankcase ventilation, air handling)



Engine	B6.7H	X10H	X15H
Displacement	6.7L	9.9L	14.5L
Power	170 – 215 kW 230 – 290 hp	220 – 280 kW 300 – 375 hp	300 – 400 kW 400 – 530 hp
Torque	900 – 1100 Nm 650 – 810 ft lb	1300 – 2000 Nm 950 – 1500 ft lb	2100 – 2600 Nm 1550 – 1900 ft lb
Emission Level	Euro VII China NS VII EPA 2027 Stage V T4F		
Architecture	Pent Roof Cylinder Head, Tumble Combustion, Spark Ignited, Direct Inject, Lean Burn, SCR Aftertreatment		

Applications

North America	MD Truck Transit Hybrid MD Regional Haul Hybrid	Transit Medium Duty HD Regional Haul Hybrid Vocational	Regional Haul Long Haul
Europe	MD Truck Inter-Urban Bus	Regional Haul Coach	Regional Haul Long Haul
China	Special Purpose Vehicle	Under Investigation	Regional Haul Long Haul
India	Regional Haul		
Off Highway	Excavators Ports & Distribution Ground Support Equipment Terminal Tractors Marine	Under Investigation	Excavator Wheel Loader Agriculture Air Compressor

Deployment schedule

2022	2023	2024	2025	2026	2027	2028	2029
R&D			Field Trials			Production scale-up	
Product Development							



Hydrogen-based Caterpillar Power Generation Solutions



- Renewable Hydrogen is one of several fuels Caterpillar's customers are considering to help reduce their carbon footprint.
- Caterpillar currently offers reciprocating engines and turbines capable of running on hydrogen and hydrogen blends.
 - Hydrogen (by volume) : 0 – 60% mixtures (engines derated as appropriate)
 - Deep performance simulation expertise (hydrogen flame propagation for combustion analysis)
 - Single and Multi-Cylinder engine performance demonstrations
- Many factors influence if and when hydrogen achieves critical mass -- infrastructure, cost, regulations, safety, storage, packaging, governmental policy & incentives, etc.
 - We expect future improvements will be made on infrastructure, storage and transportation to lower project costs.
- Caterpillar continues to participate and invest in hydrogen technology and is well positioned to serve customers as the timing and dynamics of renewable hydrogen production, distribution and storage gain speed.

Key barriers to H2 ICE development and deployment

- Economic viability of H₂ as commercial transportation fuel.
- Retail H₂ needs to be below \$5/kg to be a viable fuel.
- Infrastructure development and agreed industry standards to pressure, fueling port configuration, unified H₂ specification for automotive use....
- Recognition by regulators that blanket ban on IC (as given in CA) need to exclude IC engine that uses carbon free fuels.

Motivation for pursuing H2 ICEs

- A minor technical leap brings a large impact to drastically decarbonize transportation
- The well established workforce, raw materials, supplies, service network,...
- H₂-IC engine do not have raw materials and recycling concerns as batteries do.

In-house testing of DD16 engine Presented at 21st Century Truck meeting

- 44.5% efficiency, Ultra-Low NO_x standard achieved with 2020 production ATS
- No specific hardware issues after 450h of operation

① Main design changes and engine adaption to realize H₂-ICE with state-of-the-art spark ignition technology**Ignition system**

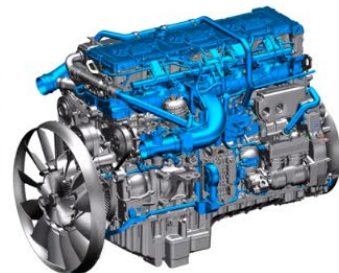
- Sparkplugs, ignition coils, adapted cylinder head & cover

Hydrogen fuel and injection system

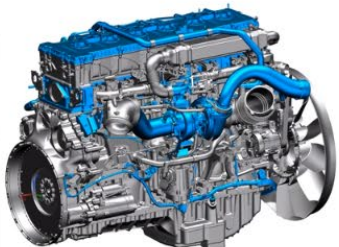
- Gas regulator, PFI-valves, common rail, vent line

ECU, software and controls

- H₂-ICE specific requirements (e.g. knock sensors)

**Turbocharger & air handling incl. EGR and fuel mixing**

- Specific matching of turbocharger and exhaust system
- Adapted air path incl. EGR mixing and port-fuel injection

**Piston**

- Layout of combustion bowl, lower compression ratio
- Aluminum piston, specific rings/pin

① Key characteristics of spark-ignited H₂-ICE vs. Diesel combustion regime:

- + Ultra low NO_x emissions with less complex ATS
- + Spark ignition eliminates pilot injection of carbon-based fuel (e.g. Diesel/HPDI), improved ZEV/CO₂ criterion (CO₂) in comparison to dual-fuel engine
- + Significantly lower injection pressure and lower peak cylinder pressure
- Engine knocking requires lower compression ratio
→ Lower cycle efficiency than Diesel
- Limited mean effective pressure/torque due to knocking & risk of pre-ignition
→ Trend towards larger displacement of H₂-ICE

High commonality with existing engines means fast-to-market, high reliability, and minimal impact to US economy

The targeted applications:

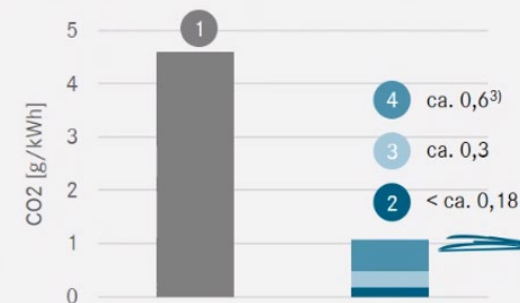
- Trucks
- Locomotives, ocean going ships, any application where diesel engine is today running on high load and high uptime

Key areas where government support of pre-competitive R&D would help.

- In addition, we need to have a common vision on decarbonizing commercial vehicle transportation and recognition that pure battery trucks will not cover all segments.
- Incentives and policies already included in IRA do not fully induce H₂-IC or fuel cell development.
- In addition, we ask EPA/CARB to reduce complex regulatory framework and enable H₂-IC reduced certification and OBD to enable fast to market approach.

Technical view: Sources of CO₂, when measuring at the tailpipe

- 1 CO₂ ambient air (ca. 416 ppm)
- 2 Carbon compounds in fuel (e.g. <100 ppm CH₄)¹⁾
- 3 Lube oil consumption (typ. value 0,05% of diesel²⁾ consumption)
- 4 Carbon content urea (CH₄N₂O)



TP CO₂ from all engine sources is ~ 1 g/kWh – Less than contribution from ambient air

1) acc. to ISO 14687 type I grade D 2) H₂ values still need to be assessed in detail
3) based on PoC engine results with NO_x raw < ca. 1g/kWh

Volvo transition to fossil free Heavy Duty transport solutions

V O L V O

Long-term ambition: 100% Safe, Net zero CO₂ and more productive

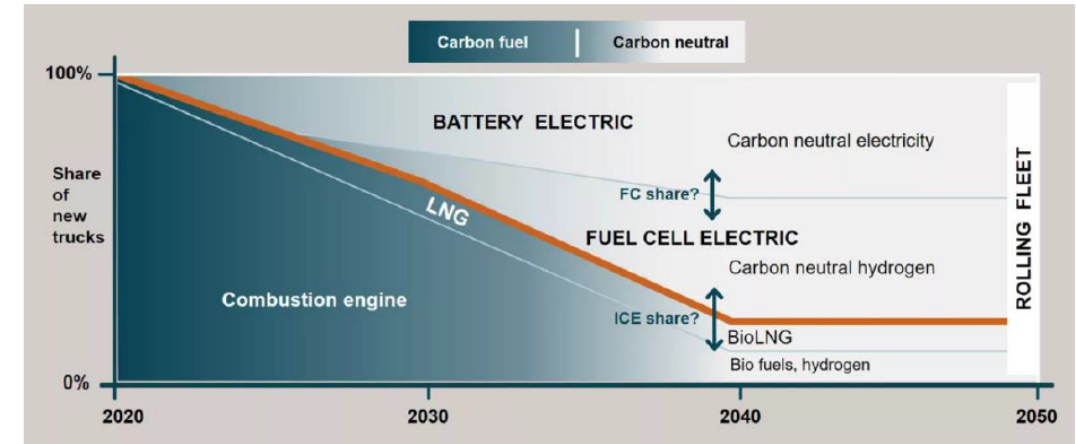
<https://www.volvogroup.com/en/future-of-transportation/going-fossil-free.html>

We support the Paris agreement and the European Union Green Deal with the aim to be climate-neutral by 2050 by a 100% fossil-free offer 2040 .

Volvo group commit to the Science-based target initiative (SBTi), to keep global warming to max 1,5° C.

We focus on three major propulsion technologies to meet climate-neutrality:

- 1) Battery and 2) Fuel cell electric vehicle, and 3) Combustion engines with hydrogen and renewable fuels.
- + Hard to abate transport-missions requires both hydrogen and more energy dense supply/fuel, due to vehicle volume limit.
- For this segment we focus bio/e-Methane ICE products for on and off-road truck and construction machinery.



3) Hydrogen ICE development in particular:

- Example of key development challenges are:
 - Stable combustion and reasonable thermal efficiency in combination with achieving true “zero-emission”
- A key advantage in relation to electric propulsion solutions is a lower production cost and less use of scarce minerals
- We are currently in an AE phase of H₂-ICE, evaluating port-fuel injection and direct (low and high pressure) hydrogen injection with spark-plug or CI pilot-fuel as ignition source
- We are and will explore the practical implications of Truck and off-road operation with these concept engines
- Important research questions:
 - Combustion: Mixing of light fuel gas into a heavy gas , velocity field at critical flow conditions and NOx emissions (for further details: see page 2)
 - EATS for H₂-ICE exhaust
 - Hydrogen storage and safety, metal hydrogen embrittlement and durability of new components

H₂-ICE research areas

Fuel injector supplier hardware (FIE) and know-how (Often "black-box")

P_{fuel}

FIE

Internal geometry

- pressure drop
- temperature change
- valve-seat flow
- nozzle cap flow
- hole flow

Visible nozzle exit

Fuel pressure (P_{fuel})

Visible nozzle exit

- # holes
- Hole configuration
- Provided info, i.e., hole direction, hole flow area

Massflow

- Rate
- Variations

Velocity at exit

- Magnitude
- Variations

Momentum / Kinetic energy

Jet geometry

- Cone angle
- Tip penetration

Velocity field *

- Spatial distribution
- Variations

Jet collapse / separation

- Conditions

Shockwaves

- Detection
- Nature
- Importance

Mixing

- Air entrainment
- H₂ concentration

Turbulence

- Edge wrinkling
- Production
- Dissipation

Jet interactions

- Jet-wall
- Jet-jet
- Wall shapes

Phase 1: Non-reacting

Phase 2: Ignition & combustion

Ignition and Combustion

- mixture preparation at hot conditions
- ignition methods & ignition event
- hot surface ignition (pre-ignition)
- end-gas ignition & knock
- flame propagation
- pre-mixed vs diffusion-controlled combustion
- formation of nitrogen oxide emissions (NO_x)

* Of special interest for CFD validation

Main Research Question:

Mixing of light fuel gas into a heavy gas ?

Research methods

- Combustion vessel (spray-chamber)
- Single-cylinder engine (SCE)
- Fully optical SCE
- H₂ jet optical methods
 - Schlieren shadowgraph
 - Planar Laser Induced Fluorescence (PLIF)
 - Raman
 - Particle Image Velocimetry (PIV)
- Other measurement methods
- Computational Fluid Dynamics (CFD) models and methods

Jet(s)

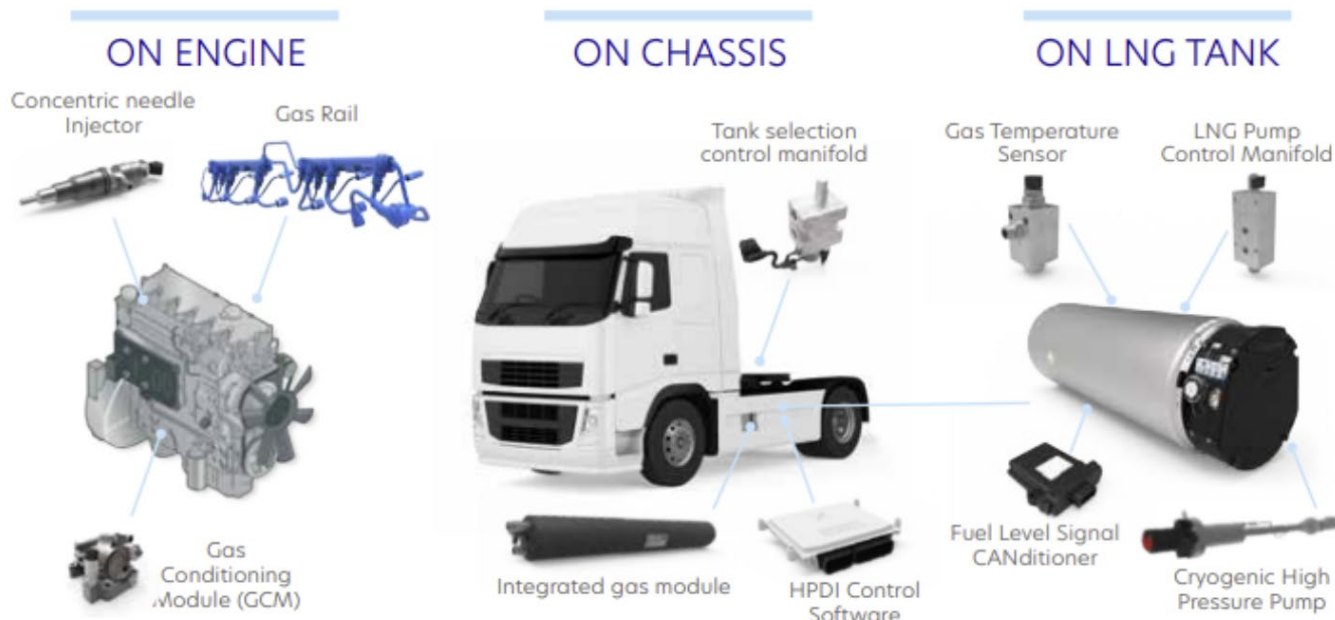
2022 demonstrator semi-truck



H2 HPDI system demonstrator presented in 2022

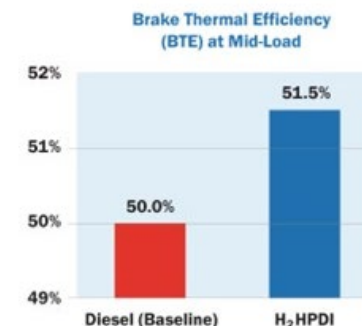
- 20% gain in power, 15% in torque
- 5-10% efficiency gain
- Diesel pilot consumption 2-6%

Developed from LNG system with thousands of units readily operational



Source: <https://www.westport-hpdi.com>

Results of H2-HPDI testing with SCANIA



The engine test results from the Scania 13-Litre CBE platform running with Westport's H₂ HPDI fuel system demonstrates even higher efficiency than the already super-efficient diesel engine.

Modified Scania 13L 6-cylinder engine using Westport HPDI system:

- Minimal engine modifications
- Euro 7 and EPA27 compatible (diesel and HPDI versions)
- Improved efficiency
- Highway-cruise load efficiency of 48.7% in HPDI operation
- High low-end torque (28bar BMEP at 900rpm)

Source: <https://investors.wfsinc.com/news/news-details/2022/Westport-and-Scania-Announce-Impressive-Test-Results-of-H-HPDI-Fuel-System-for-Heavy-Duty-Transport/default.aspx>



MAN truck (VW group, truck and bus manufacturer)

- First prototype engine testing in 2021
- Test-vehicles to be transferred to first customers in 2024. Similar durability as current diesel engines predicted by 2030.
- Serial production in 2025.
- Likely a PFI product, need to increase the engine displacement to reduce power loss (16.8L instead of 15.2L)
- 80% parts commonality

Demo vehicle with H2ICE



Sources:

[Link1](#)

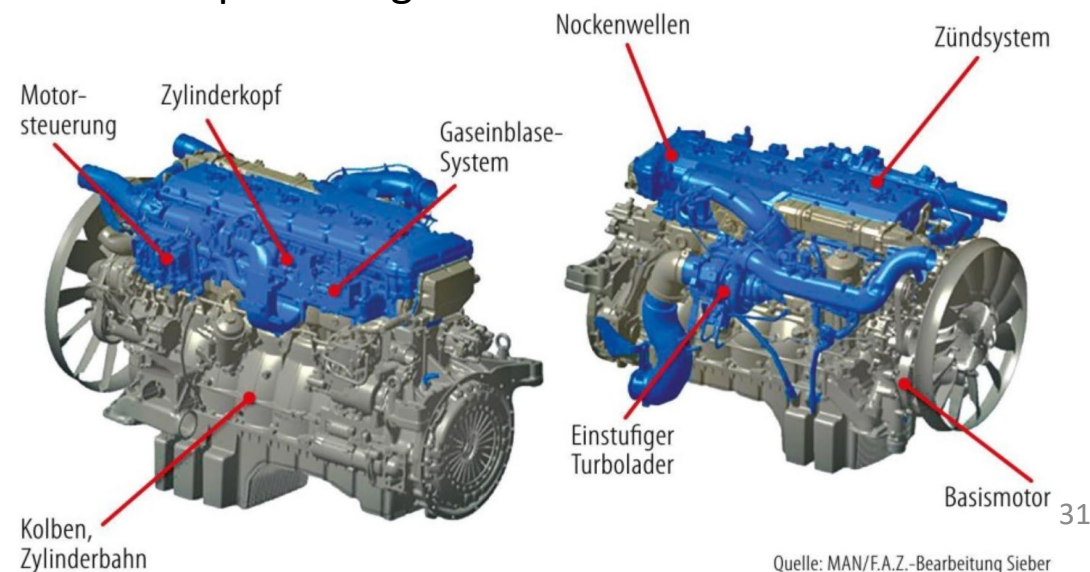
[Link2](#)

[Link3](#)

MAN Truck&Bus is developing H2ICE and H2FC in parallel HYDROGEN TECHNOLOGIES – POWERED BY MAN



Required engine modifications in blue



Quelle: MAN/F.A.Z.-Bearbeitung Sieber



£100M investment into H2ICE 2023 market entry

- 2020: Investment in FC technology (demo excavator)
- 2021: Announcement of £100M into H2ICE, claiming durability issues and cost of FC technology as fuel stopper.
- 2022: Demonstrator vehicles, first 100 H2ICEs produced. Single engine type currently H2 capable

JCB 448 AB H2 engine

- Developed from a baseline diesel platform
- Advanced turbocharging, new induction system, spark ignition
- Contradicting information about injection system
- Same power/torque performance as the baseline diesel engine
- Performance data not publicly available. Claims lower raw NOx emission than EU Stage V norm.

JCB 448 4.8L 4-cyl. H2 engine



JCB C542 Load-all H2 demonstrator



JCB H2 field re-fueling truck



Source:
JCB webpage,
accessed 1/10/2023
[Link 1](#)
[Link 2](#)
[Link 3](#)

LIEBHERR

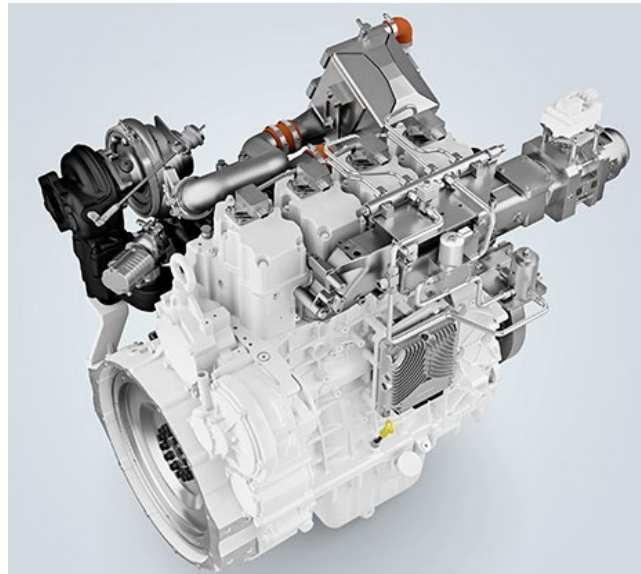
H2ICE products under development for construction equipment applications

- PFI and DI technologies
- Special H2 injector development, no lubrication needed
- Won Bauma 2022 innovation award for prototype H2ICE excavator
- Engines offer comparable equipment performance to diesel-powered products

Liebherr 9XX H2 50ton excavator



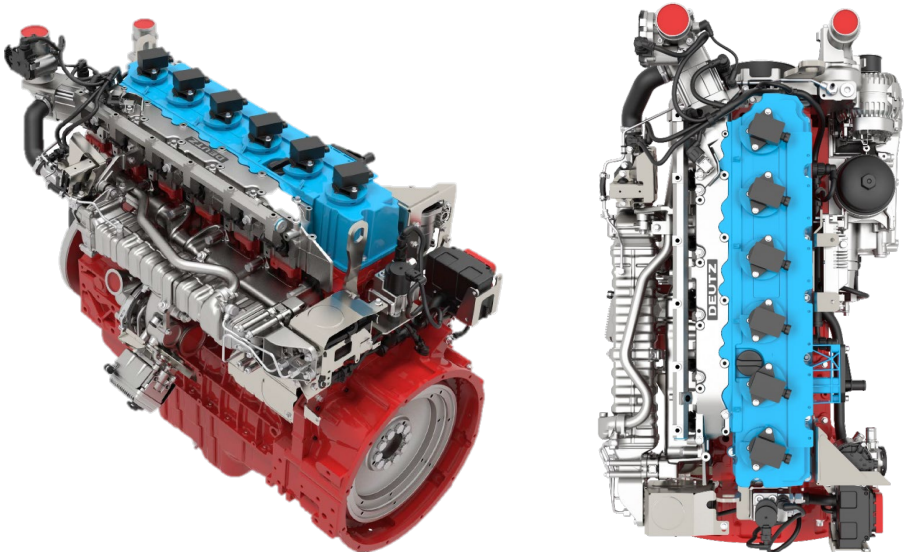
Liebherr H2DI injectors and 964 9L DI H2ICE



Liebherr 966 13.5L PFI H2ICE



DEUTZ TCG 7.8 Hydrogen ICE



Specification	
Cylinder / Displacement	6 in-line / 7,755l
Bore / Stroke	110 / 136mm
Max. Power	220 kW @ 2200rpm
Max. Torque	1000 Nm @ 1000 – 1600rpm
Architecture	Port Fuel Injection
Emission Level	EU Stage V, EU Zero Emission ¹
Exhaust Aftertreatment	SCR only ²

1. <1 g CO₂/kWh

2. necessary for high power density and dynamic

PROJECT

2021



1st Engine on Test Bench ✓

2022



Pilot Operation Genset ✓

2023

Product Industrialization

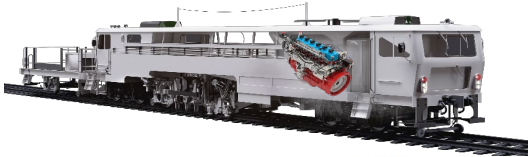
2024

SoP 

H₂DEUTZ
HYDROGEN TECHNOLOGY

FIELD TEST

Rail



Truck



Hydraulic
Excavator



First engine conversion kits in 2017

Current technology:

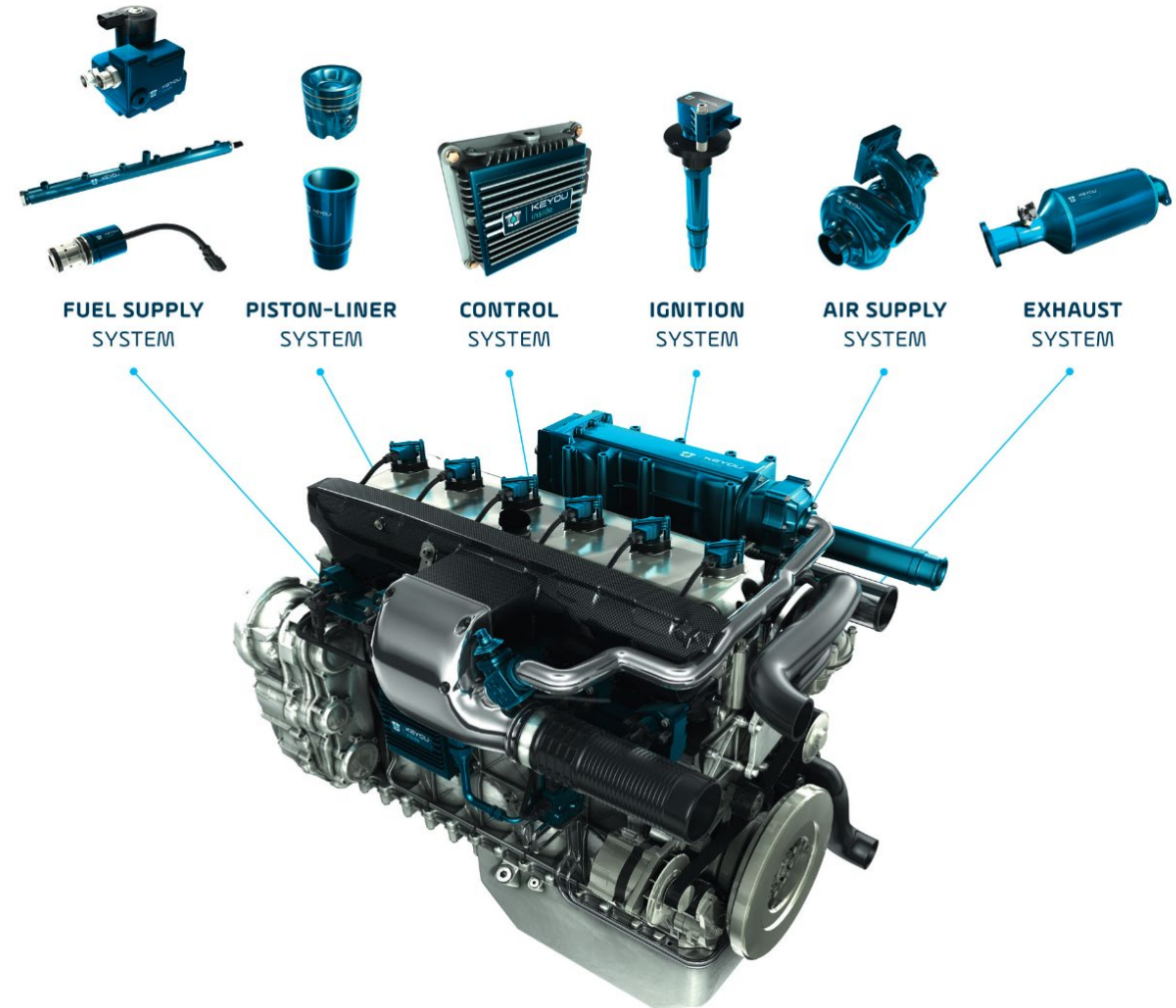
- On the base of 7.8L Deutz 6-cyl. engine
- 44.5% peak BTE, 210kW power
- Several demonstrator vehicles on the road
- **No aftertreatment needed for Euro6**

Series production (new engines) scheduled for 2024

Demonstrator vehicles



Keyou technology for conversion of diesel engines



Large-bore hydrogen engines



Many years of experience with H₂-containing special gases in large-bore internal combustion engines. In recent years the focus shifted to hydrogen addition to natural gas engines and pure hydrogen operation.

Target applications: power generation, marine, locomotive

Recent accomplishments

- Hydrogen operation in single cylinder research engines (displacement volumes between 3 liters and 6 liters) up to 20+ bar IMEP with Port fuel injection
- Medium pressure direct injection
- Lean mixtures w/ and w/o low pressure EGR

Hydrogen addition (30 v%) to natural gas and pure hydrogen operation in multicylinder engine (~ 6 liters/cylinder)

Investigation of combustion abnormalities and impact of lubricant formulations

Investigation of spark ignition and diesel pilot injection concepts

Investigation of fuel injection concepts

Investigation of air handling and turbocharging

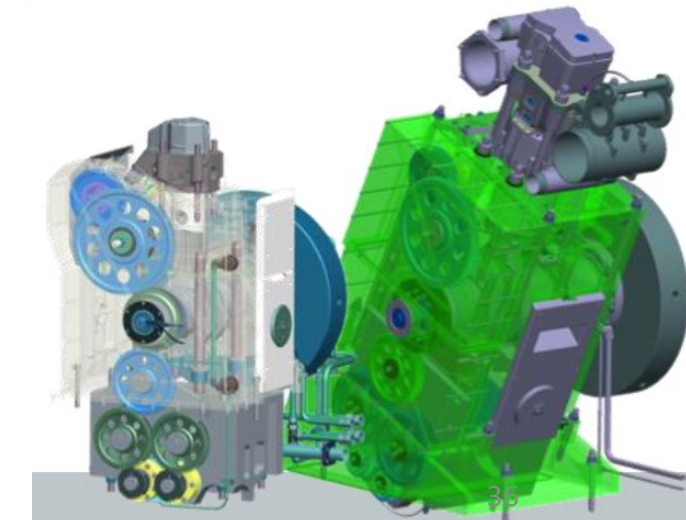
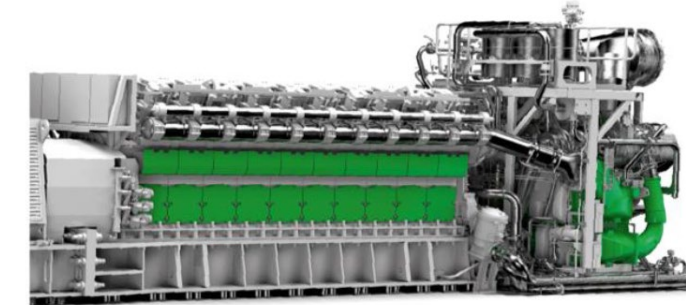
3D CFD simulation of mixture formation and combustion

Current research

- Increase of power density to be competitive with existing power plants (> 24 bar BMEP)
- Path to zero-impact emissions by combining in-cylinder measures with aftertreatment technology
- Optimization of lubricant & additives for hydrogen operation (impact of preignition, lubricant dilution, lubricant lifetime)
- Optimization of tribology system and lube oil consumption
- Deployment of latest direct injection technology
- Mitigation measures for hydrogen pre-ignition

Key challenges:

- Turbocharging technology
- High-pressure injection technology
- Hydrogen embrittlement / material availability



Achates Power (“API”) – Hydrogen Opposed Piston Engine (“OPE”)

Competitive Advantage / Motivation:

- Several features of the OP engine, most notably an enhanced ability to control trapped conditions, make it well suited for stable and efficient compression ignition of low reactive fuels. API has already demonstrated this with gasoline and alcohols.
- Because hydrogen will be expensive, optimizing efficiency will enable more rapid market adoption

Key Barriers:

- Develop compression ignition (high loads), pilot assisted compression ignition (mid loads) and spark ignition (low loads) combustion modes
- Develop controls to transition between combustion modes.
- Develop combustion and aftertreatment strategies to meet ultralow tailpipe NO_x limits (already demonstrated with diesel and only conventional aftertreatment systems (no additional control technology))

Target Customers:

- Long-haul commercial vehicles. This application segment is challenging for other zero emissions powertrains due to long routes, durability requirements (million mile), and short payback period (18 months)

achatesPOWER™

Past, Current, Planned Activities:

- | | |
|--|---------------------|
| • Developed robust OPE hardware designs | COMPLETE |
| • Efficient and stable gasoline compression ignition | COMPLETE |
| • Efficient and stable alcohol compression ignition | COMPLETE |
| • Combustion CFD models for efficient H2 OPE | IN PROCESS |
| • Single cylinder H2 OPE combustion development | PLANNED 2023 |
| • Multi-cylinder H2 OPE combustion development | PENDING 2024 |
| • Formed the Hydrogen Opposed Piston Engine Working Group. Each quarter, researchers from 20+ organizations around the world review relevant research projects. www.h-ope-wg.com | ON-GOING |

Deployment Schedule:

- Multi-fuel commercial vehicle OP engine can be production ready for Model Year 2030. This engine platform will likely launch with diesel first but will be capable of operating with hydrogen fuel.
- A hydrogen version of the platform can be ready for production sometime after 2031.

Key Areas of Government Support for Pre-Competitive R&D:

- Develop capable and efficient direct injectors
- Develop capable fuel systems, including storage and effective pressurization
- Develop basic combustion modes and control strategies



HYDROGEN OPPOSED-PISTON ENGINE WORKING GROUP

www.h-ope-wg.com



About Us



Purpose



Latest Information

“An opposed-piston engine with hydrogen combustion could well provide the best known thermal efficiency from a reciprocating engine, with the potential to match the in-vehicle efficiency of a hydrogen fuel cell. If so, it is a valuable potential option for long haul transit in our quest for sustainable transportation.”

– James Turner, MEng, PhD, CEng, FIMechE, FSAE Professor of Mechanical Engineering
Clean Combustion Research Center, King Abdullah University of Science and Technology

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aramco



BE THE DIFFERENCE.



University of Michigan



Powertrain
Control
Laboratory



SUPER TURBO
TECHNOLOGIES



Stanadyne



DI2S
Duret Innovative 2-Stroke
Consulting
& Training

Department of
AUTOMOTIVE ENGINEERING
Clemson University

UC RIVERSIDE College of Engineering –
Center for Environmental
Research and Technology

MAHLE
Powertrain

جامعة الملك عبدالله
للعلوم والتقنية
King Abdullah University of
Science and Technology

CHALMERS
UNIVERSITY OF TECHNOLOGY

10 TECHNOLOGIES
disruptive solutions for a bright future

DAF H2ICE HD-truck received 2022 International Truck of the Year award

- DAF is part of PACCAR
- The demonstration truck used PACCAR MX13 engine converted for use with H₂
- Development in cooperation with TNO Automotive – a Dutch engine development and consulting company

PRESS RELEASE

Lyon November 17th, 2021

DAF'S XF HYDROGEN WINS 2022 TRUCK INNOVATION AWARD

DAF's XF Hydrogen - a prototype of a hydrogen-fuelled heavy-duty truck with an internal combustion engine - has won the 2022 Truck Innovation Award.

The prestigious award was handed over to Harry Wolters, President of DAF Trucks, during the press day of the Solutrans Commercial Vehicle and Bodybuilder Show in Lyon, France.



The Truck Innovation Award - which acknowledges the enormous technological changes and energy transition taking place within the automotive sector - has been awarded by the International Truck of the Year (IToY) jury, a group of 25 commercial vehicle editors and senior journalists, representing major trucking magazines from Europe and South Africa.

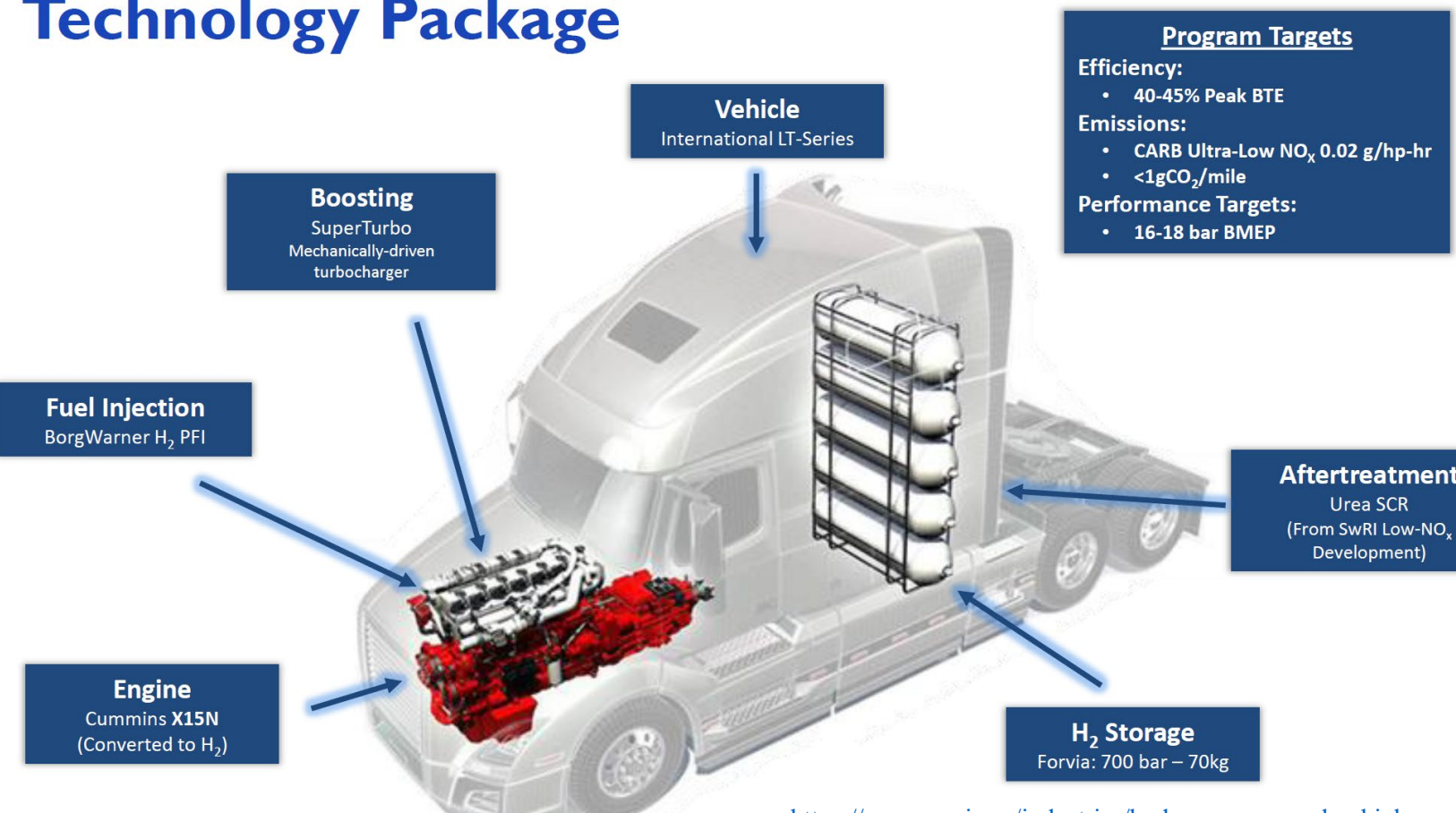
With a winning score of 92 votes, DAF's XF Hydrogen fought off the competition from Mercedes-Benz's GenH2 Truck, a fuel cell powered long-haul vehicle.

The IToY jury praised the handling characteristics, seamless acceleration and user-friendly human-machine interface (HMI) of the prototype. The HMI is similarly a feature of DAF's New Generation range, which has also been designed for future zero-emission powertrains.

H2ICE consortium overview

Demonstrator vehicle by 2024

Technology Package



Develop and build a Class 8 H₂-ICE vehicle demonstrator with PEMS to show:

- Near-zero CO₂ and PM
- Ultra-low NO_x
- Provide opportunities for trade show appearances and ride-and-drive events to show H₂-ICE is a realistic pathway for decarbonization
- **Demonstrate that CURRENT technology is capable of “Zero-Emissions”**

Ensure place for H₂-ICE among accepted ZEV technologies

Expected membership roster



<https://www.swri.org/industries/hydrogen-powered-vehicles>

<https://www.swri.org/press-release/swri-launches-joint-industry-program-develop-hydrogen>

POWERTRAIN ENGINEERING

40
swri.org

H2 ICE development and demonstration program

Key barriers for H2 ICE development and deployment:

- Unclear legislation creates uncertainty for OEM investments: ICE-bans, EURO7, CO2 emission limits
- Number of re-fueling stations

Past accomplishments, present activities

- Currently, more than 15 scientists, PhDs and technicians working on H2ICE projects
- Over €20M public and industry funding over 7 ongoing projects
- Three dedicated test rigs for H2ICE
- Developed a medium-duty truck H2ICE demonstration vehicle, participated in engine development for a light-duty H2ICE van.

Competitive technologies and motivation for pursuing H2 ICE

- FC vehicles – ICE believed to have TCO, durability and mid-to-high load efficiency advantages
- H2ICE can save the domestic supply chain. No reliance on Asia for batteries, FC, rare earths
- Synergies with FC on H2 on-board storage

Targeted applications and customers

- Light commercial vehicles, Medium and Heavy Duty. Offroad, Genset, marine, Rail. Racing

Deployment schedule

- Commercial availability expected in 2024, depending on OEMs.

Key needs for government support of pre-competitive R&D

- Support of H2ICE development and demonstration
- H2 infrastructure to decrease H2 cost
- Connection with green H2, for example through pipelines ([link](#))

Government funding



Project partners



Developed demonstrator vehicle



Hydrogen Combustion

Can be an attractive path to CO₂ neutral transportation for PC, CV and Off-road

Historical limitations of H₂ICE are disappearing:

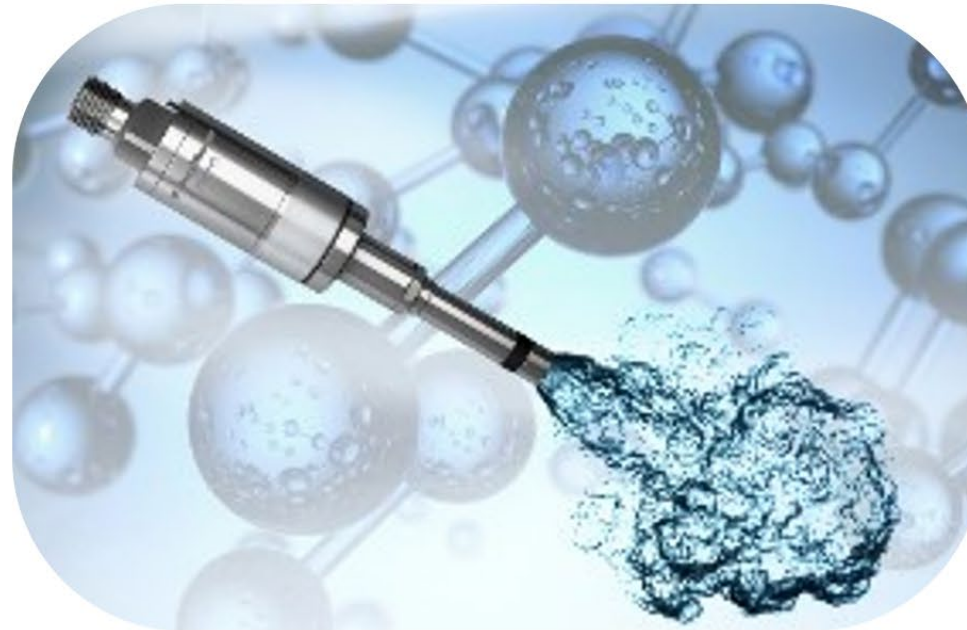
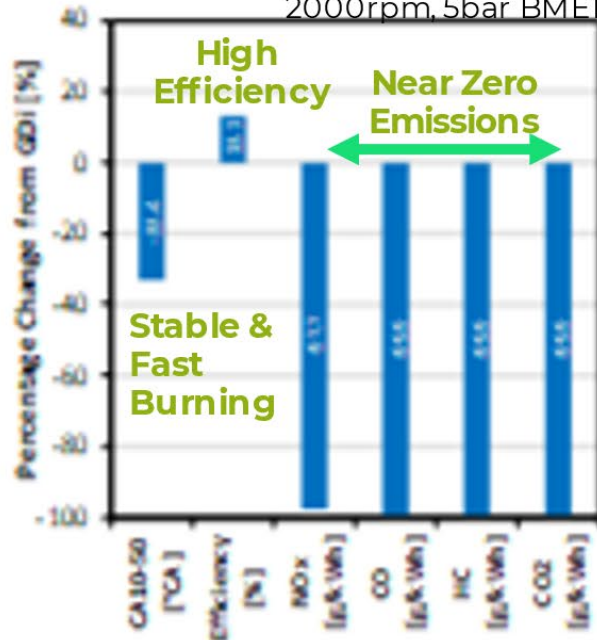
- Motivation → Push for Zero CO₂ solutions
- H₂ supply infrastructure → USA/EU/Asia support
- Combustion control → Injection system
- Broad industry commitments

BW H₂ system

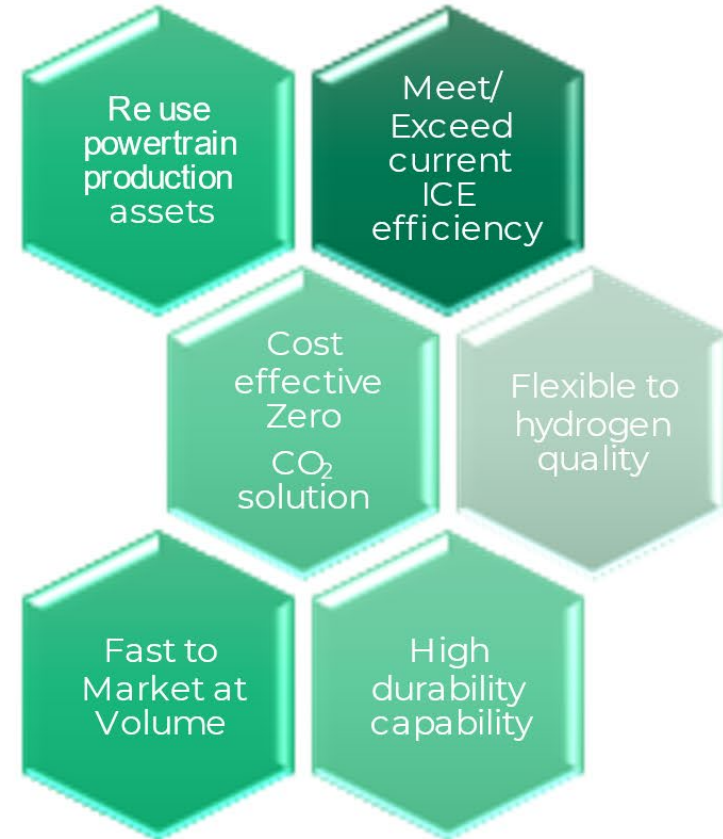
H₂, Water & SCR Injectors, Rail, Actuators & Sensors, ECU & SW

1.5L 4CYL PERFORMANCE

2000rpm, 5bar BMEP



BW has Injection systems for DI and PFI applications available which address the need for stable and high efficiency combustion



H2 Engine Research & Development Topics

MD/HD/OR Applications

**Currently, more than 130 worldwide OEMs
are interested in, planning or running H₂ engine R&D
projects w/ Bosch**

- **Your short-list of key barriers to H₂ ICE development and deployment**
 - Robustness of H₂ Direct Injection Injector over lifetime (for Commercial Vehicle market)
 - Competitive TCO compared to alternative CO₂-free powertrain solutions, strongly depending on H₂ price @refueling stations and price for electricity @charging stations
 - Availability of H₂-Infrastructure (for all H₂ powertrain options)
 - Acceptance as CO₂-free powertrain solution by authorities (Minor emission of CO₂ und other emissions, as compared to FC)
 - Acceptance as ZEV powertrain solution by authorities (ZEV here is related to criteria pollutant emissions, take approach e.g. like CARB does for LEV IV LD PHEV)
- **A description of your past accomplishments and current activities**
 - Development of H₂ PFI and DI systems, successfully tested on engine test bench, design concept for DI-injector available
 - Development of H₂ FIE, other H₂ engine components, control units and software solutions towards series intent design ongoing, various R+D - / pre-series-activities with OEM globally
- **Competitive technologies and motivation for pursuing H₂ ICEs (highlighting both H₂ICE challenges and advantages)**
 - Bosch sees H₂ engine as powertrain technology that is complementary to BEV and FC
 - Advantage of H₂ engine: lower initial vehicle cost, max re-use of existing manufacturing processes / plants and service-concepts @ OEM, carry over of existing engine and vehicle architectures, end-customer acceptance, robust technology with limited degree of novelty (compared to BEV and FC), robust against lower H₂-quality and/or contamination, possibility to retrofit existing Gasoline or Diesel-based powertrains, high efficiency especially under high load
- **The targeted application or customer**
 - All applications, especially applications with high load over long period, applications which request long mileage/quick refueling, applications with high robustness requirements e.g. harsh ambient conditions, cost-sensitive markets, markets with needs for simple service activities/ offering limited-service infrastructure
 - Examples: CV HD-LH globally, OHW-applications, markets: Globally, strong/emerging interests in India/ China/EU/US (due to low initial vehicle cost)
- **An estimate of deployment schedule**
 - Possible SOPs
 - PFI: 2024 (planned)
 - DI: 2026 (possible, dependent on OEM schedule)
- **Key areas where government support of pre-competitive R&D would help**
 - Pre-competitive R&D for H₂ engine component developments (e.g. H₂ FIE, boosting systems, low cost H₂ tank systems)
 - High-efficiency H₂ engine R&D
 - R&D for improved and alternative exhaust aftertreatment solutions
 - Support for H₂ engine vehicle demo fleet testing
 - Support drafting of technology-open regulation (see above)

H2 Engine Research & Development Topics

LD Applications

- **Your short-list of key barriers to H2 ICE development and deployment**
 - Robustness of H2 Direct Injection Injector over lifetime
 - Increase fuel efficiency on engine and powertrain level, e.g. via R&D for H2 dedicated hybrid engines
 - Competitive TCO compared to alternative CO2-free powertrain solutions, strongly depending on H2 price @refueling stations and price for electricity @charging stations
 - Availability of H2-Infrastructure (for all H2 powertrain options)
 - Acceptance as CO2-free powertrain solution by authorities (Minor emission of CO2 und other emissions, as compared to FC)
 - Acceptance as ZEV powertrain solution by authorities (ZEV here is related to criteria pollutant emissions, take approach e.g. like CARB does for LEV IV LD PHEV)
- **A description of your past accomplishments and current activities**
 - Development of H2 PFI and DI systems, successfully tested on engine test bench, design concept for DI-injector available
 - Development of H2 FIE, other H2 engine components, control units and software solutions towards series intent design ongoing, various R+D - / pre-series-activities with OEM globally
- **Competitive technologies and motivation for pursuing H2 ICEs (highlighting both H2ICE challenges and advantages)**
 - Bosch sees H2 engine as powertrain technology that is complementary to BEV and FC
 - Advantage of H2 engine: lower initial vehicle cost, max re-use of existing manufacturing processes / plants and service-concepts @ OEM, carry over of existing engine and vehicle architectures, end-customer acceptance, robust technology with limited degree of novelty (compared to BEV and FC), robust against lower H2-quality and/or contamination, possibility to retrofit existing Gasoline or Diesel-based powertrains, high efficiency especially under high load
 - Very high volumetric and gravimetric power density feasible
- **The targeted application or customer**
 - applications with high load, applications which request high mileage/quick refueling, applications with high robustness requirements e.g. harsh ambient conditions, cost-sensitive markets, markets with needs for simple service activities/ offering limited-service infrastructure
 - H2 engine for LD applications is especially attractive in HEV powertrains (e.g. series-parallel hybrids or series hybrids) due to attractive functional synergies
 - Examples: Light commercial vehicles & LD trucks w/ high payload, long range & high engine load operation, HEV passenger cars; markets: Globally, strong interests in China/Asia/EU
- **An estimate of deployment schedule**
 - PFI: 2024 (planned)
 - DI: 2026+ (dependent on OEM schedule)
- **Key areas where government support of pre-competitive R&D would help**
 - Pre-competitive R&D for H2 engine component developments (e.g. H2 FIE, boosting systems, low cost H2 tank systems)
 - H2 engine R&D for high efficiency and high power density
 - R&D for improved and alternative exhaust aftertreatment solutions
 - Support for H2 engine vehicle demo fleet testing
 - Support drafting of technology-open regulation (see above)

Component & Combustion system development for H₂ ICE

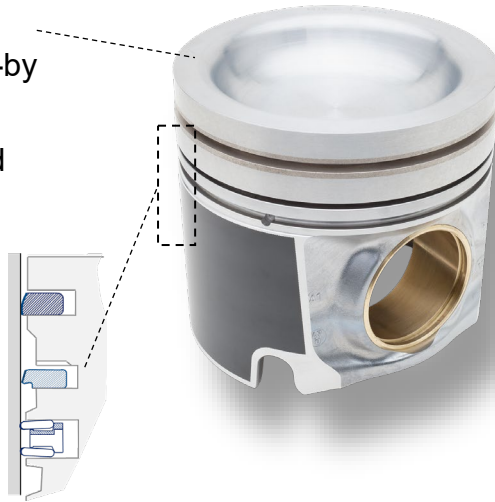
Combustion process

- MAHLE Jet Ignition (MJi) ® concept
- H₂ ICE pre-chamber ignition to enable ultra lean combustion



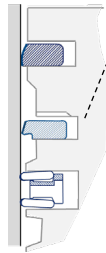
Pistons

- Low piston temperature to reduce knock propensity
- Ring groove optimized for blow-by and LOC reduction
- Reduced compression ratio and adapted bowl geometry



Ring package

- H₂ compatible material
- Blow-by reduction
- Reduction of oil consumption and related particle formation



Valve set

- H₂ compatible material
- Material combination for „dry“ operation conditions
- Corrosion resistant materials against condensation

Crank case ventilation

- Active crankcase ventilation for dilution of blow-by to reduce oil dilution by water
- Active crankcase ventilation to reduce H₂ concentration



MAHLE high pressure impactor

➤ **Evolutionary development: optimized components for zero CO₂ combustion engine technology**

Hydrogen-capable injectors as part of newly-launched P2X series (diesel, methanol, LPD, methane, ammonia, H₂)

- 100 – 1000kW/cylinder engine power
- Marine and power generation

HPDF solution:

- Up to 500bar injection H₂ pressure with diesel-pilot ignition
- Diffusion combustion operation
- Full back-up diesel operation possible (up to 2200bar diesel pressure)
- Capable of operating on any of the low-ignition fuels with pilot ignition

Dedicated H₂ medium-pressure DI:

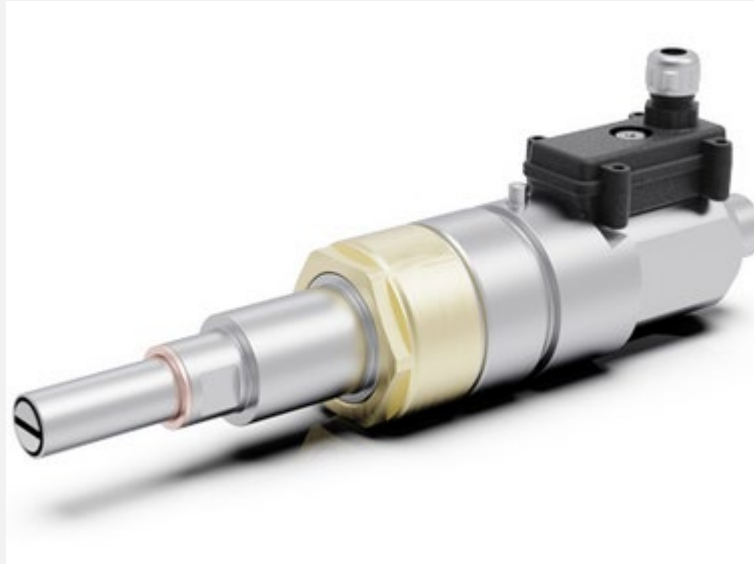
- Up to 30bar injection pressure
- No leakage

Port injection options:

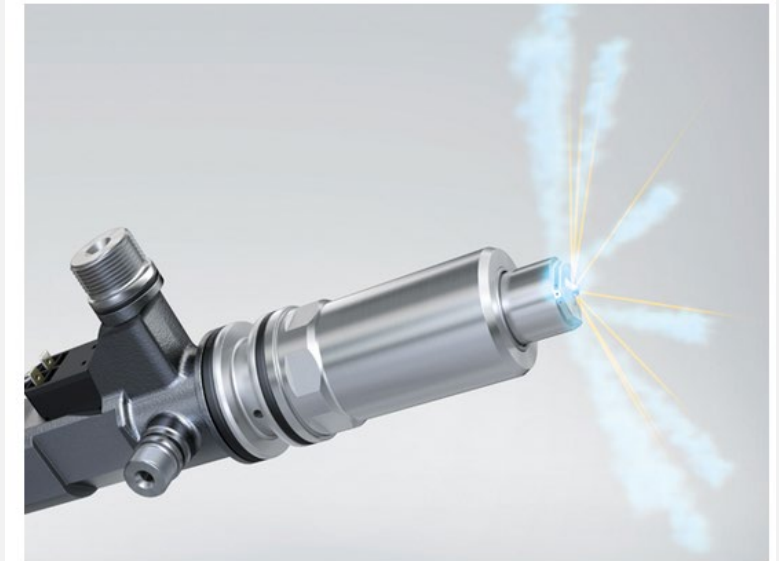
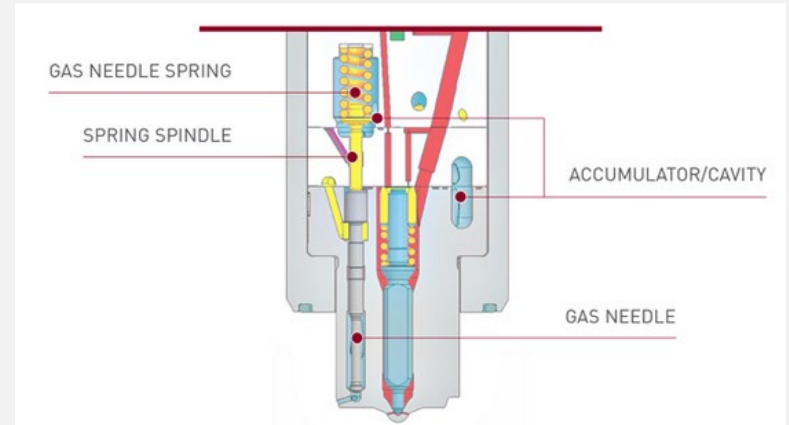
- Modification of existing NG engine products

Source: <https://www.woodward.com/about/about-woodward/woodward-lorange/produkte/p2x-multi-fuel-injectors>

Direct injector for H₂
30bar operating pressure



Dual-fuel gas-diesel high-pressure direct injector (HPDF, up to 500bar)



Allianz Wasserstoffmotor - Alliance for Hydrogen Engines

Industry and academia advocacy group focusing on pre-competitive H2ICE research

Main focus areas:

- H2ICE system design
 - Safety, complexity, OBD
- H2 injection and combustion
 - Development and testing of H2 DI – Durability, opt. configuration
- H2 tank system for mobile applications
- Aftertreatment systems
 - Urea SCR DeNOx:
 - H2 SCR DeNOx
- Components H2 compatibility
 - Valves, piston rings, piston materials
- H2 engine peripherals
 - Crankcase ventilation
 - Lubricant configuration

Main statements/conclusions

- H2 as an energy carrier for commercial vehicle is imperative to reach Paris agreement goals
- H2ICE is a very attractive technology in terms of robustness, time to market and cost
- H2ICE can complement BEV and FC in commercial drives to meet customer needs
- Basic research and predevelopment needed for H2ICE commercialization. Members to develop a demonstrator vehicle by Q1 2023, small-series production by 2024
- H2ICE offers opportunity to maintain technical leadership in potential key future technology. Competences and manufacturing readily available in Germany.



Acce/eron	Albonair	APL Group	AVL
Bendion	BorgWarner	BOSCH	bp
Castrol	CLAAS	Cummins	DAIMLER TRUCK
DEUTZ	Eberspächer	EDAG	FEV
Flexider AUTOMOTIVE	FREUDENBERG INNOVATING TOGETHER	FUCHS	Georgsmarienhütte GMH GRUPPE
HELLER	Hirschvogel Group	HJS	IAV
ISUZU	ITAZ GmbH	JW FROEHLICH Test and Assembly Solutions for Powertrain	KÄSSBOHRER Gelenkverkehrs AG
KIT Karlsruher Institut für Technologie	KST	LIEBHERR	Linde
MAHLE	MAN	michael rein Entwicklungslösung & Consulting	MWM Energy Efficiency Environment
NAGEL HYDROGEN SUPPLYING	NGK	POPPE+POTTHOFF	SCHAEFFLER ENGINEERING
Simerics TECHNOLOGY BY DESIGN	STADLER	STILL	tmax
TUPY	umicore	Webasto	WESTFALIA Metal Hoses
Westport Fuel Systems	WITZENMANN Managing Flexibility		

Netherlands – Green Transport Delta – Hydrogen consortium

Consortium partners:

Main objective – develop three technologies:

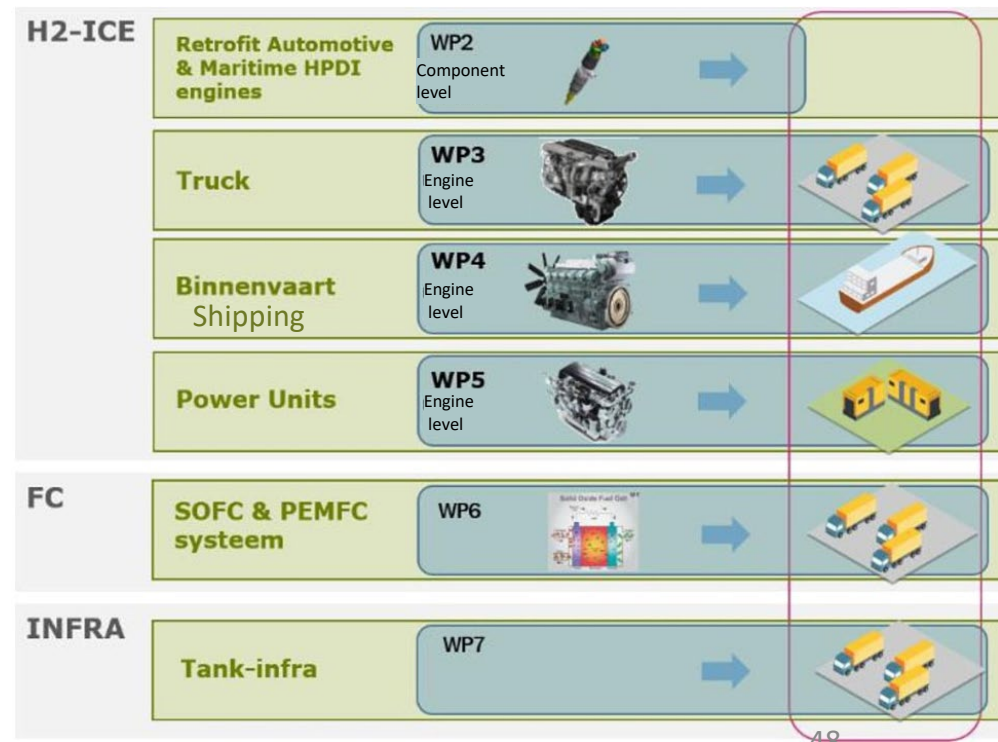
- Hydrogen combustion engines
- Hydrogen fuel cells
- Next-generation H2 refueling technology

Funding by Dutch government: €37M (~\$40M)
Cost share: €26M
Period: 09/2021 – 12/2025
Lead: DAF (PACCAR company)

Specific objectives:

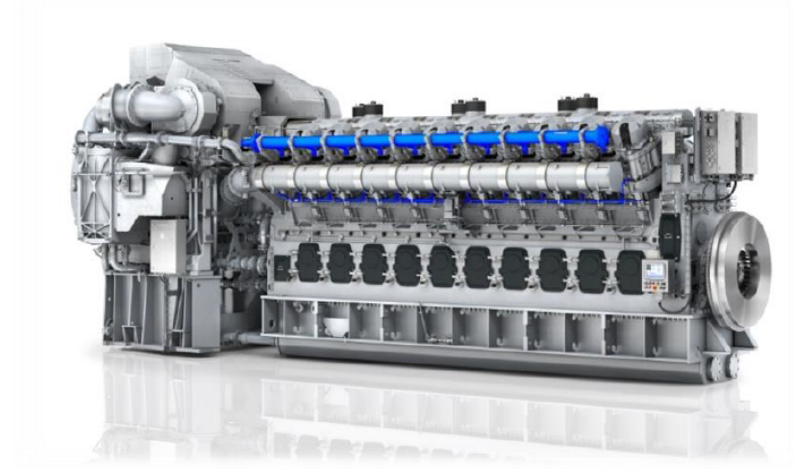
- Flexible hydrogen injection system for retrofit of automotive and marine diesel engines to H2
- Develop efficient H2ICE for trucks, barges and mobile power units
- The development of a modular SOFC fuel cell system and a completed study of dynamic loading of PEMFC fuel cells in relation to degradation limits
- The development of flowmeters and calibration technologies for the further development of hydrogen refuelling infrastructure

By building up a strong competitive position, the consortium partners can keep the production of the technologies that are still to be developed, in the Netherlands in the long term and reduce the dependence on foreign suppliers.



MAN ES - H₂ ICE

- Key barriers to H₂ ICE development and deployment
 - Backfire, (Lube oil) Pre-Ignition, and Fuel availability, Knock, Storage
- Past accomplishments and current activities
 - MAN ES gas engines are H₂-ready up to 25%
 - 100% H₂ is in development, supported by R&D projects (e.g. HydroPoLEn)
- Competitive technologies and motivation for pursuing H₂ ICEs
 - Fuel Cell; Advantages ICE: Costs, power density, fuel flexibility (Impurity substances), familiarity with technology (supply chain, knowledge, repair shop), cooling system
- Targeted application or customer
 - Power applications and short to medium distance marine applications
- Deployment schedule
 - 25% H₂ : Engine released in 2021, 100% H₂ for power plants in approximately 2028
- Key areas where government support of pre-competitive R&D would help
 - Funding of R&D, Implementation of infrastructure and ensuring the security of investments





Major manufacturer of gensets and CGP plants, 250kW – 10MW
Over 48,000 units in operation

Ready for Hydrogen program:

- All types can operate on up to 25% H2 in NG blend (in addition to operating on biogas, landfill gas, sewage gas, mine gas, coal gas, syngas)
- Type 4 (500-900 kW) can operate on 100% H2 and any blend of NG/H2.
- Demonstration unit installed in HanseWerk Natur in Hamburg, Germany
- 90 hydrogen-rich fuel projects across 28 countries, INNIO has more than 30 years of experience with engines running on up to 70%
- Retrofit of existing engines to “Ready for H2” technology possible

190MWe and 192MWth CHP NG power plant
Kiel (Germany) district heating plant, 20 J920 engines
45% electrical efficiency (newest gen. 49%) , 90% total efficiency
(example of how future H2 CHP plants could look like)





WÄRTSILÄ

Diesel and gaseous-fuel engines, 0.8MW – 43MW power

Marine propulsion, power generation and CHP

Gaseous engines as dual-fuel or pure gas fuelling

All gaseous-fuel engines can be modified to run on up to 25% H2 in blend of NG

Expecting to have a 100% H2 engine solution by 2025, active R&D currently on the way

Alternative solution to H2 is NH3 – a NH3 engine expected to be market-ready by 2023

55MWe NG power plant in MI, USA

Uses 3x SG50 engines, 50.2% electr. Efficiency

Selected for testing NG-H2 blends operation



Key barriers to H2 ICE development and deployment

- Available direct H2 storage technologies and cost,
- ICE power density, inversely proportional to engine specific cost [€/kW], limited by pre-ignition sensitiveness (low ignition energy).

Past accomplishments and current activities

- Up to 25%-volume H2 ready since 2015. Testing to higher contents ~40%-vol.
- 100% H2ICE under development since 2020: Pre-mixed flame propagation and high pressure injected mixing controlled. Experimental activities on Spray chamber, Rapid Compression Expansion Machine, and Single Cylinder Engine. H2 modelling capabilities. Initiated research project with Aalto University and VTT within model development.

Motivation for pursuing H2 ICEs

- H2 energy conversion for PtXtP (PtH2tP) power plants at high power levels for mitigating availability of renewables, and also seasonal storage. Possibility for fossil gas back-up.
- Best efficiency at nominal power compared to Fuel cells with optimum at part load.
- Possibility for mid-range marine applications in coastal operation
- Versatile energy conversion technology, well known and flexible for vast number of applications. ICE's has comparably high power density.

The targeted application or customer

- Initially for stationary peaking/grid stability power plants PtH2tP, later possibly for marine coastal operation
- 100% H2ICE pilot power plant in 2025-2030 range.

Key areas where government support of pre-competitive R&D would help

- H2 mixing and combustion modelling
- Fundamental research on pre-ignition phenomena in ICE related to lube oil, including their additives, and hot surfaces in the combustion chamber. Lube oil and its additives transportation in ICE's combustion chamber and interaction with H2.



Toyota: exploring potential of LD-H2ICE applications through motorsport program

- Successfully participated in a 24h endurance race using a modified DI engine with comparable performance to a gasoline version

Significant effort invested into understanding and mitigating pre-ignition (presentation JSAE 20224660)

- Tested 4 different engines using H2 DI and PFI to understand the aspects of engine design and load on pre-ignition
- Effort on spark-plug design to minimize pre-ignition tendency
- Visualized hot-spot pre-ignition on a hot spark-plug electrode using endoscopic imaging
- Developed prototype hydrogen DI technology with in-house injector manufacturer DENSO
- Simulations of in-cylinder mixture formation effect on pre-ignition

Toyota Corolla endurance race car



2022 Toyota Cross H2ICE concept

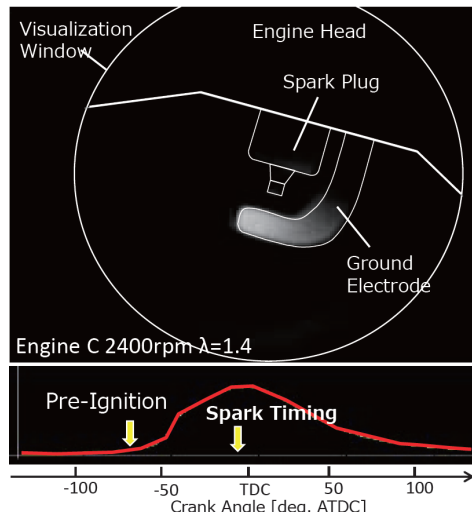


2022 Yamaha 5.0L V8 H2ICE

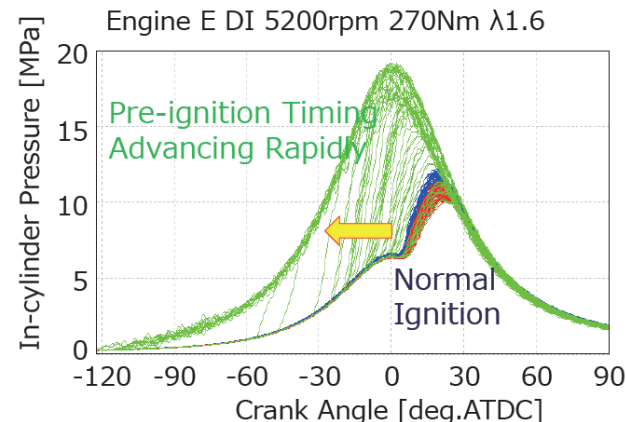


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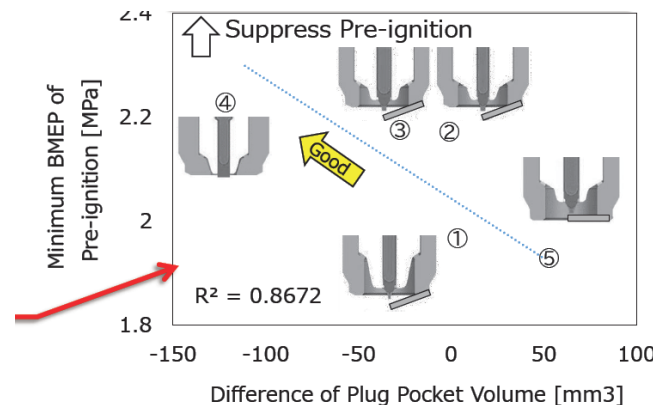
Visualization of hot spark-plug electrode



Runaway-type Pre-ignition



Pre-ignition tendency of different electrodes



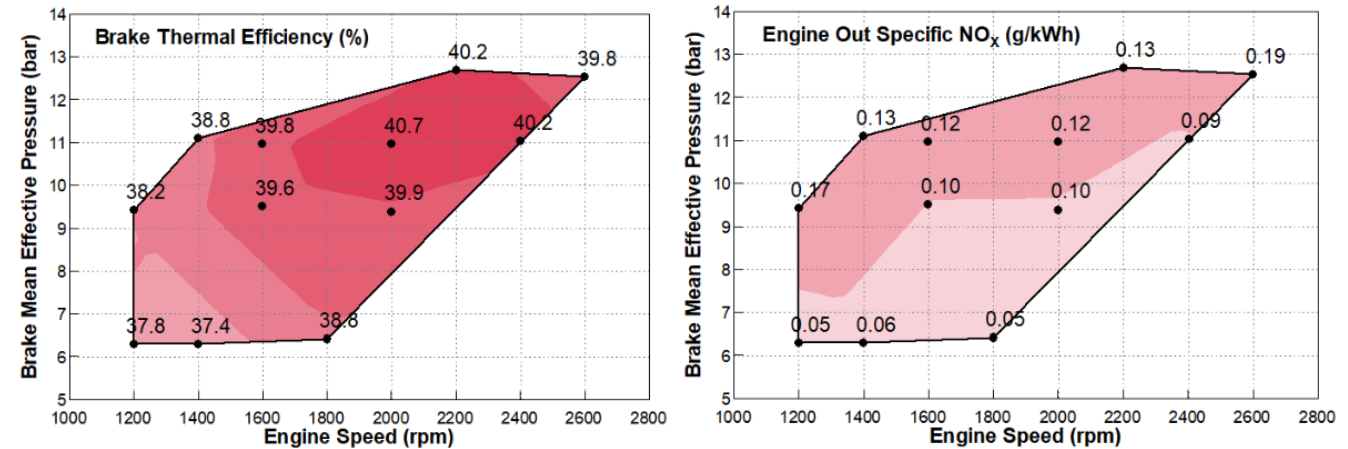
Source: A Study of Abnormal Ignition in Hydrogen Combustion Engine, [https://tech.jsae.or.jp/paperinfo/en/search?q\[0\].id=13&q\[0\].v=st202205](https://tech.jsae.or.jp/paperinfo/en/search?q[0].id=13&q[0].v=st202205)

- Fuel cell cars in series production since 2013, over 20,000 units sold
- Provided FCEV 50 trucks for demonstration project in Switzerland, fleet accumulated 3MM miles

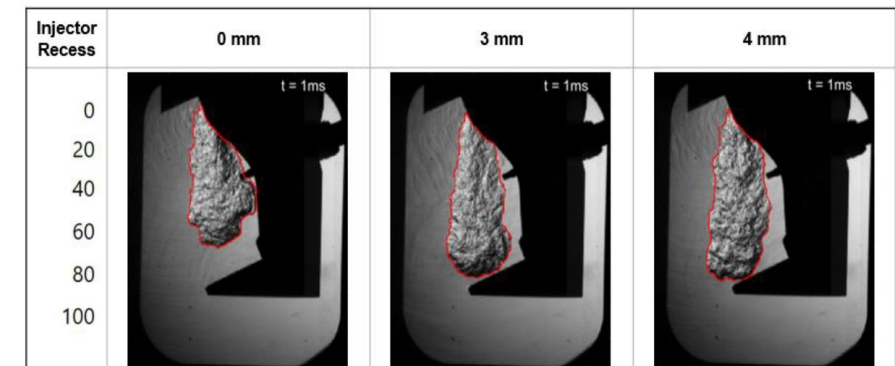
Recent development of H2ICE

- Presented at 2022 Thiesel conference, together with FEV and BorgWarner
- Tested within a typical operating range for ICE in hybrid powertrain
- Production engine with small modifications

Test engine efficiency and NOx emission 1.6L 4-cylinder turbo engine with DI



Visualizations of H2DI plume evolution



Source: Thiesel 2022,
Hydrogen Internal Combustion Engine: Viable Technology for
Carbon Neutral Mobility

Authors: Y. H. Chi, B. S. Shin, S. Hoffmann, J. Ullrich, P. Adomeit, J. Fryjan, R. Drevet

DOOSAN



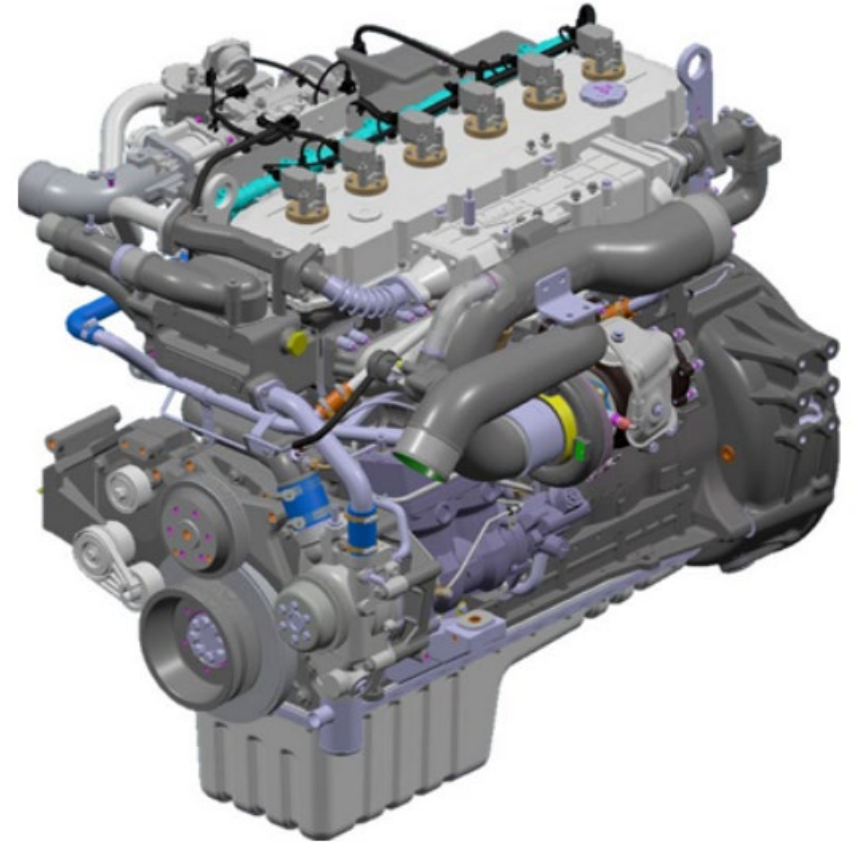
Doosan H2ICE rendering

Plans to develop 11L 6cyl. 300kW H2ICE

Funded by Korea Ministry of Trade, Industry and Energy

2024: Demonstrator vehicles developed: trucks, bus,
construction machinery

2025: Series production



Dual-fuel engine (launched in 2020)

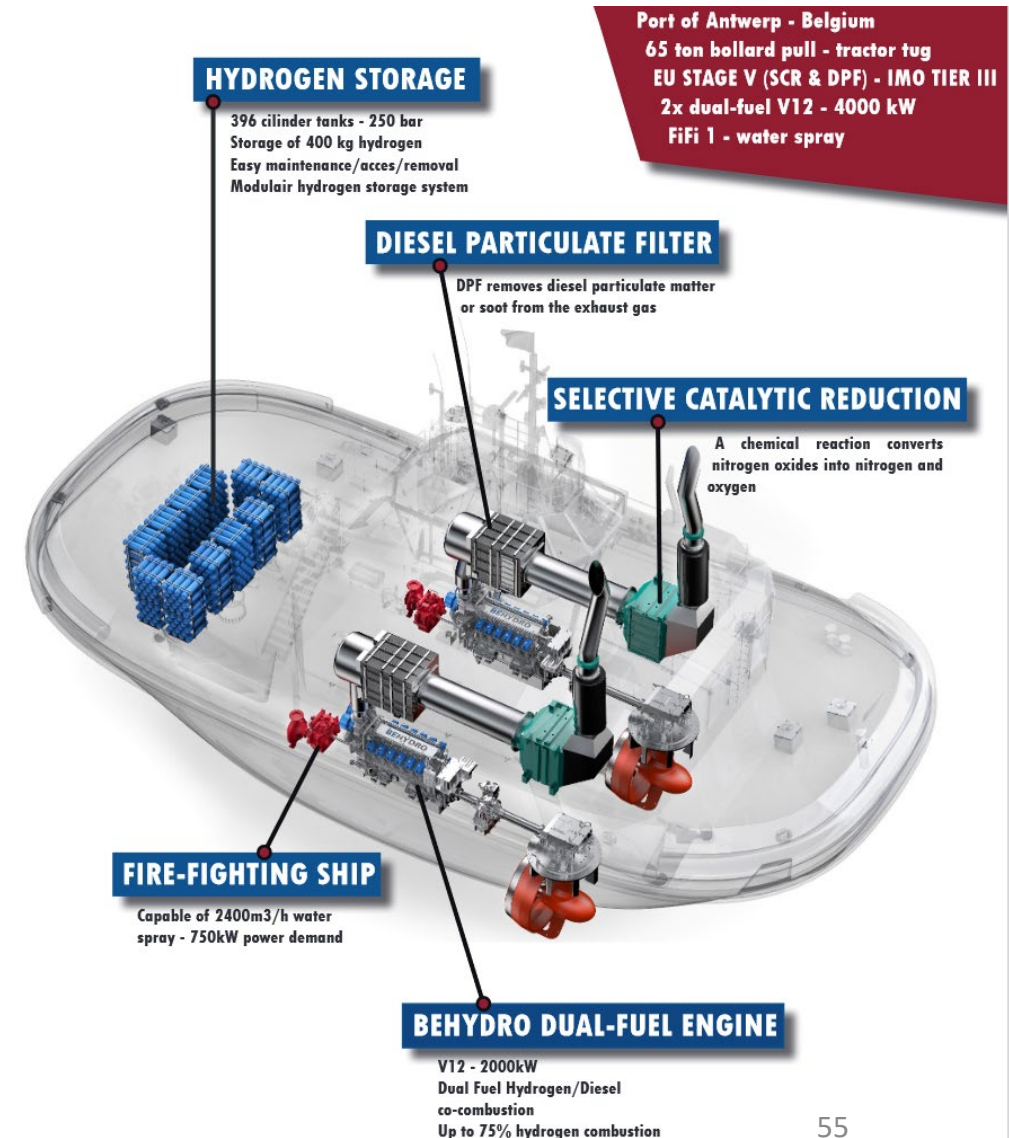
- Modification of existing diesel line to operate on H₂ with PFI
- Up to 85% substitution of diesel with H₂, 1.0-2.7MW power
- About 30% power-derated from diesel equivalent
- Demonstration vessel fully-operational in Q1 2023
- Back-up operation with diesel possible, reduced requirements for H₂ fuel-reserve storage to be legislation compliant

Spark-ignition 100% H₂ engine (launched in 2022)

- Modification of existing diesel line to operate on H₂ with PFI
- Same power rating as dual-fuel engine
- No back-up diesel operation

Applications:

- Marine (Tugboat HydroTug1, fully operational in Q1 2023)
- Power-generation (mobile units for supplying power to ships while docked in port)
- Power-generation - electricity
- Railroad engines (retrofit of existing units with Belgian Rail)



Mitsubishi Heavy Industries Engines and Turbocharger Ltd:

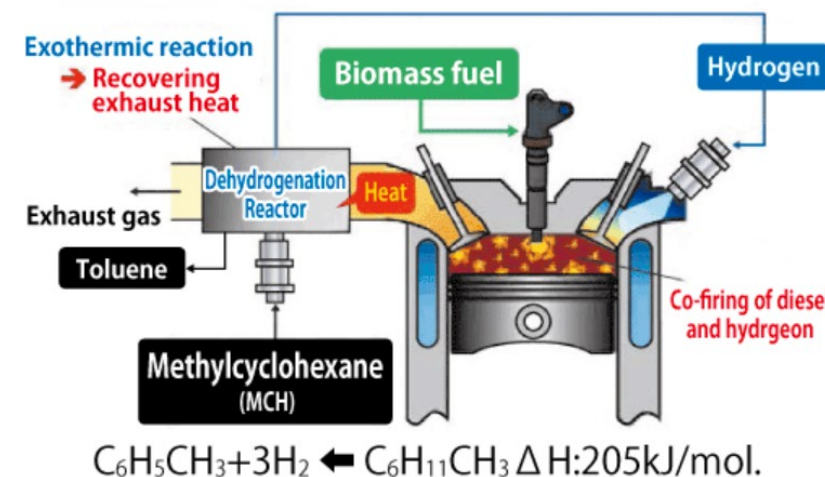
- Plans on developing 1MW-class H2ICE for power generation and CHP – market introduction in 2030
- Initial testing in collaboration with academia demonstrated on a 1-cylinder 5L natural gas engine converted to H2 operation
- Lean-burn, PFI, spark ignition
- No efficiency data available
- Currently foreseeing about 25% power derating due to pre-ignition challenges
- Source: <https://www.mhi.com/news/210121.html>

1-cyl. H2ICE test rig at AIST Japan



- H2ICE projects ongoing at AIST since at least 2017
- Integration of H2-ICE into H2 energy supply chain using chemical hydride storage – waste heat used for H2 recovery from storage media
- Source:

https://www.aist.go.jp/fukushima/en/unit/HyCaT_e.html



[Fig. 9] Next-generation Co-generation Engine System Using Organic Chemical Hydride

Liquid Hydrogen Carrier demonstration ship, future H2-diesel dual-fuel engine

Demonstrator vessel launched in 2022
(H2 import from Australia)

Planned 160,000m³ LH2 carrier (mid 2020s)

Preliminary approvals for 2.4MW H2-diesel dual-fuel engine for vessel propulsion

- Up to 95% diesel energy substitution with H2
- Can use H2 boil-off as fuel

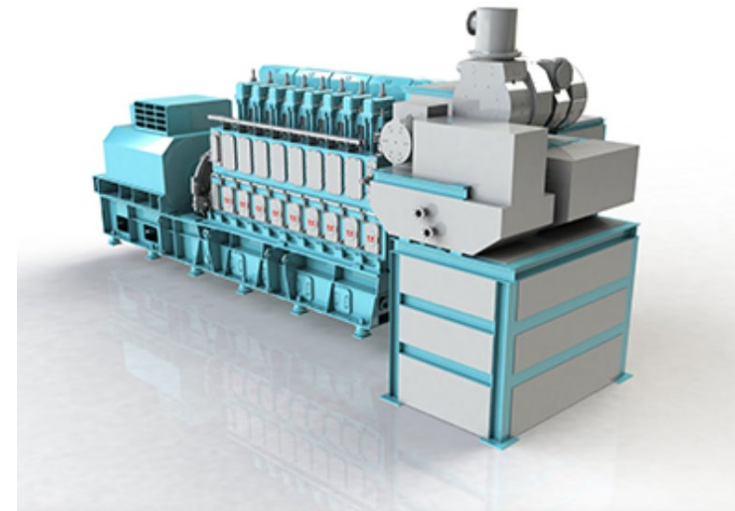
Suisa Frontier vessel (1250m³ liquid H2)



Planned 160,000m³ LH2 carrier (mid 2020s)



2.4MW H2-diesel dual-fuel engine





Joint venture to develop H2-ICE for marine applications

- Kawasaki – large 4-stroke H2ICEs
- Yanmar – small-medium 4-stroke H2ICEs
- Japanese Engine Company – 2-stroke H2ICE

Each company plans to commercialize their corresponding H2ICE product by 2025.

Source:

<https://www.yanmar.com/eu/news/2021/05/31/93017.html>

ISUZU *DENSO*

TOYOTA

 **HINO** 

Key Japanese companies announced joint pre-competitive research for H2-ICE for HD applications in 2022

Key points of the announcement:

- Foundational research fostering each companies experience and capability on H2-ICE.
- H2-ICE seen as one solution for the need to rapidly decarbonize HD sector
- Expanding options to achieve carbon neutrality
- Economy of scale: increasing the number of stakeholders in producing, transporting, and using hydrogen
- Each OEM to develop proprietary solutions if H2ICE is deemed feasible based on the pre-competitive research

Key technical challenges (from personal communication):

- Combustion chamber design for fast combustion
- Pre-ignition
- In-cylinder mixture formation to reduce NOx and improve efficiency
- Turbocharging with ultra-lean combustion
- Suppression of NOx during load transients
- Crankcase ventilation and dedicated lubricant development

Source: <https://global.toyota/en/newsroom/corporate/37544174.html>

Wabtec/ORNL/ANL/Convergent Science CRADAs on H₂/diesel dual-fuel locomotive engines

Key barriers to H₂ ICE development:

- H₂ preignition leading to backfire or knock
- Maintaining compatibility with diesel fuel while H₂ infrastructure is deployed
- Fuel system hardware (fuel injectors, compressors)
- Engine performance (efficiency, torque, combustion stability) with H₂
- Pollutant emissions (especially NOx)
- Durability of engine components and materials
- H₂ cost, availability, delivery, and storage

Current H₂ ICE R&D Activities:

- Use simulations and experiments to design and evaluate combustion strategies and engine hardware for both retrofit and new engine applications to:
 - Maximize H₂ displacement of diesel
 - Maintain full compatibility with diesel fuel
 - Prevent backfire and engine knock
 - Maintain engine efficiency and power density
 - Minimize NOx emissions

Targeted applications:

- Rail, marine, stationary/backup power

Estimated deployment schedule:

- CRADA completion date: 2026
- Wabtec locomotive demonstration planned for 2030?
- Commercial deployment depending on customer orders

Competing technologies:

- Fuel cells

Motivation for H₂ ICEs:

- Challenges:
 - H₂ preignition
 - NOx emissions
 - Engine efficiency
- Advantages:
 - Compatibility with diesel fueling infrastructure provides a transition strategy to accelerate H₂ uptake in existing vehicles
 - Near term CO₂ emissions reductions through retrofits
 - Existing engine supply chain
 - Proven durability
 - Relatively low cost

Key areas for government support

- Development of simulation tools, combustion strategies, and engine hardware for dual-fuel diesel/H₂ engines
- H₂ fueling infrastructure
- Demonstration programs to prove the technology



ARGONNE'S H₂ ICE RESEARCH

Past accomplishments:

- Led H₂ ICE light-duty research for DOE VTO (2005-2012):
 - Unsurpassed LD engine performance (45.5% BTE) and emissions.
 - Developed X-ray diagnostics for high-pressure gaseous jets.
 - Developed CFD modeling of H₂ injection and mixture formation in ICEs.

Current activities (target application = off-road, rail, stationary power/CHP):

- HIL capabilities and increased H₂ supply for benchmarking H₂ ICE vs FC.
- Development of advanced CFD models for H₂ injection/mixing.
- Improvement of X-ray diagnostics to account for real H₂ fuel effects.
- Development of best practices for modeling H₂ ICEs for rail/off-road/CHP.

Competitive technologies:

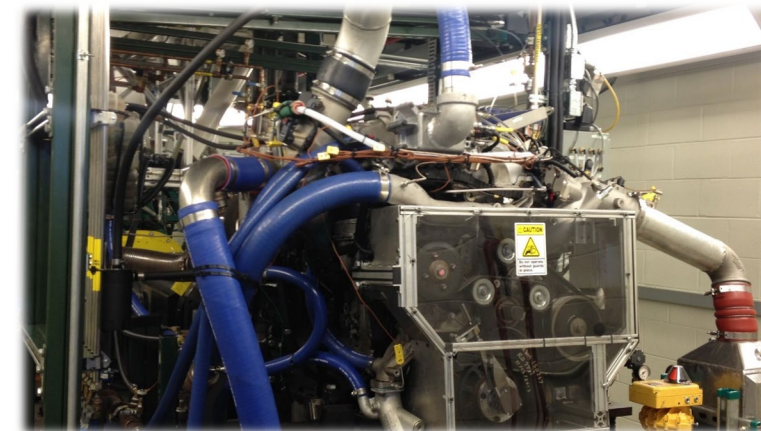
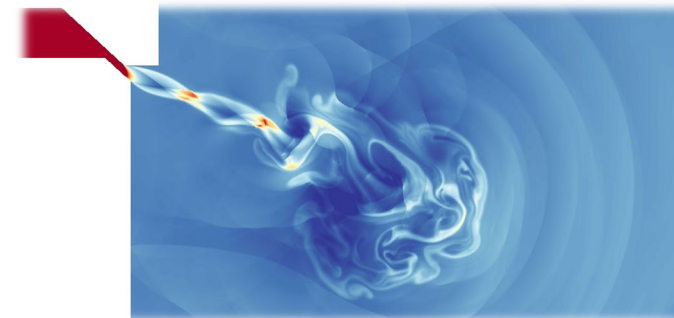
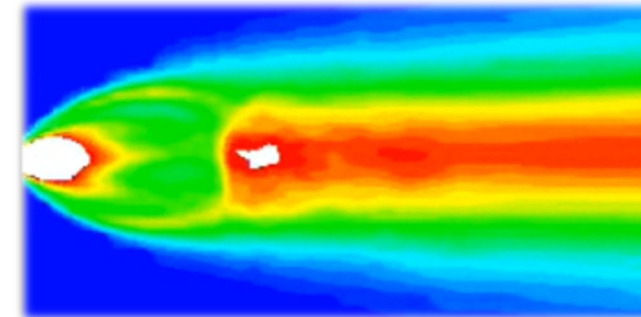
- H₂ FC + net-zero carbon engine technologies (NH₃, MeOH, renewable/bio-fuels)

Key barriers to H₂ ICE development and deployment:

- H₂ injection system development.
- Abnormal combustion detection & risk mitigation.
 - Ignition/combustion system development.

Key areas where government support of pre-competitive R&D would help:

- Development of predictive models for hydrogen injection and combustion.
- Development of advanced diagnostics for hydrogen injection and combustion.
- Update of experimental facilities for analysis of H₂ ICE performance.



H2 INTERNAL COMBUSTION ENGINE MAIN CHALLENGES ADDRESSED BY IFPEN

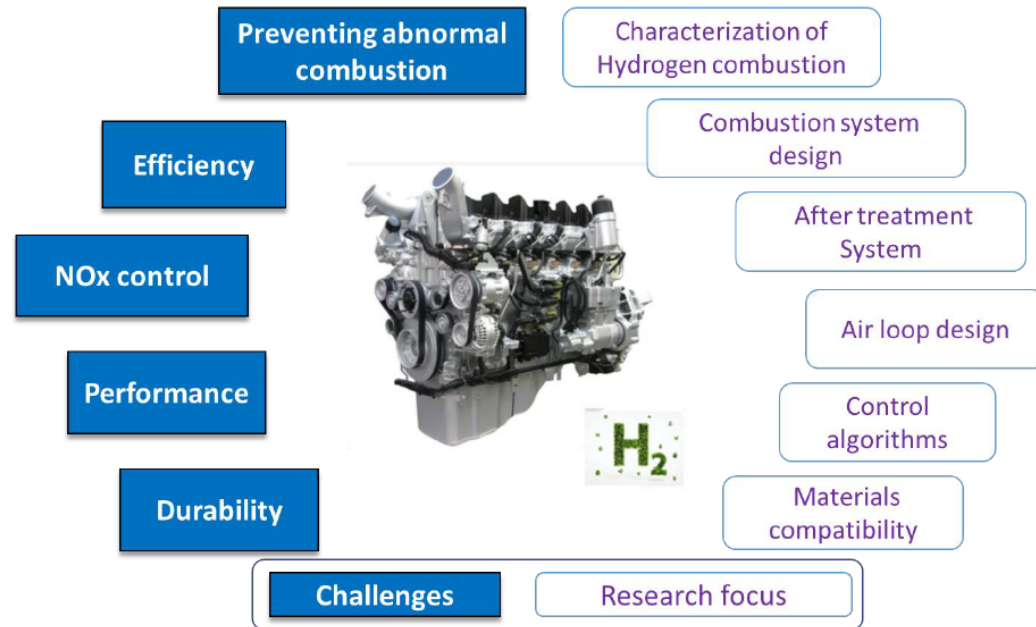
Why Hydrogen ICEs?

- Carbon free in use technology for mobility
- No impact on air quality
- Cost-effective solution
- Based on existing technologies and infrastructure

A technology dedicated to high-power applications when BEVs does not meet specifications

- HD and LD vehicles / off road / motorsports

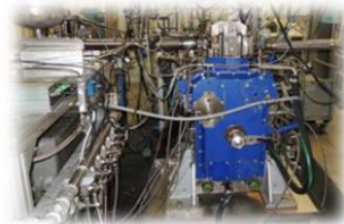
Remaining challenges and IFPEN research topics



Focus : Hydrogen combustion R&I @ IFPEN

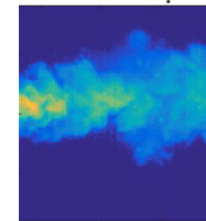
Development of a SCE dedicated to Hydrogen combustion research

HD application – single cylinder 2.2L
Port Fuel and/or direct Hydrogen injection

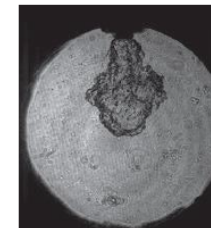


Development of advanced diagnostics to support the improvement and validation of 3D CFD modeling and the development of H2 ICEs

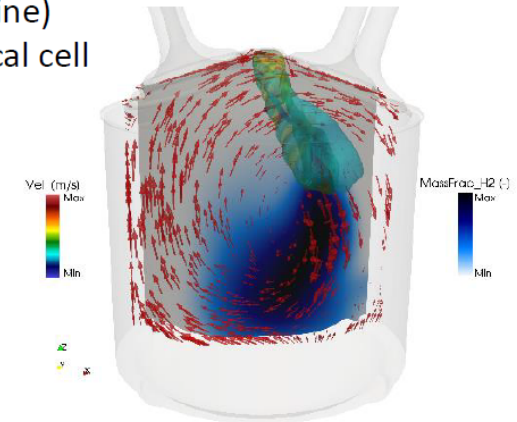
- Identification of the origin of **abnormal combustions** within in situ visualization (optical access on full metal engine)
- In situ heat flux measurement to characterize **transient wall temperature and heat losses** (optical cell and full metal engine)
- **Injection and mixture characterization** in optical cell



LIF



Schlieren



Development of advanced 3D CFD models and methods to support the H2 ICE design and optimization

Hydrogen injection, Hydrogen/Air mixture, Hydrogen combustion, Wall heat losses

Key barriers for H2 ICE development and deployment:

- Technical: lack of dedicated injection equipment is hindering research
- Legislative: Legislation should specifically allow H2ICE with clear and meaningful limits on NOx and CO2 emission to allow OEMs and Tier1 suppliers clear development goals
- Legislative: background CO2 should be accounted for in CO2 emission legislation. Otherwise, even FCEVs emit CO2 from the tailpipe
- Long term aspect: move away from ICE conversions and build dedicated H2ICE hardware for best efficiency

Past accomplishments, present activities

- CFR engine experiments in support of octane number characterization, Argon cycle research and HCCI research
- KAUST begun testing in HD engines, jet characterization in vessels and associated modelling and CFD activities
- Saudi-Aramco FUELCOM4 program will exclusively focus on H2ICE (injection, EGR effects, kinetics of H2, combustion modelling, advanced ignition systems, lubricant development)
- Optical HD engine and thermodynamic HD engine ready to start H2ICE research
- Installing a Wankel engine with intention to operate it on H2. Effort to be supported by CFD

Competitive technologies

- PEM fuel cell – in-house analysis suggests higher TCO for PEMFC than for H2ICE, even with lower labor costs of Saudi Arabia

Targeted applications and customers

- Initially, focus on HD trucks
- Also planning light-duty H2ICE (SI and Wankel – range extenders and heavy-drones)

Key areas where government support would help:

- Development of boosting systems
- Transferring common light-duty engine technologies to HD engines
- Meaningful emissions targets and timeframes to be established
- Hydrogen infrastructure and refueling interfaces – legislation needed
- Legislation allowing fuel-flexible engines (gasoline and H2, or diesel and H2) to promote initial market acceptance, with proper incentives

Key barriers for H2 ICE development and deployment:

- Power density: DI, potentially high-pressure
- Advanced ignition strategies to match diesel engine efficiency, while maintaining low NOx
- Injection equipment

Past accomplishments, present activities

- Argon cycle project for ultra-efficient zero-NOx stationary applications (started in 2020). Included studies of H2 mixing, CFD efforts and engine experiments
- Participating in Dutch Green Transport Delta project
- Building a new H2-ICE single-cylinder research engine

Competitive technologies

- Renewable liquid fuels are naturally competitive and in most cases easier to use and handle
- Ammonia is only other CO2-free fuel. TU/e participated in a large Dutch universities program on NH3/H2 ICE program. H2 is superior from production and ICE application perspective

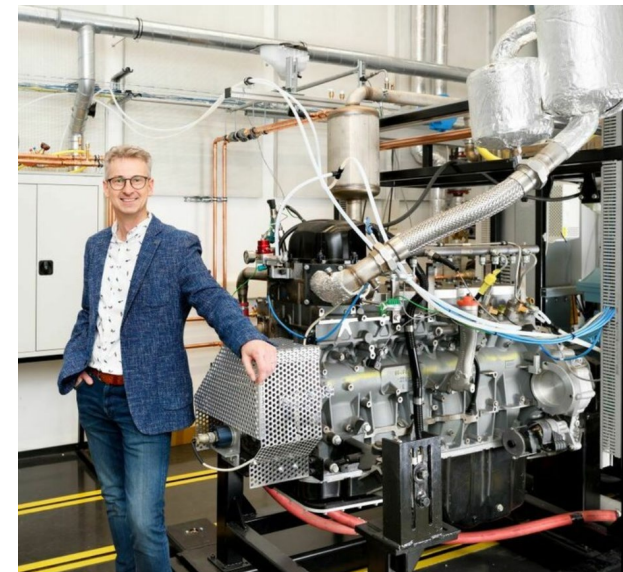
Targeted applications and customers

- Argon power cycle is targeted at stationary applications
- Long-term plan will focus on heavy-duty long-haul truck applications

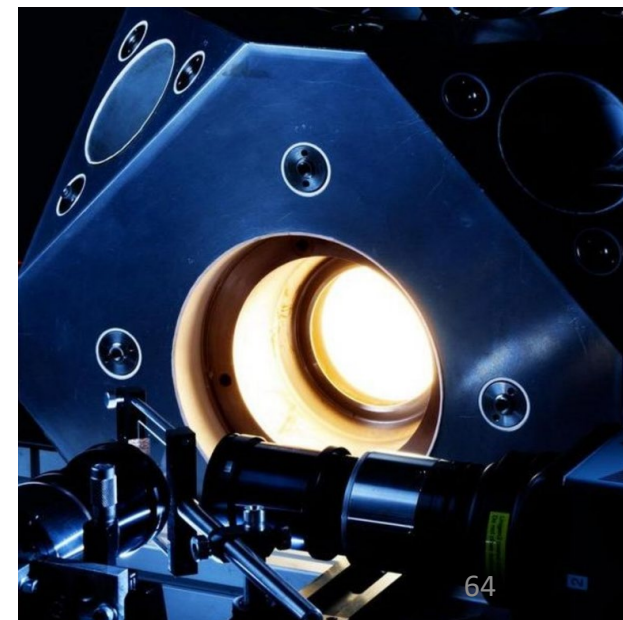
Key areas where government support would help:

- Support of pre-competitive research
- Legislation permitting minimal percentage of carbon-containing fuels used in ICE would allow for dual-fuel combustion concepts with superior performance

Argon cycle test engine



Combustion vessel for
Argon cycle research



H2 ICE R&D in SNU

H2 ICE Advantages

- Zero CO2 Emission → decarbonization of transport
- Application of existing ICE technology and infrastructure
- Economic benefits of production, transportation and storage costs
- Easy and quick access to market and customer

H2 ICE Challenges and Methods

Efficiency

- Lean combustion, Turbo-charging
- Chamber design, gas exchange optimization

Performance

- 2-stage charging, 48V e-S/C
- Up-sizing

Emission (NOx)

- After treatment system
- Ultra-lean mixture, EGR, water injection

Abnormal Combustion

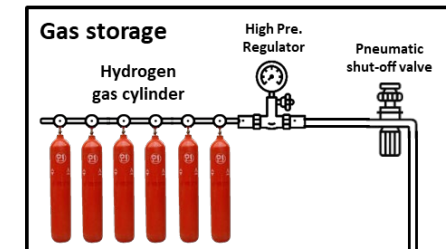
- Direct injection (high/low pressure)
- Mixture quality, air dilution

Past ICE R&D in Seoul National University Automotive Lab.

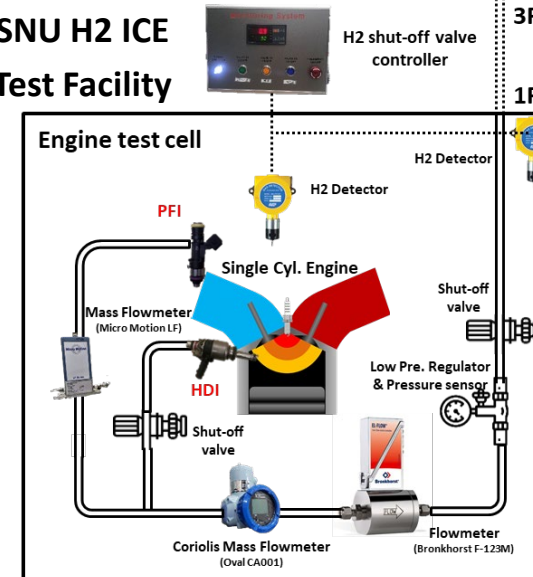
- Dual-fuel HCCI → load expansion (chamber optimization, in-cylinder flow field)
- Lean combustion → lean limit expansion (advanced ignition system, enhanced tumble)

Hydrogen Combustion using a Single-cylinder Research Engine

- To maximize **thermal efficiency** and to reach **near zero emission** by optimizing the hydrogen combustion systems
- Injection strategy → mixture formation (Homogeneous / stratified charge)
- Stroke-bore ratio → heat transfer, in-cylinder flow, mixture formation
- Compression ratio → thermal efficiency, abnormal combustion
- Water injection → EGR effect, combustion temperature, abnormal combustion
- Researches aimed at H2 ICE for passenger vehicles
- R&D investment in injection system, aftertreatment system and optimization of H2 ICE is essential for the further development of H2 ICE.



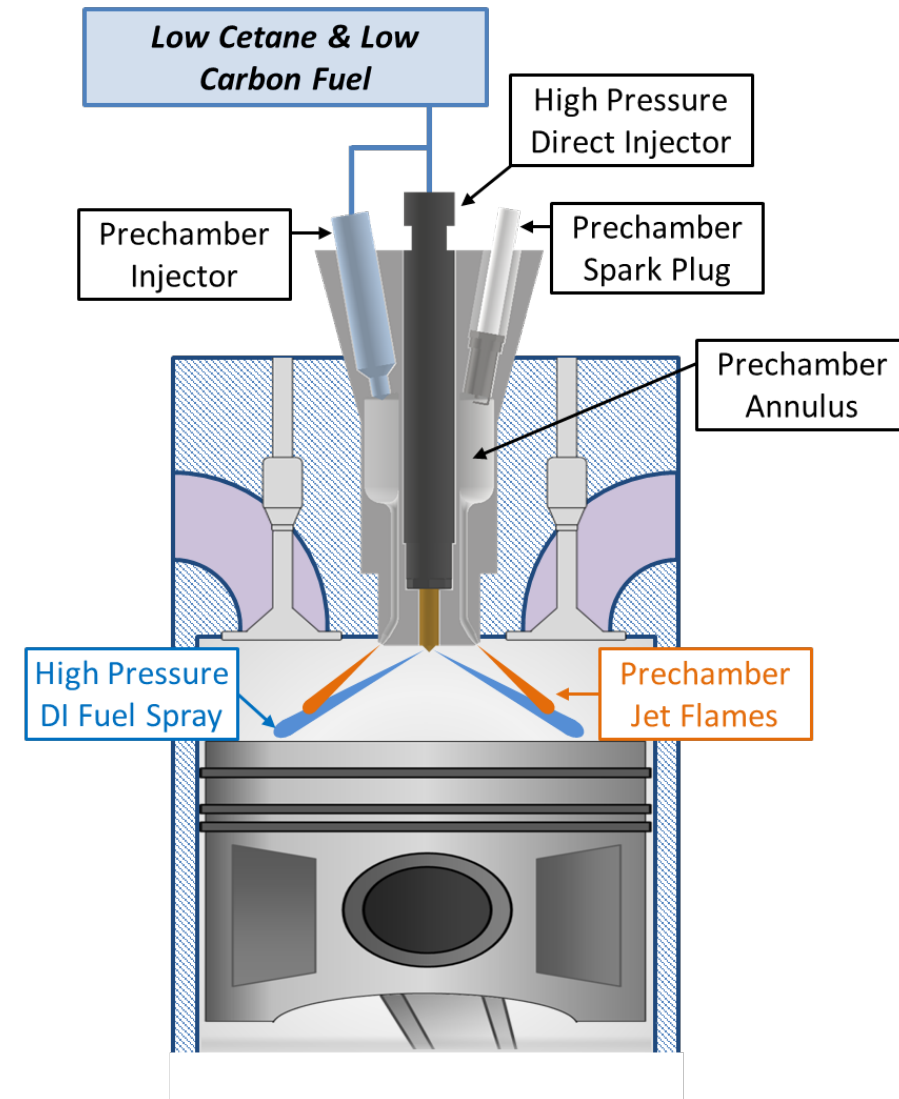
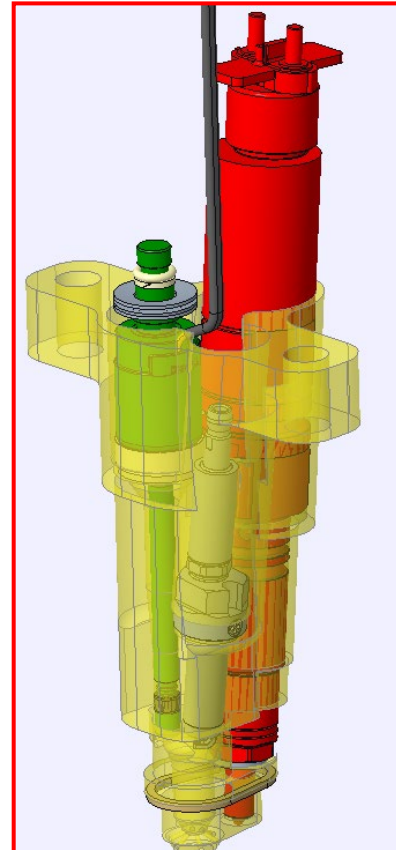
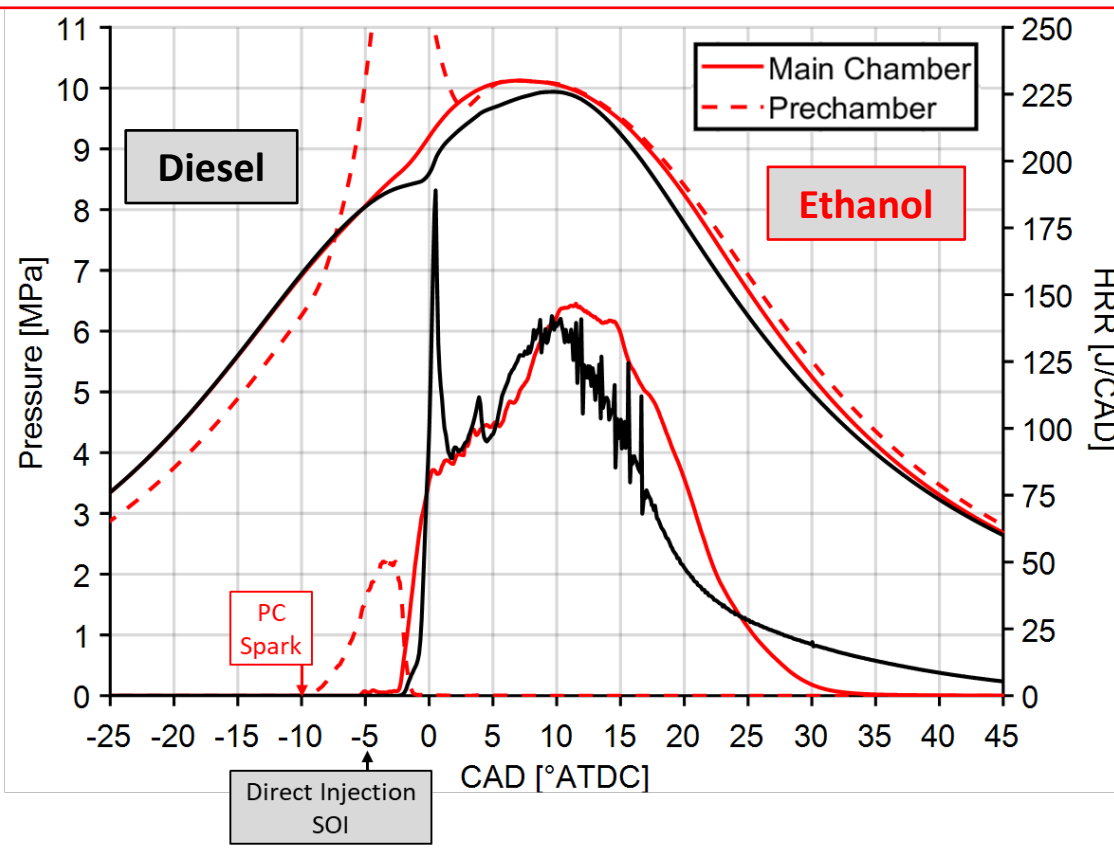
SNU H2 ICE Test Facility



Fuel Agnostic Combustion Strategy for Low Carbon Heavy-Duty Engines

Prechamber Enabled Mixing-Controlled Combustion (PC-MCC)

- Prechamber jet flames are “ignition” source for the DI fuel
- No limitations from knock or pre-ignition, diesel-like snap torque
- Achieve MCC with variety of low cetane fuels → **Fuel Agnostic**
- Fuel Candidates: **Hydrogen**, Alcohols, Natural Gas, & Ammonia



1. Key barriers to H₂ ICE development and deployment

- ✓ Operational problems associated with the uncontrolled pre-ignition and backfiring into the intake manifold of hydrogen engines.
- ✓ Reduced volumetric efficiency
- ✓ Large-scale storage and transportation issue
- ✓ Safety issue
- ✓ Lack of research infrastructure and R&D activities.

2. Past accomplishments and current activities

- ✓ Developed prototype of single cylinder laser ignited hydrogen engine
- ✓ Investigated flame kernel of Hydrogen-CNG air mixture using laser ignition in constant volume combustion chamber.
- ✓ Developing multi-cylinder engine running on laser ignition system for HCNG fuelled engine.
- ✓ It was observed that hydrogen enrichment enhanced the flame speed and offer superior combustion characteristics.

3. Targeted application or customer

- ✓ Automotive Engine Application
- ✓ Rocket Engine Applications

4. Competitive technologies and motivation for pursuing H₂ ICEs

- ✓ Hydrogen has a distinct advantages of being a non-carbon fuel.
- ✓ It has wide flammability range and does not produce unburned hydrocarbon and carbon monoxide emissions.
- ✓ Hydrogen is probably a unique and versatile fuel, which can provide solutions to fossil fuel depletion and global environmental problems.
- ✓ Hydrogen can be best suited with CNG and by utilizing electrode less ignition system such as laser ignition system.
- ✓ Structural improvements in the ignition system, injection system, or combustion chamber to cope with the more sensitive combustion characteristics of hydrogen.

5. An estimate of deployment schedule

- ✓ It depends on various other factors.
- ✓ However, the deployment of laser ignition technologies for commercial hydrogen fueled engine can be expected by 2030.

6. Key areas where government support of pre-competitive R&D would help

- ✓ Promoting R&D activities in collaboration with Academia and Industry.
- ✓ Government support are need to be accelerated in the production infrastructure of hydrogen.

H2ICEs research at State Key Laboratory of Engines, China

In recent years, SKLE has made some progress in the development of H2ICEs, mainly in cooperation with the industry. The H2 ICE application areas include passenger cars, heavy-duty trucks, general aviation, ship & power generation, etc. The technical route of H2ICE is direct injection with low injection pressure and lean combustion of hydrogen.

- Key barriers to H2 ICE: H2 fuel system with high injection pressure, Turbo-charger with high expansion ratio, Anti hydrogen embrittlement material, Platinum free spark plug, NOx after-treatment with high efficiency at low temperature
- SKLE past accomplishments: Fundamental theory of hydrogen turbulent combustion, Knocking combustion of H2ICE, H2ICE combustion technology based on different engine platforms.
- Current activities: Pre-ignition of H2 combustion, Effects of lubricating oil of pre-ignition, Lean H2 combustion, Combustion system development of H2ICE to improve BTE.
- Competitive technologies and motivation for pursuing H2 ICEs: Improving reliability, Near zero-emissions, Improving efficiency, Reduce engine and powertrain costs
- The targeted application of H2ICEs: passenger cars (include hybrid application), LD & HD trucks, general aviation, ship & power generation
- An estimate of deployment schedule: The application of H2ICEs depends on green hydrogen, infrastructure and H2ICE reliability. In 2025, a small number of H2ICEs will enter the market, and there will be a large increase in 2030. After 2035, there will be a rapid growth. However, H2ICEs will be mainly used for heavy equipment, HD trucks, ships and power generation (renewable energy storage devices).
- The development of H2ICE in China is mainly supported by industry. The Chinese government mainly support hydrogen fuel cell. Also, the government support ammonia hydrogen hybrid engine and the power system of ammonia and hydrogen.

FPT (Iveco Trucks, Case New Holland)

- H2ICE not announced officially
- New Cursor XC13 engine developed to use multiple fuels with maximum engine commonality

Prinoth

- H₂-powered snow groomer
- Modified XC13 engine, 338kW power
- 4h endurance using compressed H₂ tanks
- Commercially available

FPT XC13 13L multi-fuel engine



Prinoth Leitwolf H₂ motion



- **Key areas where government support of pre-competitive R&D would help**

Italy lacks a clear-cut hydrogen strategy, nevertheless it has manufacturing, technological and scientific skills to develop the hydrogen supply chain

Diverse policy matters could be identified

Being the conductor of a European strategy through a vision involving other EU countries and North Africa along the hydrogen industrial value chain

Accelerating the development of hydrogen industrial value chain leveraging on the creation of innovation ecosystem and leading role of national energy champions

Supporting decarbonized hydrogen production at national level

Promoting a widespread diffusion of hydrogen in the end-use sectors

Developing specific competencies linked to the hydrogen value chain

Raising awareness of the value of the hydrogen in the public opinion and the business community

- **Challenges to Hydrogen as fuel for vehicles:**

Low volumetric energy content (MJ/m^3) due to its low density

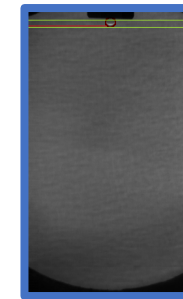
Pre-ignition and knocking phenomena due to the minimum ignition energy

Flame backfiring in the intake manifold for PFI config

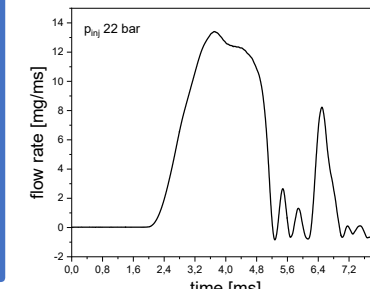
NO_x formation if not in lean operations or high EGR level

Safety concerns and tank capacity

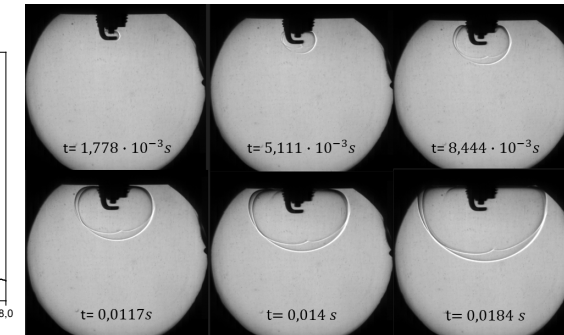
- **Past achievements**



Spray Imaging

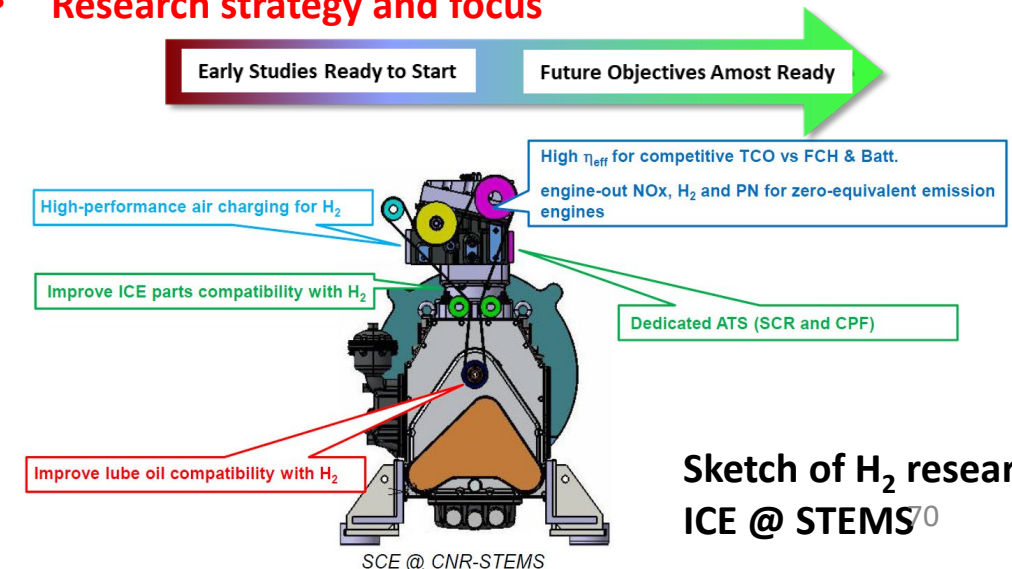


Flow rate



Gaseous mixture combustion

- **Research strategy and focus**



Sketch of H_2 research
ICE @ STEMSTO

Short-list of key barriers to H₂ ICE development and deployment

Storage, dedicated injection system hardware, cyber-physical system for deployment

Past accomplishments and current activities

In framework of ARENA 2018/RND011 (Australia) project, “Enabling efficient, affordable and robust use of renewable hydrogen in transport and power generation”:

- Detailed optical visualisation of the evolution and combustion of hydrogen jet under direct-injection compression-ignition engine conditions
- H₂ jet autoignition displays considerable run-to-run variation at temperature and pressure conditions typical of conventional compression-ignition engines.
- H₂ jet flame recesses upstream to stabilise close to the nozzle after ignition. The stabilisation position of the H₂ jet flame raises concerns about the potential emission and thermal stress effect on the nozzle.
- World-first demonstration of an H₂-diesel dual-fuel direct-injection engine at UNSW that can operate up to 90% hydrogen substitution by energy, with a significant reduction in CO₂ emission (more than 80%).

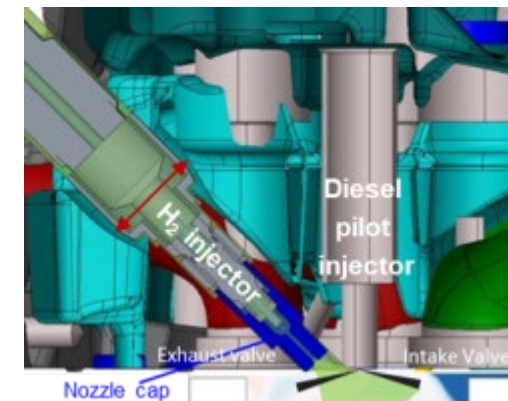
Competitive technologies and motivation for pursuing H₂ ICEs (highlighting both H₂ICE challenges and advantages)

H₂-fuelled reciprocating engines have several competitive advantages over H₂-fuelled gas turbines and fuel cells stemming from their lower capital costs, better dynamic response, greater robustness to fuel impurities and inherent higher efficiency than gas turbines. If minor modifications to existing engines are only required to incorporate H₂, this implies that H₂-fuelled engines can have the same capital and non-fuel operating costs as conventional engines, with higher efficiency potential because of H₂ fuel properties.

Targeted application or customer

Stationary power generation, heavy-duty transportation applications utilising compression-ignition reciprocating engines

H₂-diesel dual-fuel single cylinder engine



News release:

<https://newsroom.unsw.edu.au/news/science-tech/new-system-retrofits-diesel-engines-run-90-cent-hydrogen>

Key barriers to H2ICE:

- Control of abnormal combustion
- DI injection system
- Combustion heat loss
- Power density in lean operation
- H2 metal embrittlement, lube oil dilution with water

Past achievements:

- Control of abnormal combustion for highly-boosted gasoline engines
- Direct injector development with DENSO
- Heat loss minimization through in-cylinder flow and DI
- Evaluation of CFD simulation accuracy and H2 fuel diffusion

Current H2ICE research

- Closed-cycle H2ICE using Argon for high efficiency and no Nox
- Combination of lean and stoichiometric operation for improving drive-cycle efficiency and NOx emissions
- In-cylinder heat-loss reduction by controlling in-cylinder gas motion

Target applications of H2ICE

- Passenger cars (Toyota)
- Retrofit of HD trucks (RIKEN, Tokyo University)
- Marine engines (KHI, YANMAR, DAIHATSU)
- Combined heat and power (MHI, KHI)

Working toward a carbon-neutral future.

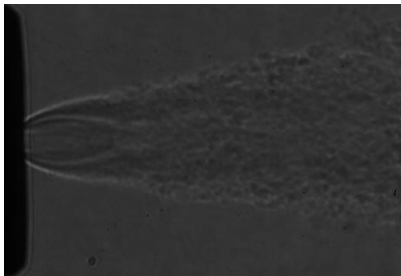
The driving force behind Japan's future growth is the challenge of achieving carbon neutrality.

Now is the time for Japan-A technological superpower
One world-changing innovation after another.

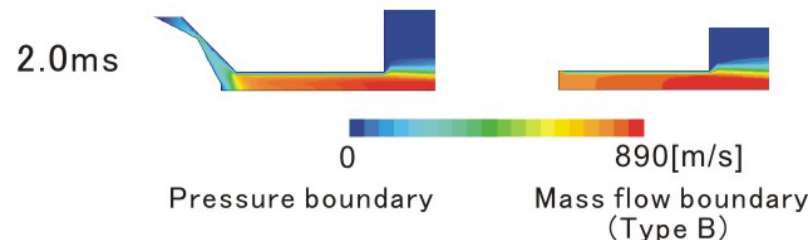
Working together to create a carbon-neutral future.
A new Japan is waiting in 2050.

NEDO(Ministry of Economy, Trade and Industry), Ministry of Land, Infrastructure, Transport and Tourism, Ministry of the Environment have much budget for carbon neutral society by 2050

H₂ jet visualization

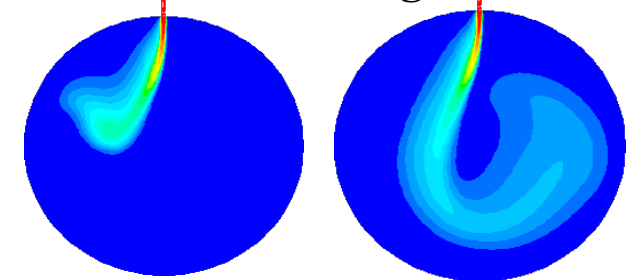


In-nozzle flow simulation



千葉大学
Chiba University

Mixture stratification using swirl and DI

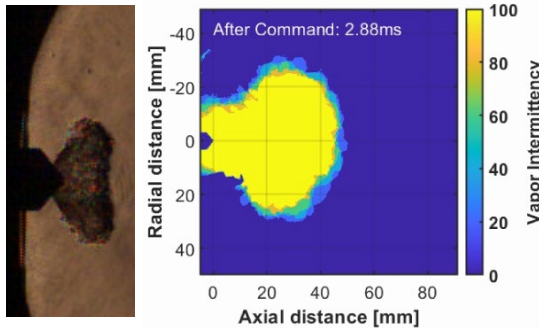


Hydrogen Jet analysis

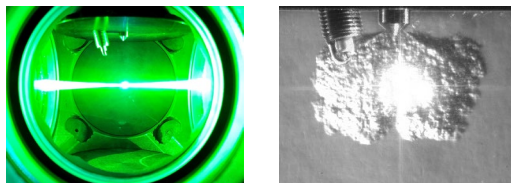
Jet Characteristics

@ Constant Volume Vessel

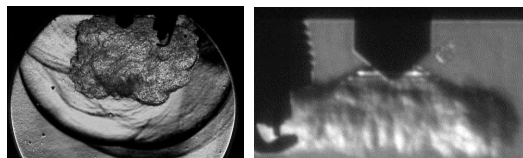
- (10 MPa) Jet visualization



<High-speed Schlieren imaging>



<LIBs Equivalence ratio Measurement>



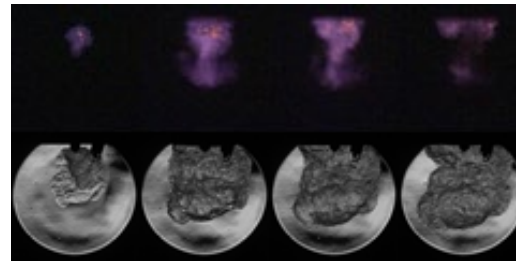
<Shock analysis>

Combustion Visualization

Hydrogen combustion

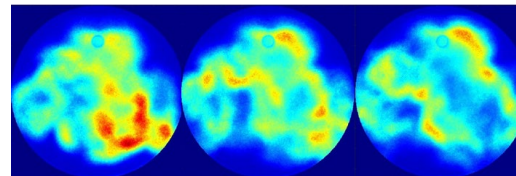
@ Constant Volume Vessel

- Energy Conversion analysis



<Direct flame visualization (Top)
Schlieren flame surface visualization
(bottom)>

- Measurement of high temperature heat release location



<OH* Chemiluminescence>

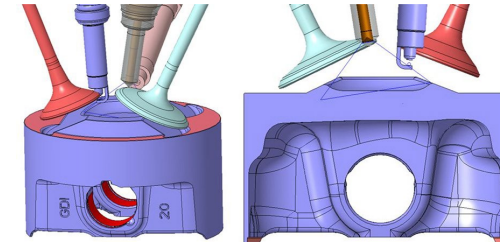
- Energy conversion **efficiency**

H₂ICE Single-cylinder

Performance & Emission

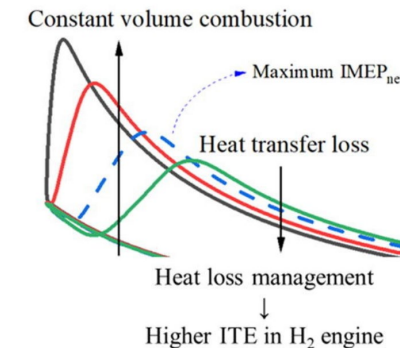
@ Single-cylinder research engine

- Evaluation of hydrogen lean stratified combustion engine



<Jet-guided DISI engine heat schematic>

- CO₂ & PM emission analysis
- Local rich-hydrogen
→ NO_x emission measurement



- Heat loss analysis

Focus – Light-Duty H2 engines

Topics and methodology

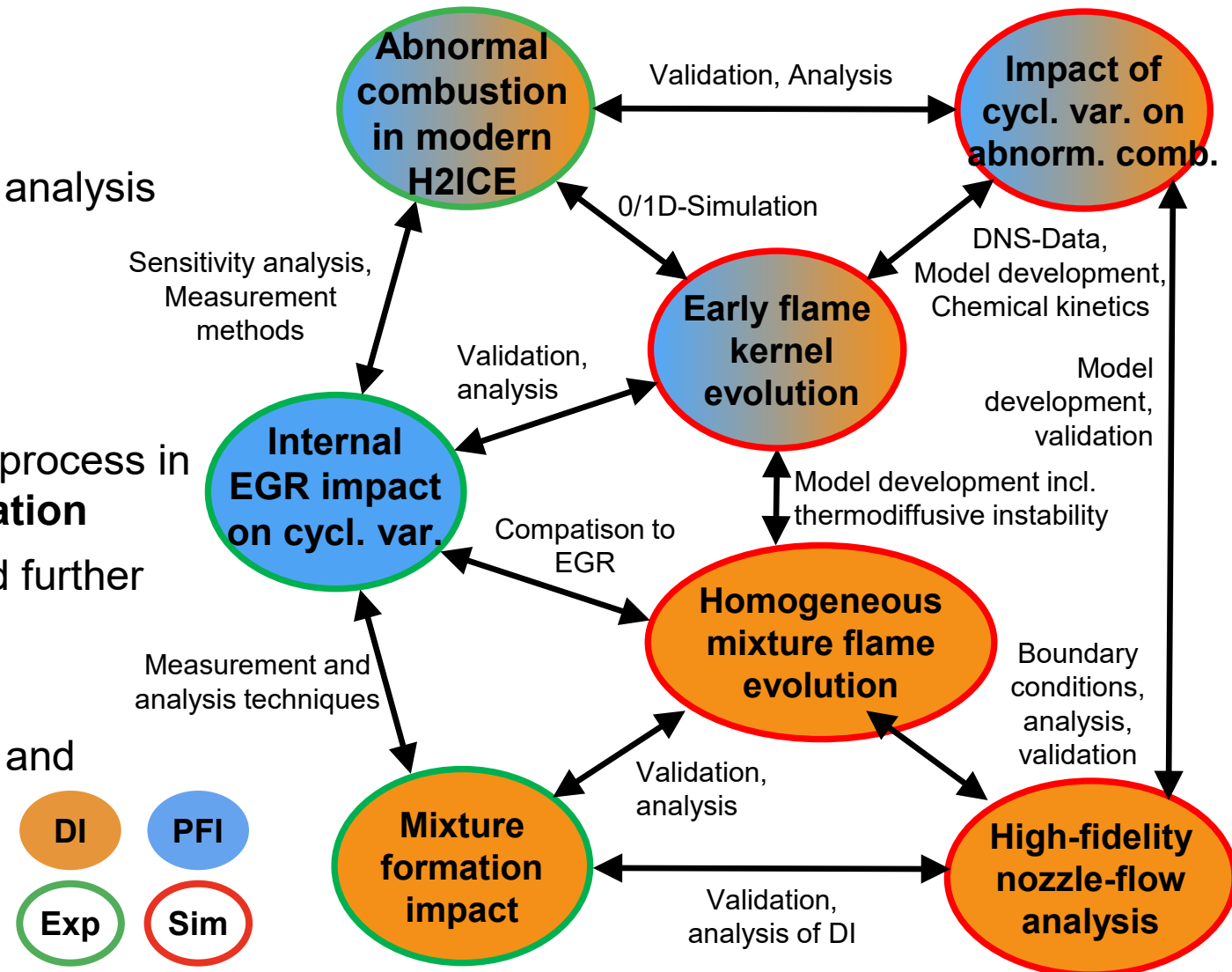
- Experiment, Simulation, Modelling and Data analysis
- Homogenous and stratified mixture (H₂ PFI or DI)

Approach

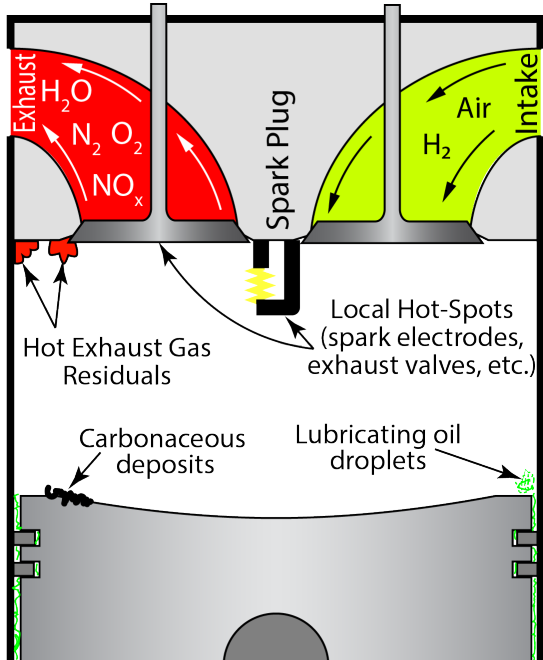
- **Separate investigation** of relevant individual process in cooperation between **Experiment and Simulation**
- **Model validation** through joint application and further evolution of **data analysis processes**.
- **Model development**
- **Scientific exchange** regarding measurement and analysis methodology

→ Main scientific task for the unit:

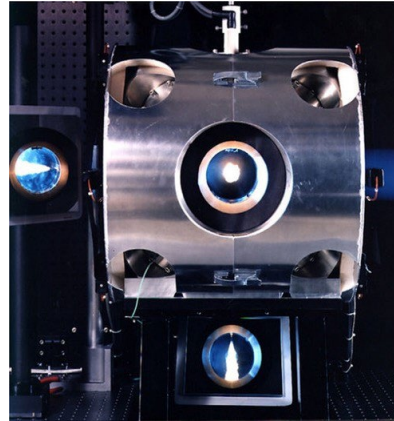
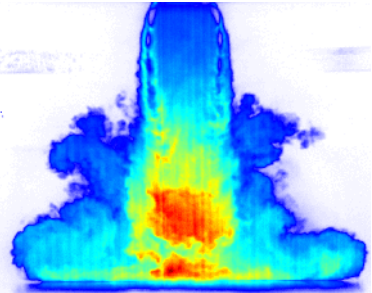
Synthesis of individual findings



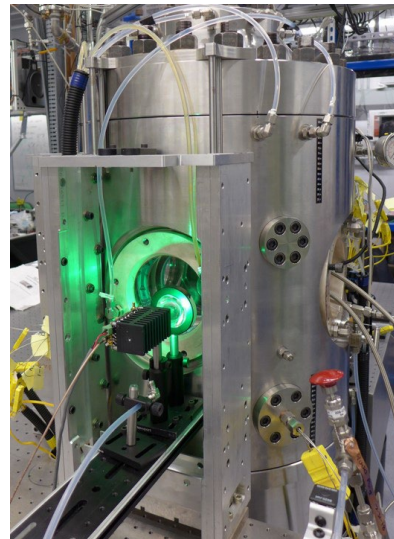
Pre-ignition mechanisms Pre-burn spray vessel



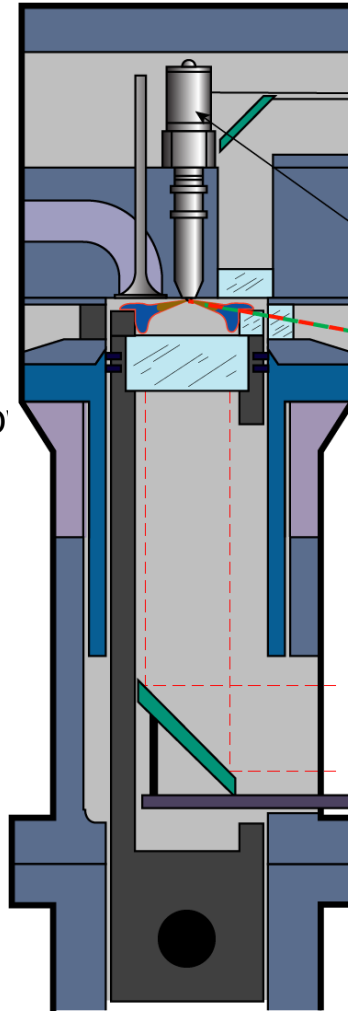
H₂ DI jet visualization In-cylinder mixing



High-speed, continuous-flow spray chamber



Heavy-duty H₂ optical engine



Optical engine, spray vessel and CFD simulations to understand key barriers:

H₂ direct-injection:

- Near-nozzle flow and temperature field
- Effects of H₂ diffusivity
- Optimization of injector configuration
- In-cylinder mixture distribution and its effects on performance, ignition, and NO_x
- Interaction between injection and engine flows

Understanding of pre-ignition mechanisms

- Unique experimental capabilities to explore pre-ignition under controlled conditions
- Characterization of key mechanisms, CFD

Pollutant formation

- Correlations between mixing and NO_x
- Visualization of NO_x formation

Advanced ignition systems

- Pre-chamber igniters for knock mitigation
- Plasma ignition systems

Wall heat transfer and mitigation

- Quantification, correlation to in-cylinder mixing
- Simulations and simplified modelling

H₂ICE Impact on Medium and Heavy Duty Truck Applications



Ram Vijayagopal, Aymeric Rousseau
Argonne National Laboratory

Contact: ram@anl.gov

February 22nd 2023

Discussion on using hydrogen in ICE for H2IQ

These are preliminary results from an ongoing study on H₂ICE evaluation for trucks

Executive Summary

H₂ICEs De-risk H₂ Infrastructure Investments While Offering a Viable Option for Freight Decarbonization.

- Assuming **HFTO & VTO⁽¹⁾ targets** are achieved, FCHEVs will be economically competitive by 2030, against diesel and H₂ICE vehicles.
- Freight decarbonization solutions remain highly uncertain: Energy cost (diesel, electricity, H₂), powertrain requirements, component durability, thermal management, performance degradation, fueling/charging infrastructure, CAPEX...
- Hydrogen Earth Shot is critical for any H₂ fueled vehicle competitiveness.

While meeting HFTO H₂ cost targets remain critical, H₂ICEs could de-risk some of the investments, jump-starting the H₂ economy.

(1) HFTO: Hydrogen and Fuel Cell Technologies Office; VTO: Vehicle Technologies Office

Overview

▪ Background

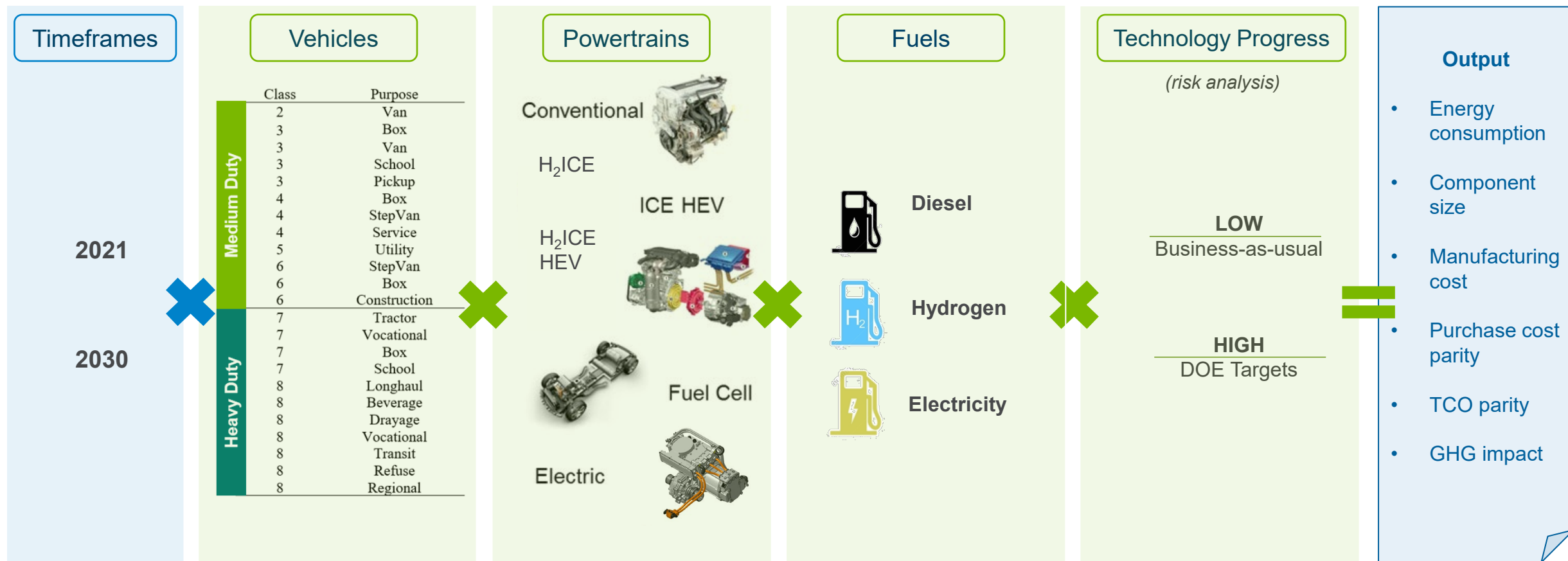
- Diesel engines can be adapted to burn H_2 , potentially accelerating adoption of hydrogen as a fuel
- State-of-the-art H_2 ICE engine test data is not readily available. H_2 ICE potential was evaluated using information from publications and inputs from industry partners

▪ Questions

- Under which conditions can H_2 ICE vehicles compete against other powertrains including diesel ICE vehicles, FCHEVs & BEVs?
 - Factors considered: vehicle cost, energy consumption & TCO
- How will hydrogen cost uncertainties impact the overall results?
- Which medium and heavy duty truck applications show the most promise?

Approach

Quantify the impact of DOE-funded technologies on energy consumption, performance, and cost of advanced vehicles



- Automated large-scale simulation process developed to handle hundreds of combinations in the case of this study, to inform on consumption, characteristics, costs, and emissions of current and future MDHD vehicles.
- H₂ICE evaluation was done for StepVans, Box, Refuse, Drayage and Longhaul trucks

Powertrain Configurations and Fuels Considered

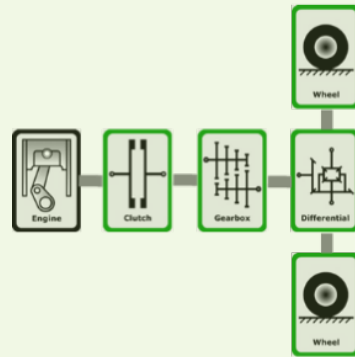
New technologies (H₂ICE, ICE HEVs, FCHEVs and BEVs) will compete with Diesel trucks

Long haul truck is the first evaluation candidate.

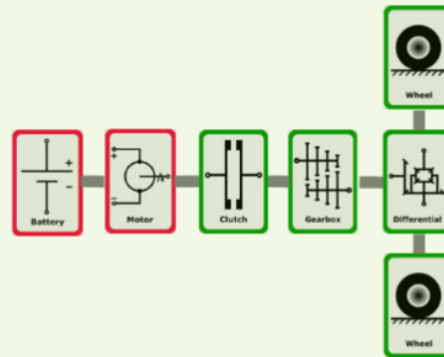
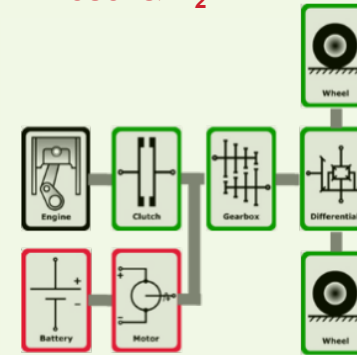
Designed for 500 mile range.

Longer range truck are possible with FC & H₂ICE systems.

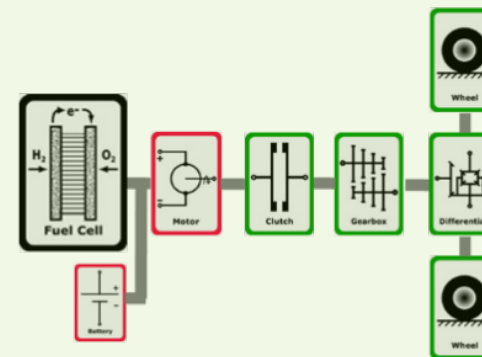
ICE : Diesel & H₂



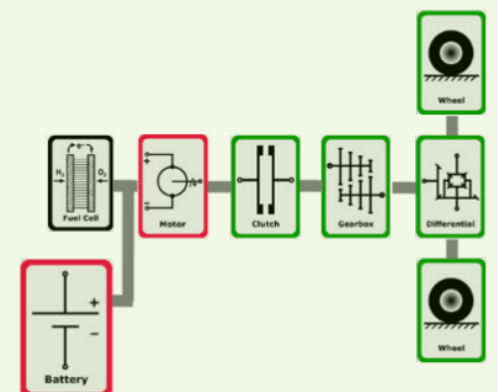
Parallel Hybrid : Diesel & H₂



Battery Electric (BEV)



FCEV : Fuel cell dominant



FCHEV : Fuel cell + Battery

Performance Based Sizing is Critical for Fair Comparison

Sizing criteria and tests are updated periodically with inputs from 21CTP & USDRIVE partners

■ Sizing Updates

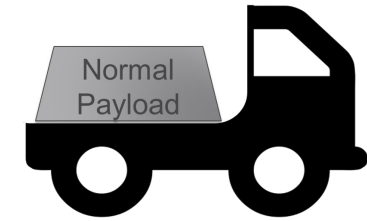
- Launch at grade
 - Highway gradeability
 - Performance at max GVWR for each class
 - Energy consumption tests with vocation specific cargo loads
 - Test durations added for electric powertrains
- Vehicle specifications & sizing logic details are published as supporting documents of VTO Benefit Analysis report

Sizing



- Performance tests @ max GVWR
 - Cruising speed
 - 1% Grade @ 65mph
 - 6% Grade climb for 11 miles at 30mph
 - Launch @ 15% grade
 - Acceleration & Passing
 - 0-30mph & 0-60mph
 - All Electric/Driving Range

Analysis



- Fuel economy tests @ regular load
 - Real World Cycles (Livewire, FleetDNA, CERC)
- TCO (Total cost of Ownership)
 - DOE cost targets & industry feedback
- Fuel Costs
 - AEO report

Class8 Long haul Truck Evaluation as a Potential Candidate for H₂ICE

Purchase price & TCO parity checks can give a fair comparison of the technology benefits

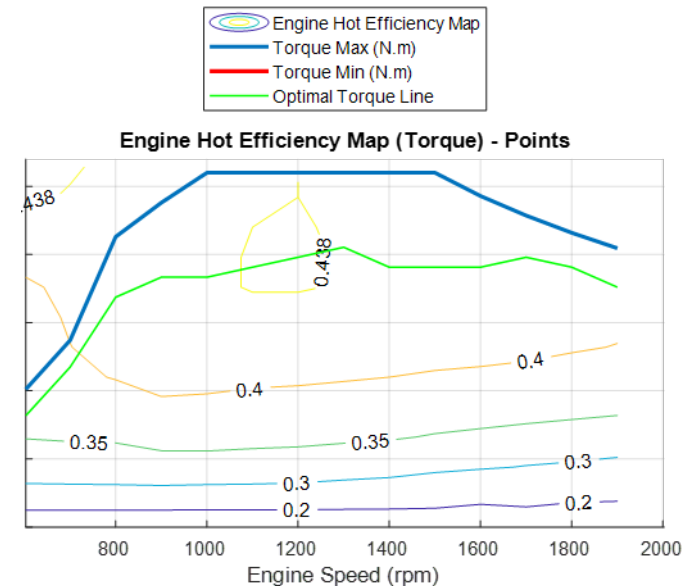
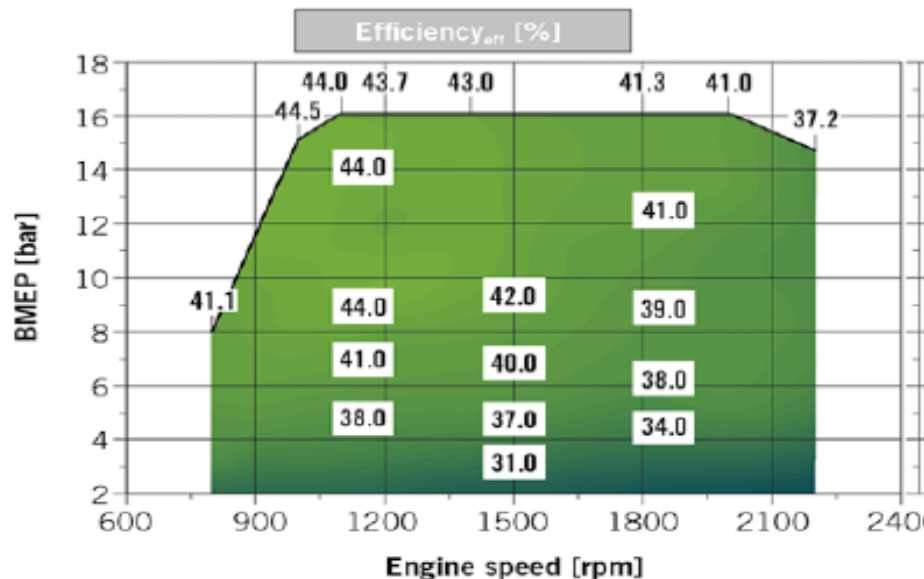
- Expect all technologies to improve over time
 - Improvements in Cd, Cr, light weighting etc will benefit all powertrains
 - Component specific improvements are as shown below

Parameters	Present	2030 (BAU)	2030 (High)
Diesel ICE peak efficiency	47%	50%	54%
H ₂ ICE peak efficiency	44%	48%	49%
FC peak efficiency	60%	64%	68%
FC Cost (\$/kW)	185	110	75
Storage cost (\$/kg)	310	275	250
Battery cost (\$/kWh)	140	100	75

- A simplified TCO calculation provides the costs associated with vehicle and fuel use.
(please see backup slide for simplified TCO calculation assumptions)

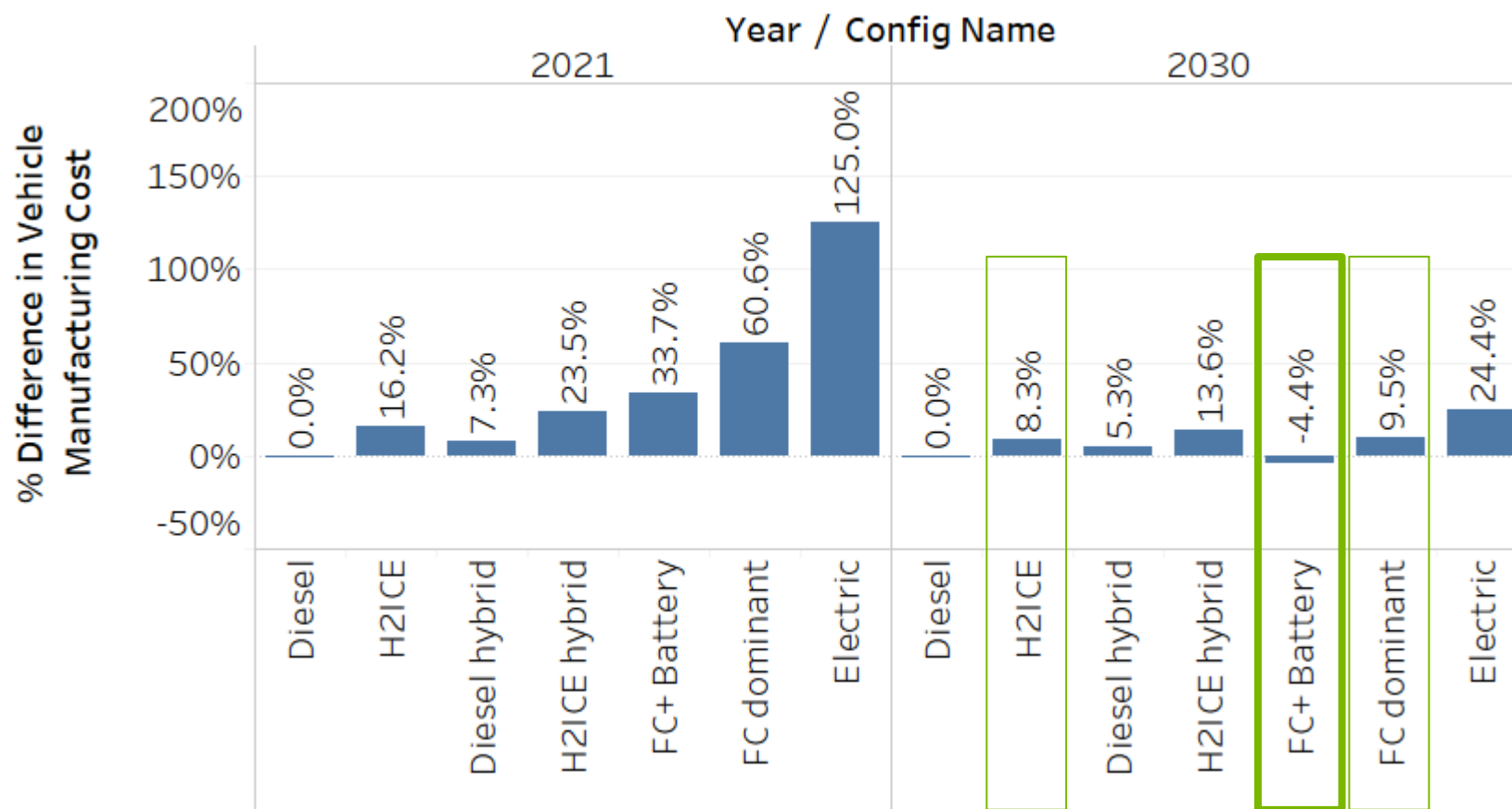
Heavy Duty Truck H₂ICE Fuel Map

- Peak thermal efficiency:
 - 44% (current); 48-49% (2030)
 - Studies have shown that efficiency can be improved further <https://doi.org/10.1016/j.fuel.2021.121909>
 - MECA believes low NO_x targets can be achieved with H₂ICE.
- Engine map modified for Class 8 longhaul and vocational applications based on inputs from industry partners.



* H₂ ICE map developed based on work by Koch et. al

Considering 2030 HFTO and VTO Targets, FCHEV Manufacturing Costs are Lower than Diesel and H₂ICE Vehicles



- Assumes HFTO/VTO R&D targets are met
 - cheaper, durable fuel cells*
 - no appreciable performance loss over the years**
 - hybridized architecture with larger battery pack
- Uncertainly about FC targets
 - Under BAU scenario, FCHEV will be ~9% costlier than diesel.
 - H₂ICE option has lower uncertainty.

* Assuming high volume production for fuel cell systems.

** No oversizing is assumed.

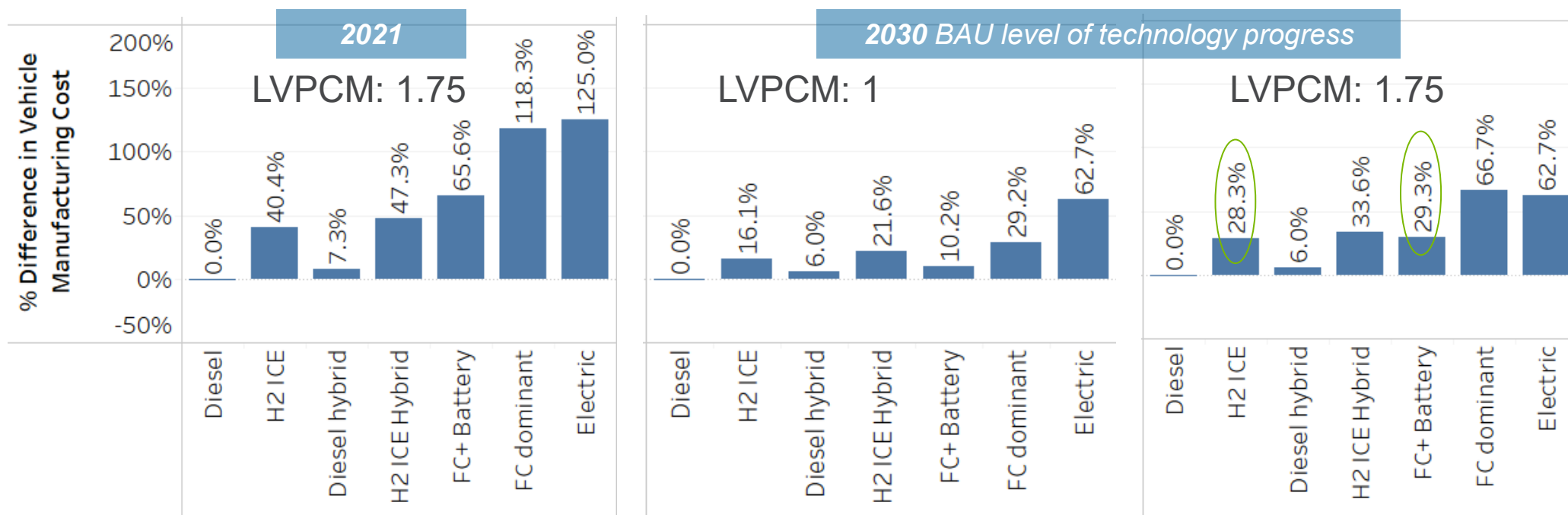
BAU Scenario: H₂ICE Vehicles & FCHEVs have Comparable Vehicle Costs. Both are ~30% Costlier than Diesel Baseline Vehicles.

LVPCM (low volume production cost multiplier) of 1.75 applied for a volume or few thousand units.
At 100k units, this multiplier becomes 1 (HFTO inputs).

Estimated FC cost in 2030

\$75/kW : high production volume

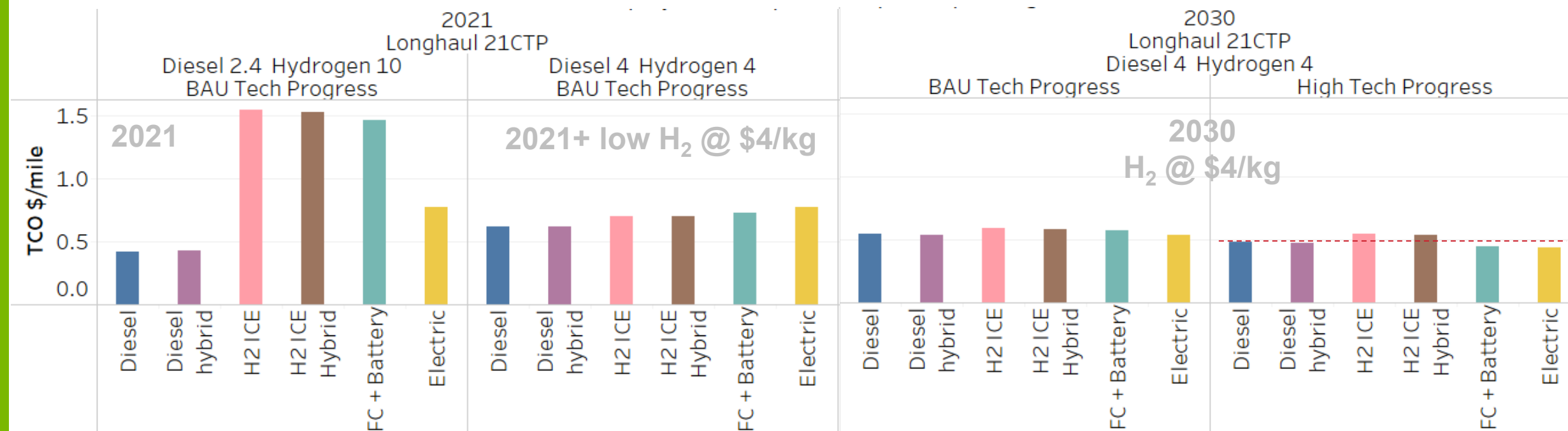
\$130/kW : low production volume



Fuel Cost is Critical to Vehicle Technology Assessment

Long term H₂ cost target from HFTO is \$4/kg.

H₂ICE approaches operating cost parity with diesel vehicles at this cost level.



Note: H2ICE improvements assumed in this work are not as aggressive that in case of diesel ICE or FC systems.
DOE funded research could potentially improve H₂ICE even further.

Class 8 Long Haul Overview Summary:

Present day scenario (assuming high volume production for FC)

Negative values denote cases that are better than the baseline vehicle considered

	Vs. Conventional Diesel			Vs. FC HEV	
	H2ICE Conv	H2ICE Hybrid	FC HEV	H2 ICE Conv	H2 ICE Hybrid
Fuel Consumption (diesel equiv)	14%	8%	-4%	18%	12%
Manufacturing Cost	16%	24%	34%	-14%	-8%
TCO Diesel \$4/gallon H ₂ \$4/kg	25%	22%	14%	10%	7%

Class 8 Long Haul Overview Summary: 2030 high technology progress scenario

Negative values denote cases that are better than the baseline vehicle considered

	Vs. Conventional Diesel			Vs. FC HEV	
	H2ICE Conv	H2ICE Hybrid	FC HEV	H2 ICE Conv	H2 ICE Hybrid
Fuel Consumption (diesel equiv)	20%	5%	-14%	40%	22%
Manufacturing Cost	8%	14%	-4%	13%	19%
TCO Diesel \$4/gallon H ₂ \$4/kg	26%	16%	-4%	31%	21%

Overall GHG Impact

Results from GREET: Assuming NG-SMR for H₂ pathways, both current and future

WTW CO ₂ e g/mile	Diesel	H ₂ ICE	H ₂ ICE Hybrid	FCHEV
2021	1,724	2,009	1,903	1,691
2030 high	1,365	1,644	1,438	1,177

Cleaner H₂ production is necessary to further reduce the overall CO₂ emission for FCHEVs and H₂ICE.

Compared to Diesel Engines, H₂ICE Offer Significant NO_x Emission Benefits

H₂ICEs have comparable NO_x output as diesel for higher loads and are significantly cleaner at low loads.

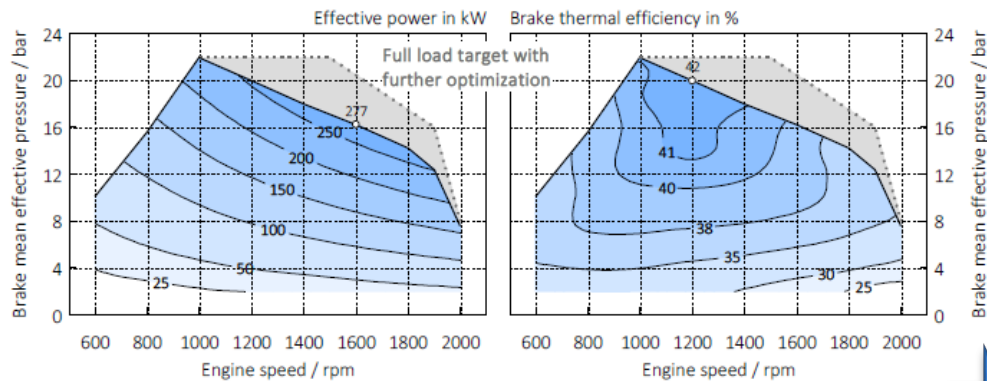


Figure 6: Effective power (left) and brake thermal efficiency (right) in MPI operation

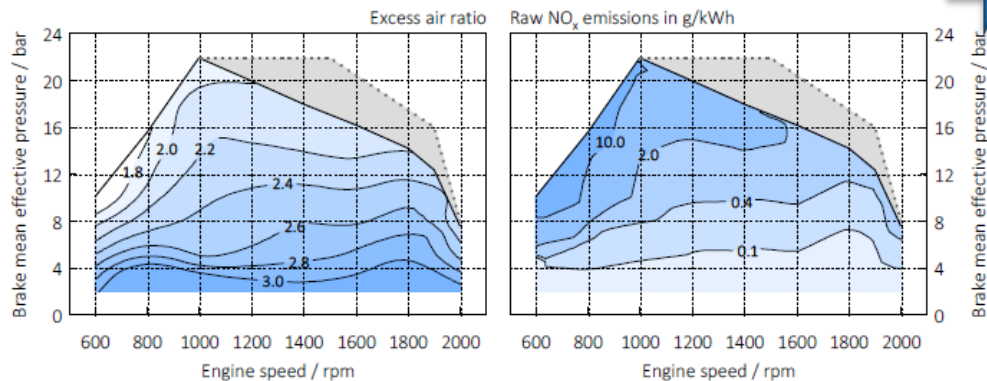
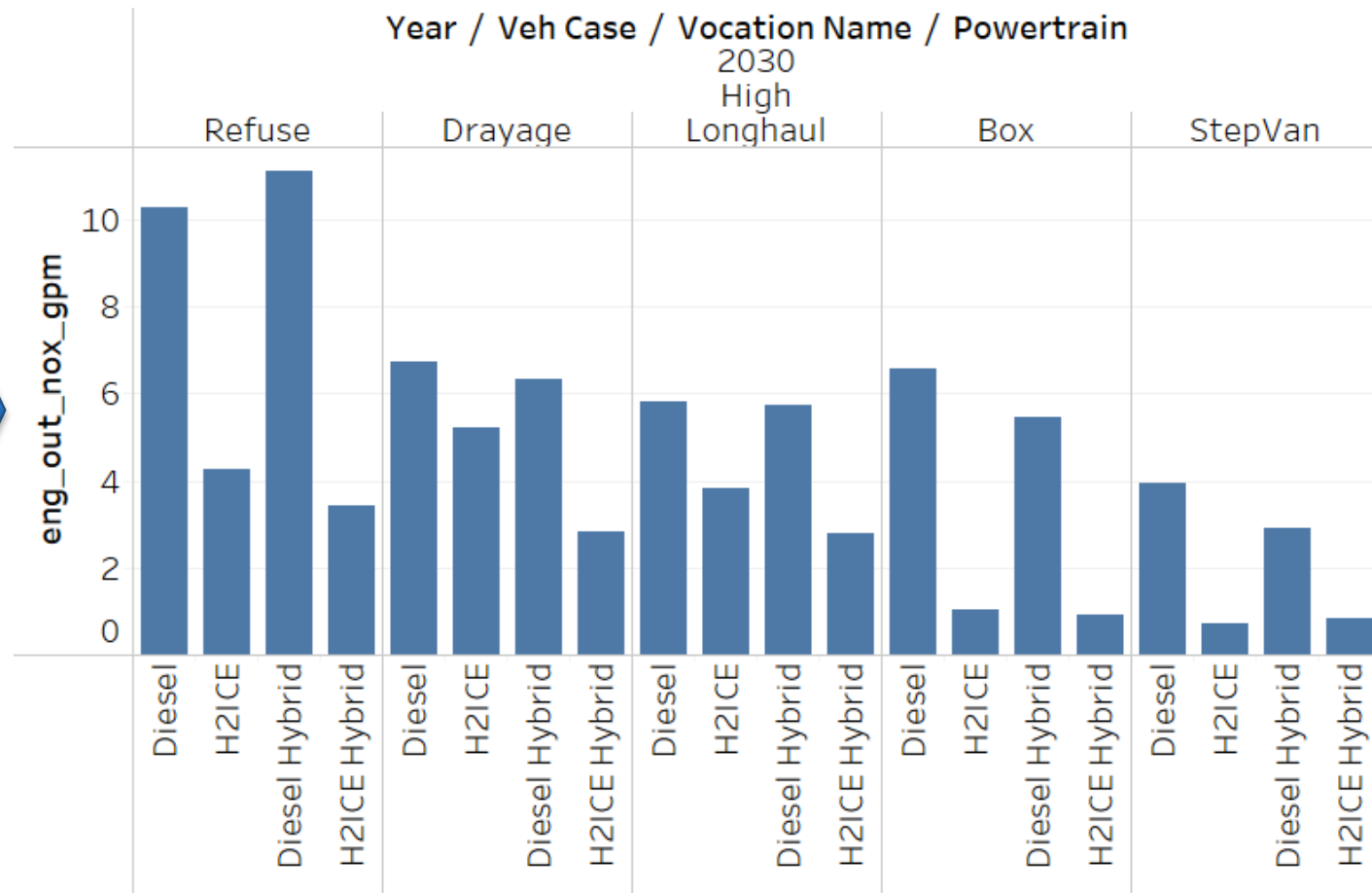


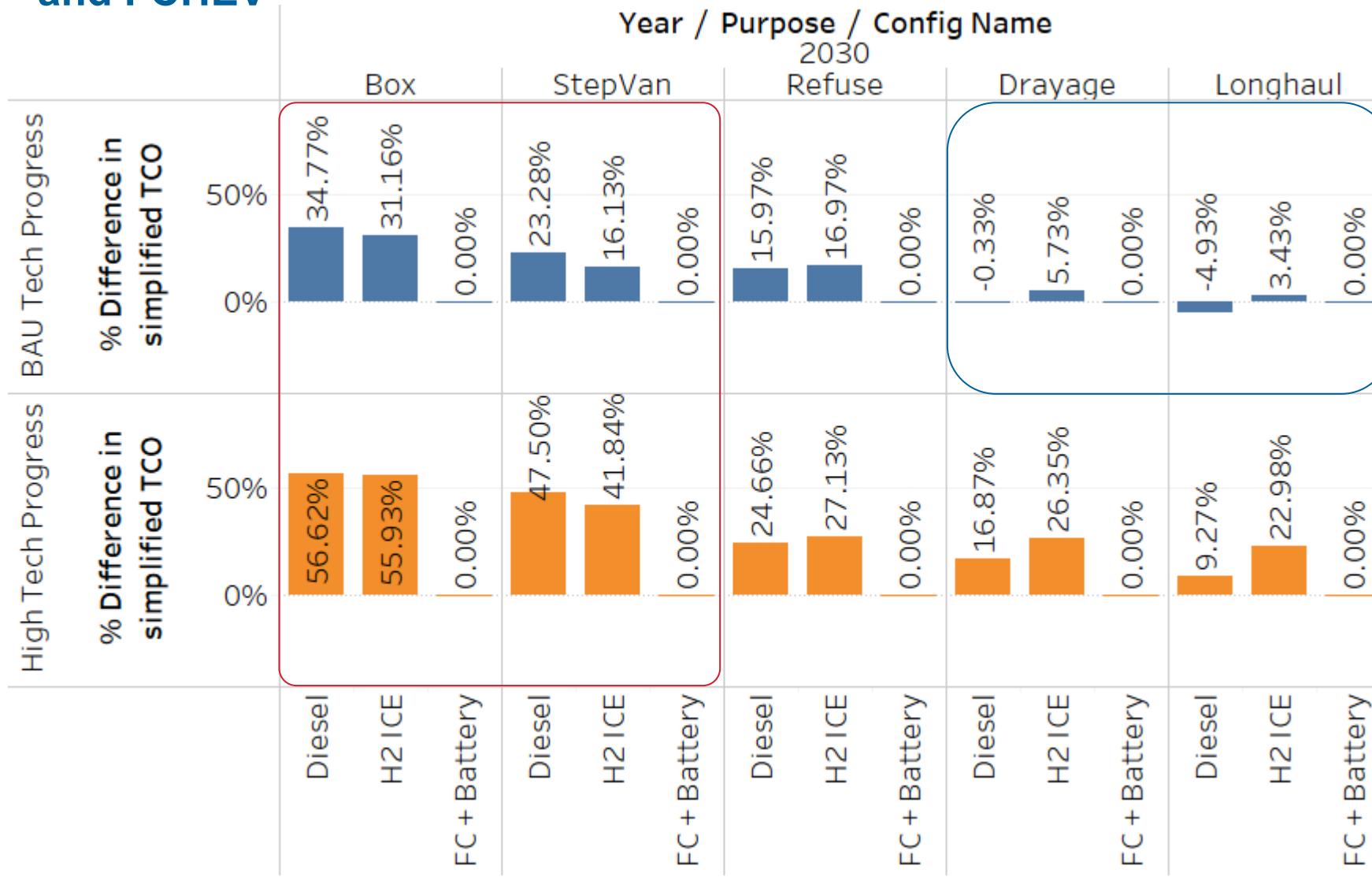
Figure 7: Excess air ratio (left) and raw NO_x emissions (right) in MPI operation



Based on AVL's work on a 12.8L engine

Under BAU scenario, FCHEV & H₂ICE has comparable ownership costs for heavy duty vehicles.

H₂ is assumed to be \$4/kg. Cheaper hydrogen can reduce the TCO difference between H₂ICE and FCHEV



- Under a low technology progress assumption, H₂ICE can be a viable backup
- H₂ICE can provide an economically attractive alternative to Diesels in medium duty applications

Summary

H₂ICEs have the potential to be a bridge technology until HFTO interim targets are met

- **H₂ICE** de-risk H₂ infrastructure investments while offering a viable option for freight decarbonization.
 - H₂ICEs can provide an immediate switch to H₂ as fuel.
 - Help improve the demand and user base for hydrogen infrastructure.
 - DOE funded research can further improve H₂ICE.
- If **HFTO targets & VTO battery targets** are met, FCHEVs will be economically competitive by 2030.
- Hydrogen earth shot is critical for any H₂ fueled vehicle competitiveness

Potential Next Steps

- Include H₂ICE as part of a larger analysis to quantify the potential benefits across more modes of freight transportation and non-road applications.

Thank you!

Contact:

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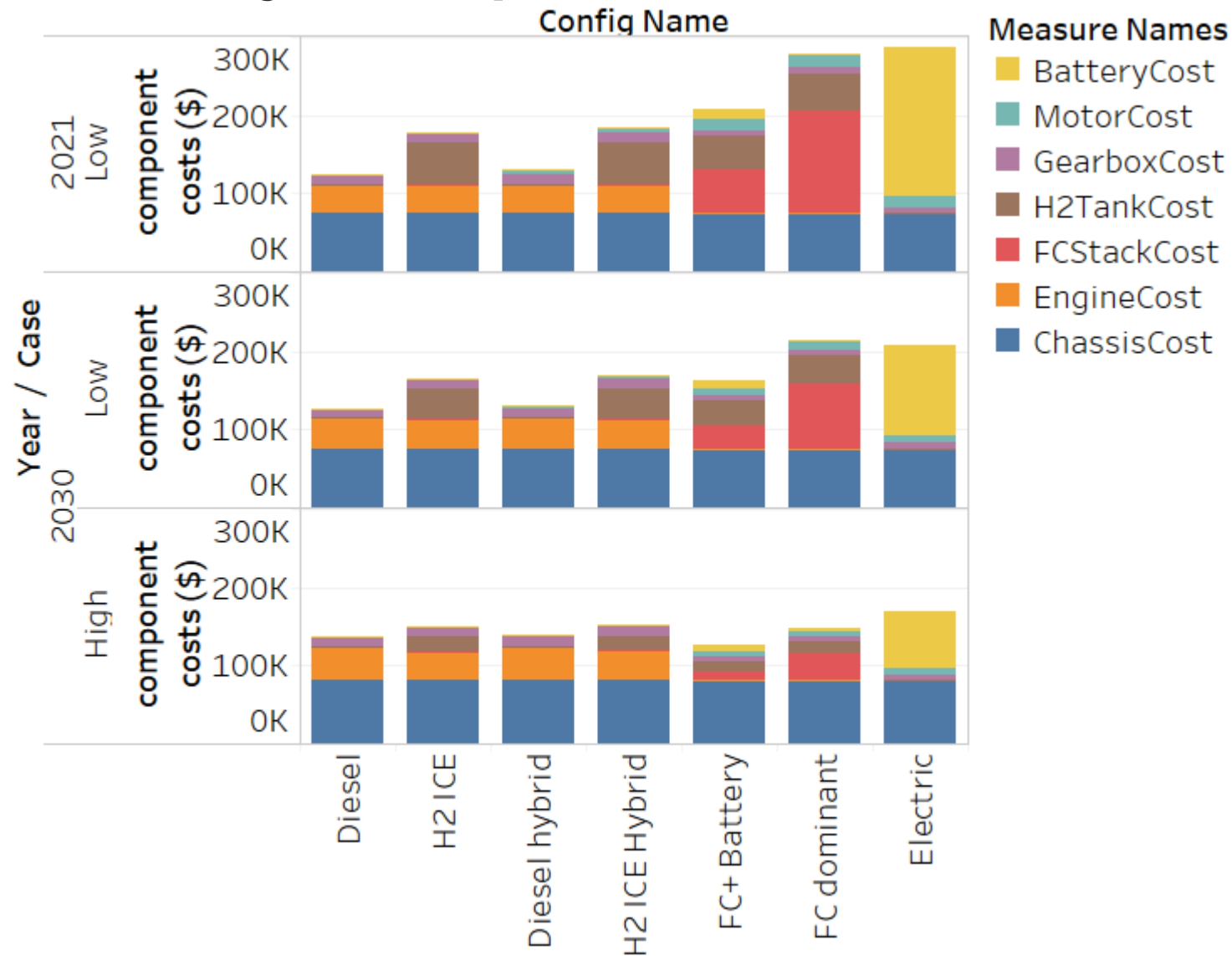
Vehicle System Analysis Group

Vehicle and Mobility Systems Department

TAPS Division

Argonne National Laboratory

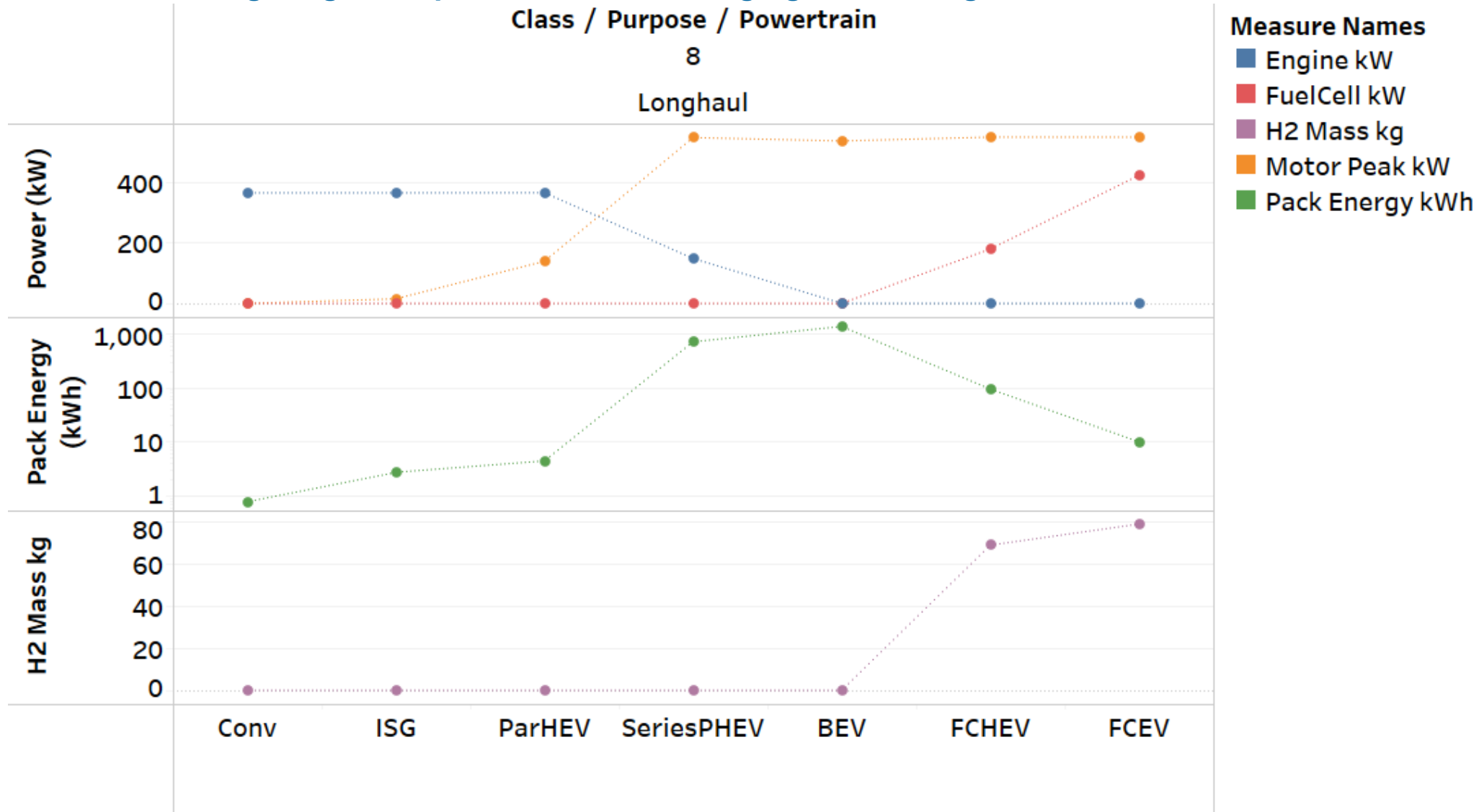
Cost of major components. Evolution over 2021-2030



Note: This cost split up includes LVPCM of 1.75 for 2021 and 2030 low technology progress case

Long haul truck: Component sizes from performance based sizing

500 mile driving range is expected between charging or refueling



Factors considered for Simplified TCO calculation

- Ownership cost comparison covers cost related to vehicle and fuel use.
- Wages, insurance etc are constant across powertrains.

	Parameters	Simplified TCO
Capital expenses	Vehicle purchase price	yes
	Resale value	yes
	Financing costs	no
	Insurance	no
	Registration	no
	Taxes & Incentives	no
Operating expenses	Fuel cost	yes
	Driver Wage	no
	Maintenance	no
	Tolls	no
	Charging time penalty	no
	Cargo limit penalty	no

Parameters	Vocational/Longhaul
Vehicle lifetime	15 years
Service time for TCO	15/5 years
Discount rate	5%
Miles travelled	22k/100k per year

The vehicle purchase price is determined by multiplying the vehicle manufacturing cost by a retail price equivalent (RPE) of 1.2. Resale value is calculated assuming a 15% depreciation year over year. Future expenditures are discounted at 4% per year. Diesel costs are based on the Annual Energy Outlook 2020 after removing federal and state taxes. In all cases, fuel tax will not be considered in the simplified TCO calculation

HEV/PHEV control can be adapted to improve NOx emissions

