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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).

Housekeeping

This webinar is being recorded.

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Technical Issues:

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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

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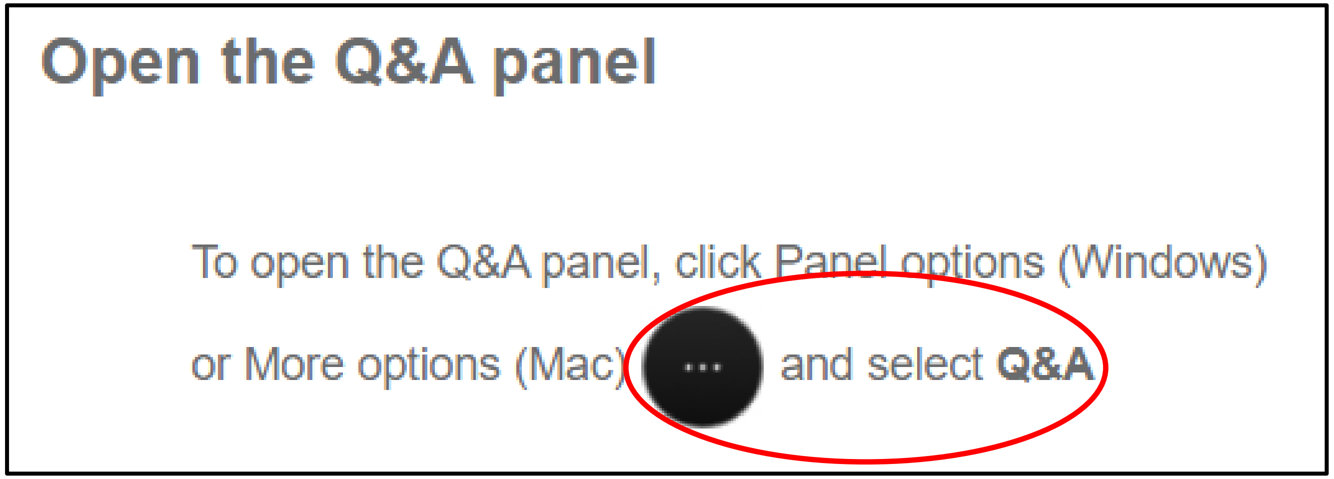
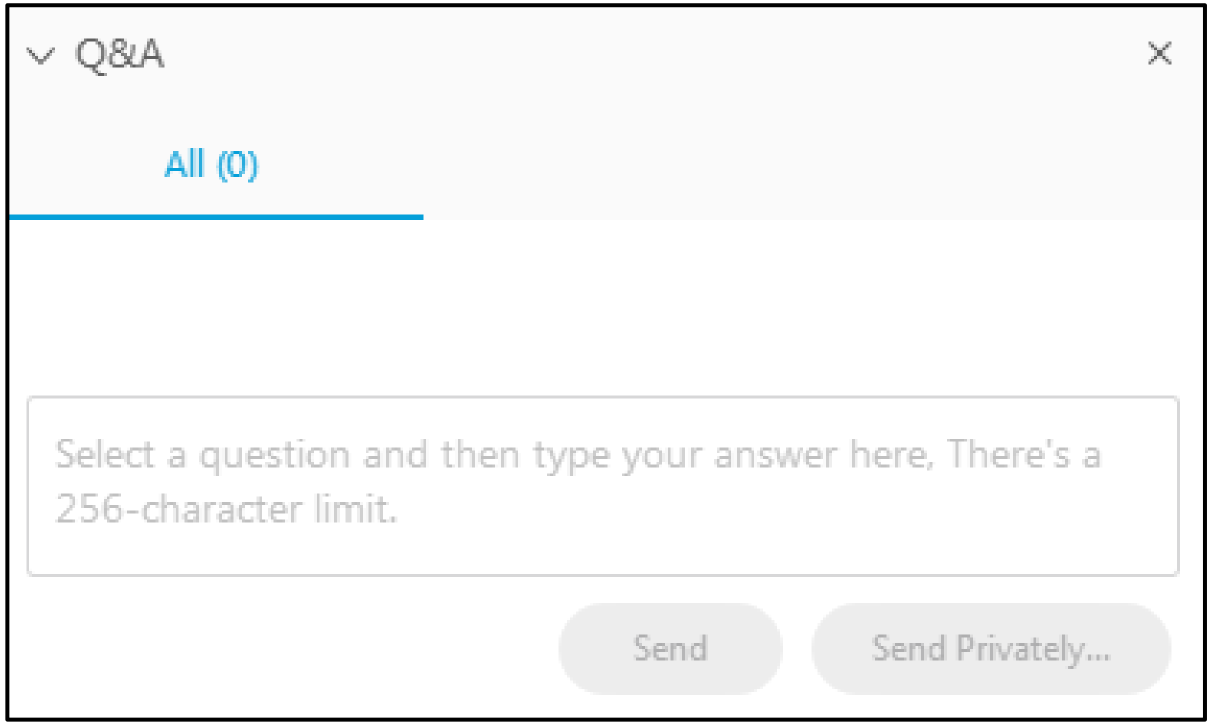
The #H2IQ Hour Q&A

Please type your questions into the Q&A Box





Energy &
Homeland Security

Is there a place for H_2 internal combustion engines?

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KEY TAKE-AWAYS

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

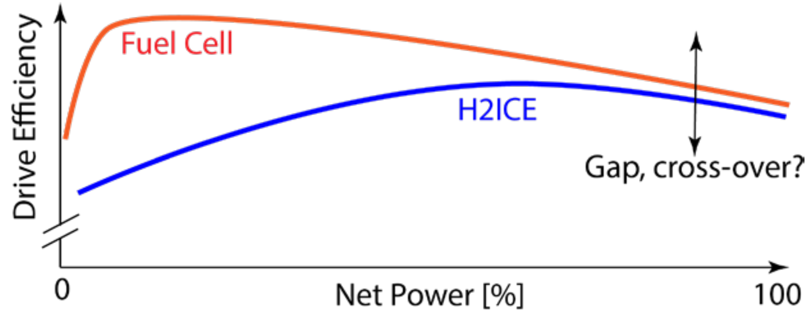
Retrofits

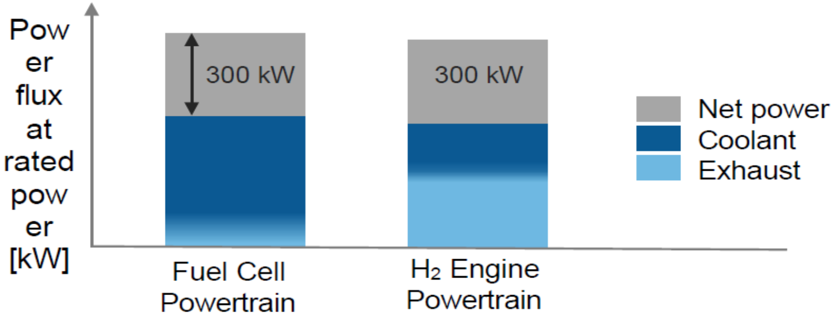
Current engine generational updates and near-term new engine releases

High-efficiency, low emission future generation engines

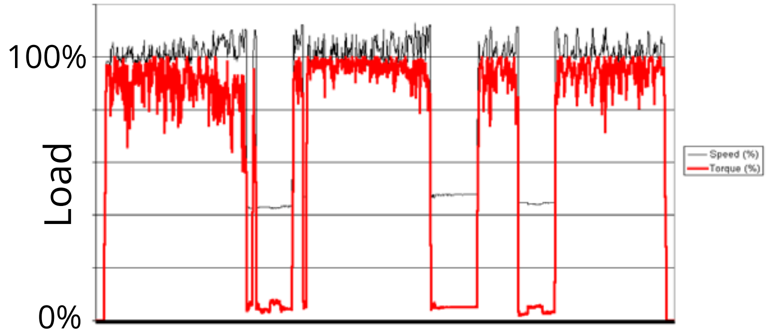
RELATIVE STRENGTHS OF H2ICE AND H2FC – TODAY'S TECHNOLOGY

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



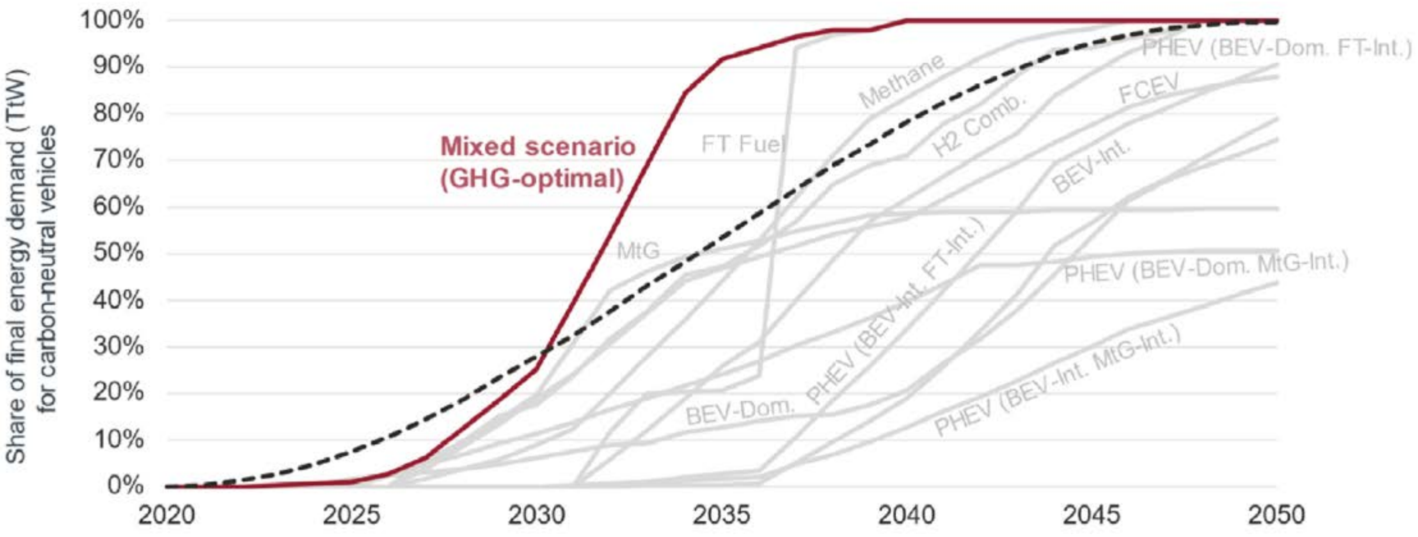
A MIX OF TECHNOLOGIES IS RESILIENT TO MATERIAL & INFRASTRUCTURE BOTTLENECKS AND SUPPLY CHAIN DISRUPTION

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

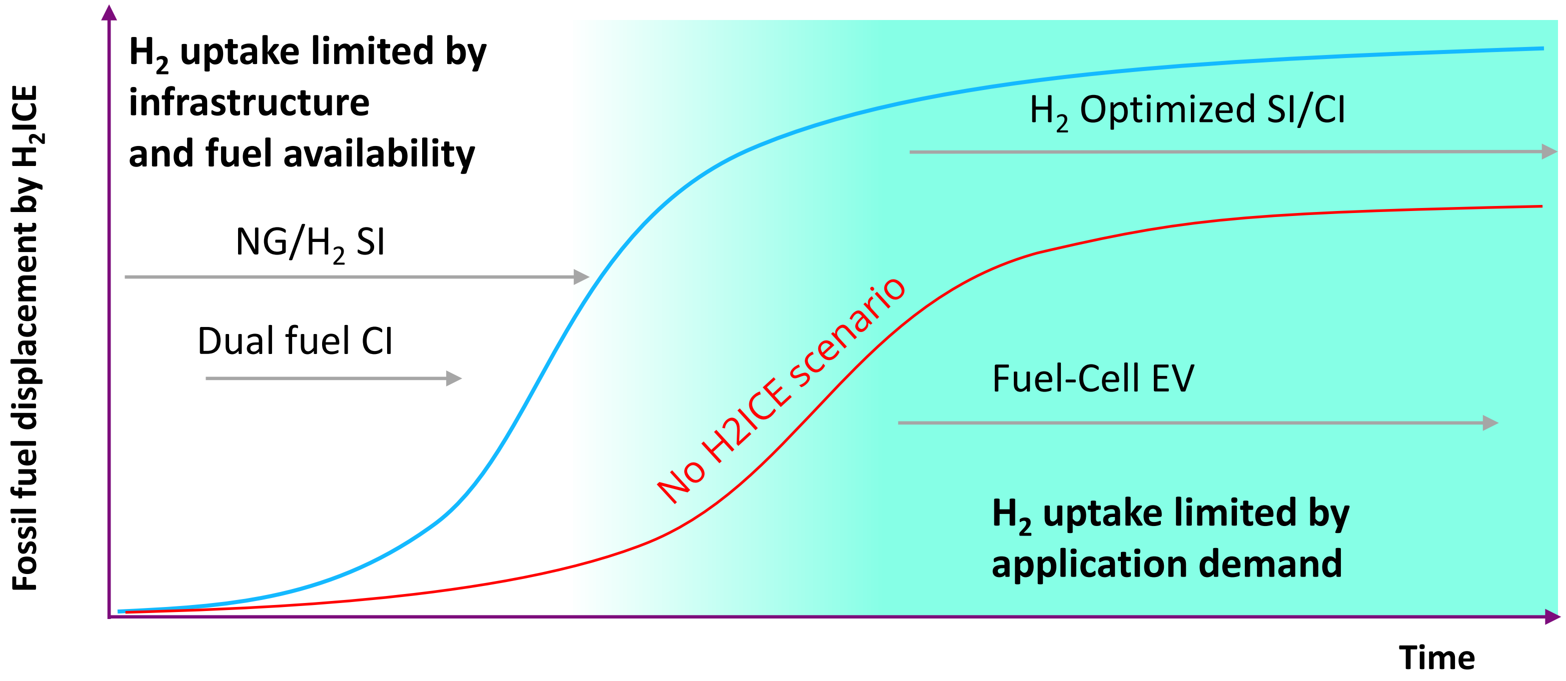
Rate of decarbonization scenarios: Accounting for material/infrastructure limitations



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

H2ICE CAN SPEED DECARBONIZATION & INFRASTRUCTURE DEVELOPMENT



Early adopters

Fuel flexibility: (NG/H_2 blends, low-purity H_2, backup diesel operation

Retrofits: key to decarbonizing the existing fleet

Full H_2 economy

Robustness/TCO:
H_2 penetration into applications challenging for H_2-FC

Key H2-ICE advantages in time

H2ICEs provide for a smooth, continuous transition as H_2 supply and infrastructure develops and the existing fleet turns over

THE CHOICE OF H2ICE OR FUEL CELL IS APPLICATION DEPENDENT

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	+	+		+

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

PREDICTED TCO ADVANTAGE OF FC OVER H2ICE, BUT A CLOSE CALL

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

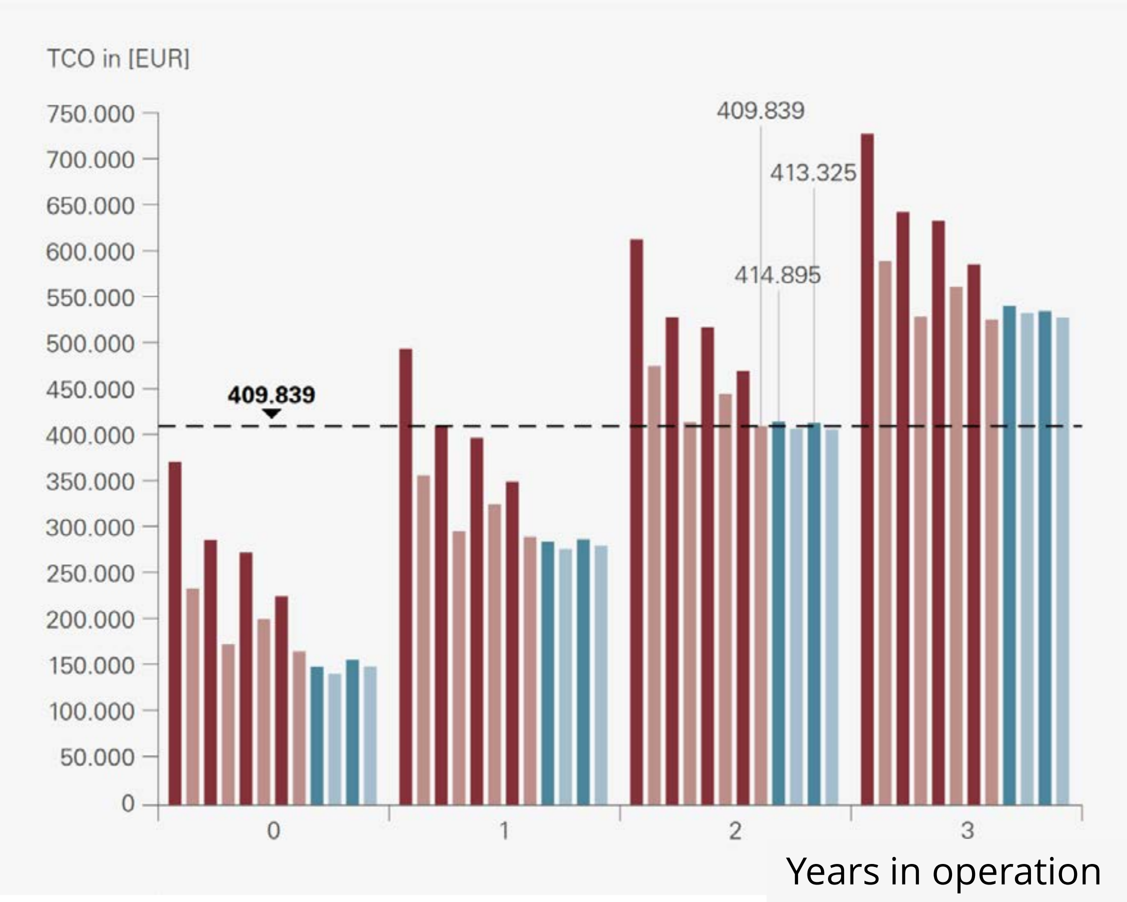
Heavy-Duty trucking
2025 technology and cost:

- 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 H_2 cost, H2ICE: 20% efficiency penalty



Red: FC cases/configurations; Blue: H2ICE configurations

Adapted from: https://www.e-mobilbw.de/fileadmin/media/e-mobilbw/Publikationen/Studien/e-mobilBW-Studie_H2-Systemvergleich.pdf

ADDITIONAL DRIVERS FOR H2-ICE – LEGISLATION, MATERIAL AVAILABILITY, ECONOMIC CONCERNS

DRIVERS for H2ICE

LEGISLATION
ICE bans
Tank-to-wheel legislation
Difficult-to-abate sectors

MATERIALS & INFRASTRUCTURE
ICE: no limitations
FCEV: Platinum
Battery: Lithium/Cobalt
Electrical grid limits
Mining ramp-up

TCO / UPFRONT COST
Low upfront cost
TCO
Resale value

RAPID DECARBONIZATION
No carbon in the fuel
Green, pink H2 potential
Low-carbon CCS H2 pathways

JOB SECURITY
High added value jobs
Domestic labor instead of imported materials

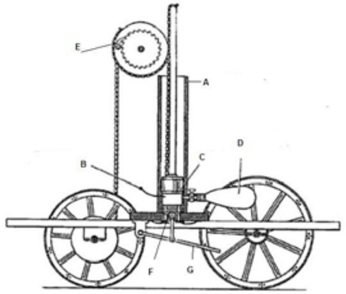
GEOPOLITICAL SECURITY
No reliance on imported minerals
Lower reliance on oil

SUPPLY CHAIN
Domestic supply chain
No shortages foreseen

H_2ICE HAS A LONG HISTORY, CURRENT R&D WAVE UNPRECEDENTED

1800 - 1970

1807: ICE invention (De Rivaz)
First engines run on H_2



Town-gas power generation

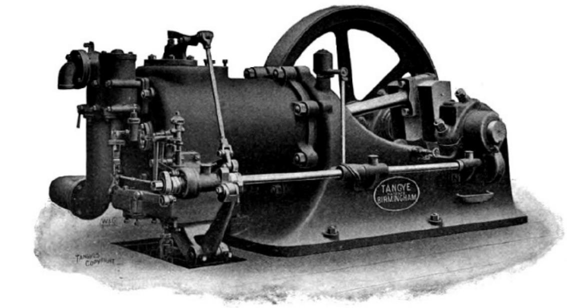


Fig. 54.—Tangye Horizontal Engine.

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

1970-2000

No activity

2000-2012

BMW Gen 1 H_2ICE luxury sedan

BMW Gen 2 H_2ICE
100 units sold (2005-07)
uses DI tech.

GM-Opel
LD commercial
demonstrator

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

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

Dutch H_2-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

2020 - present

Revived interest in H_2ICE:

- Heavy-Duty
- Off-road
- Power gen

MAN, JCB, SCANIA, HINO, ISUZU, DAF, Wabtec Corporation, DEUTZ, HYUNDAI, PACCAR, CAT, BOSCH, INNIO, LIEBHERR, VOLVO

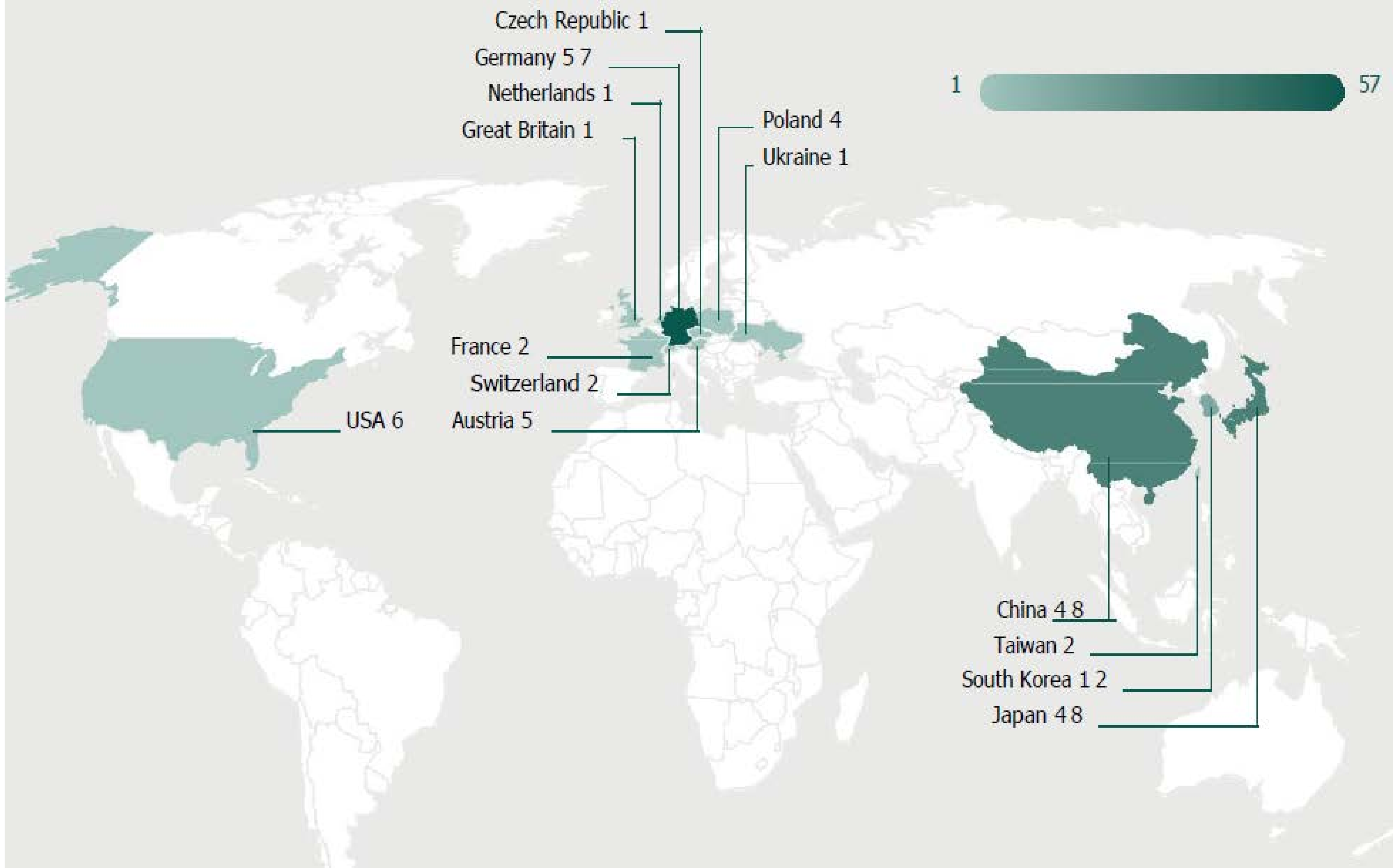
mtu A Rolls-Royce solution, DAIMLER TRUCK, RENAULT TRUCKS, Cummins, FPT Powertrain Technologies, MITSUBISHI HEAVY INDUSTRIES, NGK, Westport Fuel Systems, Kawasaki Powering your potential, DENSO, JOHN DEERE, ANGLO BELGIAN CORPORATION We power your future, BorgWarner, TENNECO, MAHLE, WÄRTSILÄ, CLAAS, achatesPOWER, SuperTurbo Technologies, HOERBIGER

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

GEOGRAPHICAL DISTRIBUTION OF PATENTS RELATED TO H2 ENGINE COMBUSTION

- 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/

OVERVIEW OF H2ICE LEGISLATORY FRAMEWORK

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

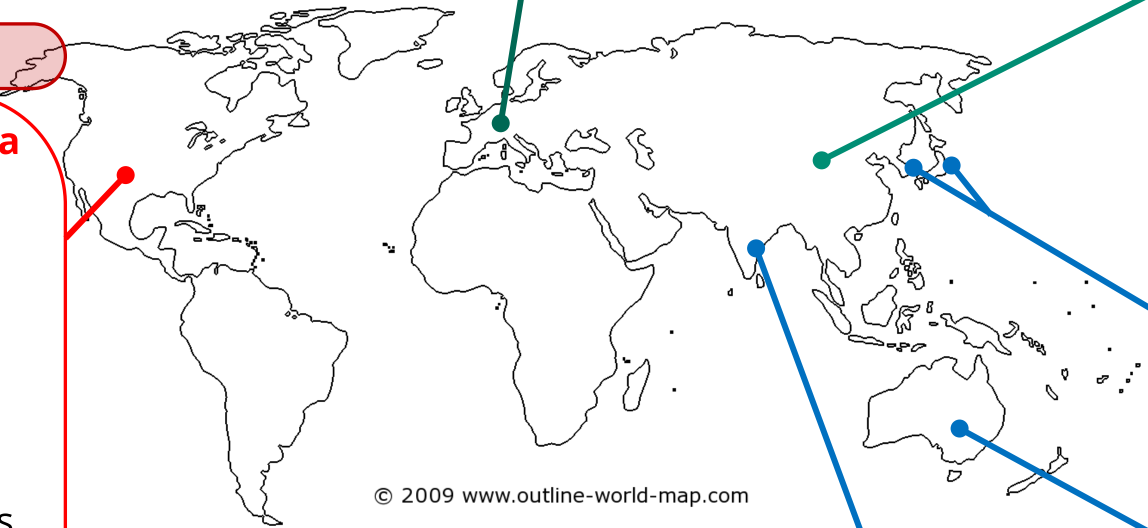
- **H2ICE listed on strategic level[2]**
  Strategy lists R&D needs for advanced and alternative fuels
- Strategy promotes formulation of “urgently needed” standards

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 H_2 exporter (green and blue H_2)

[1] EU 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)

ALLIANZ WASSERSTOFF MOTOR

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

HYDROGEN OPPOSED-PISTON ENGINE WORKING GROUP

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

Hoerbiger H2DI inj.

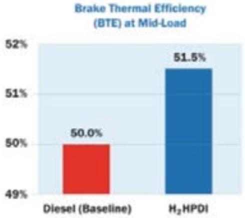
Westport H2 HPDI

BorgWarner H2ICE LDV demonstrator

Daimler DD15 PFI H2ICE 44.5% efficiency, 335kW

DAF HF H2-ICE demo 2022 truck innovation award

Scania 51.5% BTE using HPDI



BorgWarner H2-DI injector series production

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
Hoerbiger injection system

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
Hoerbiger injectors

Liebherr
H2-DI injectors

Liebherr 966
H2ICE, PFI, 13L

Liebherr
BAUMA 2022
award

50ton H2ICE excavator demo.

Start
Wabtec CRADA
H2ICE for rail

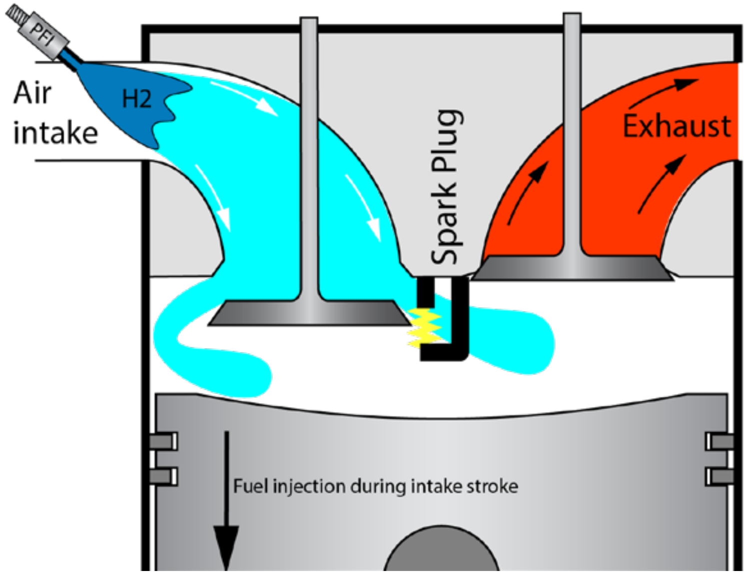
Wabtec CRADA completed (PFI and DI technologies)

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

Kawasaki YANMAR J-ENG

H2ICE TECHNICAL CONCEPTS DIFFERENTIATED BY FUEL INJECTION

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

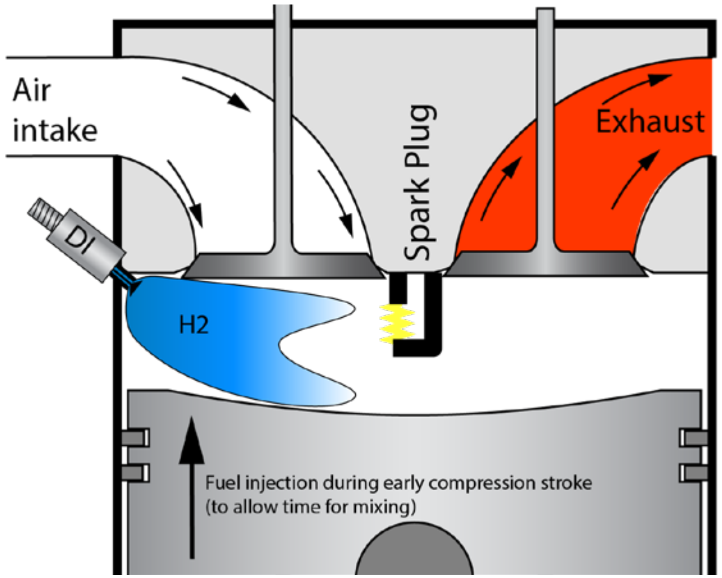


Key challenges: power density, abnormal combustion, efficiency

"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

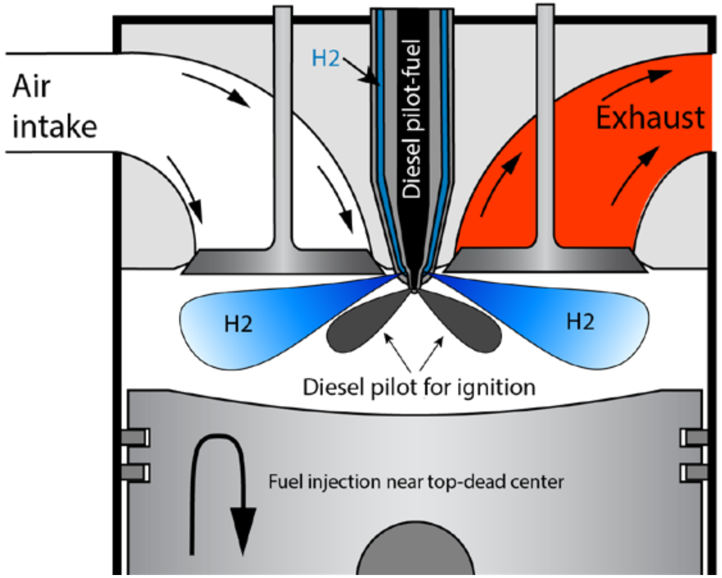


Key challenges: injection technology, abnormal combustion

"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

AFTERTREATMENT OPTIONS

Current legislation –
Option (1) series diesel aftertreatment is sufficient

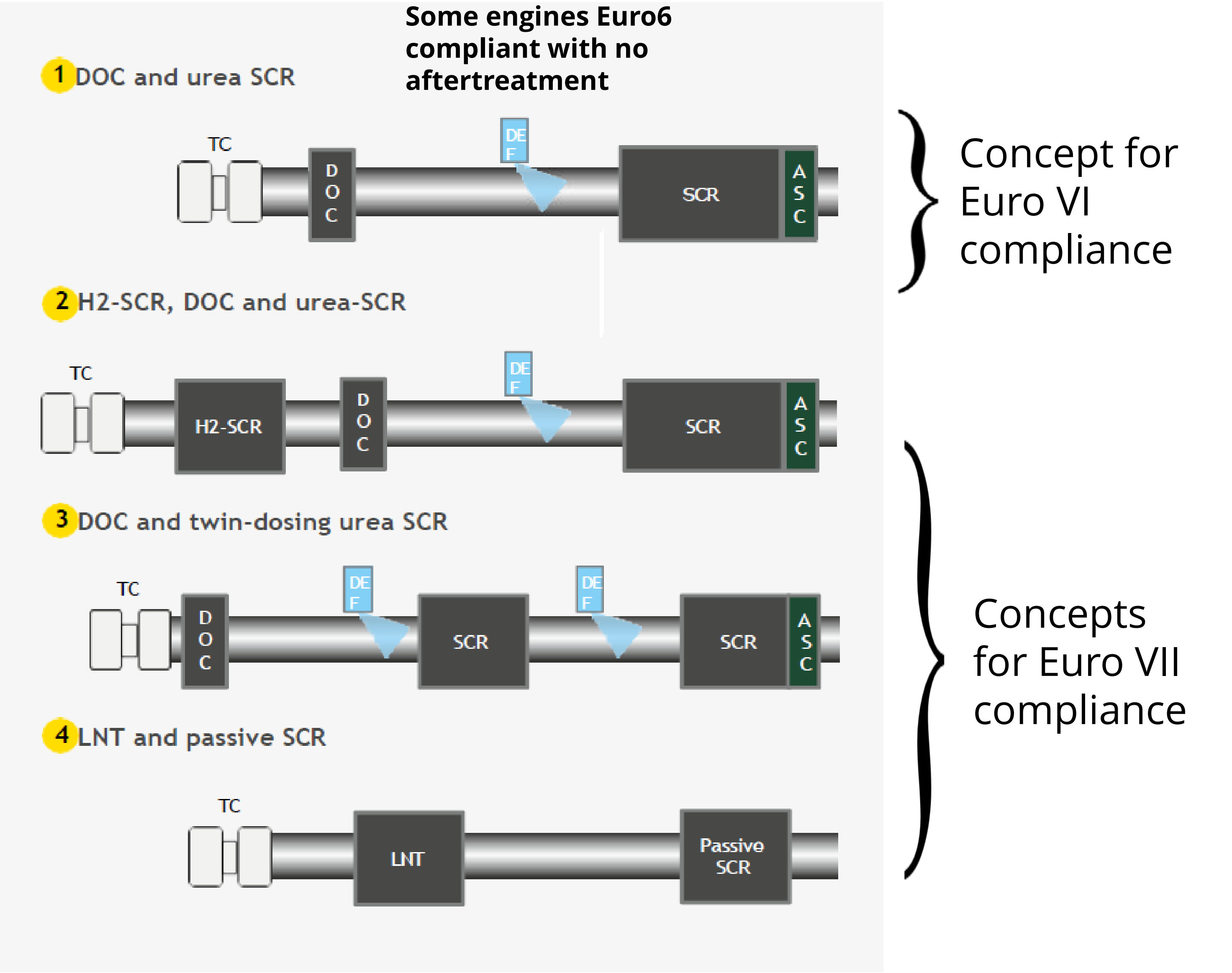
- 0.58g CO2 / 1g NOx emissions from DEF fluid
- Some engines compliant without aftertreatment (<0.1g/kWh in most op. points)

Future legislation (Euro VII, CARB27)

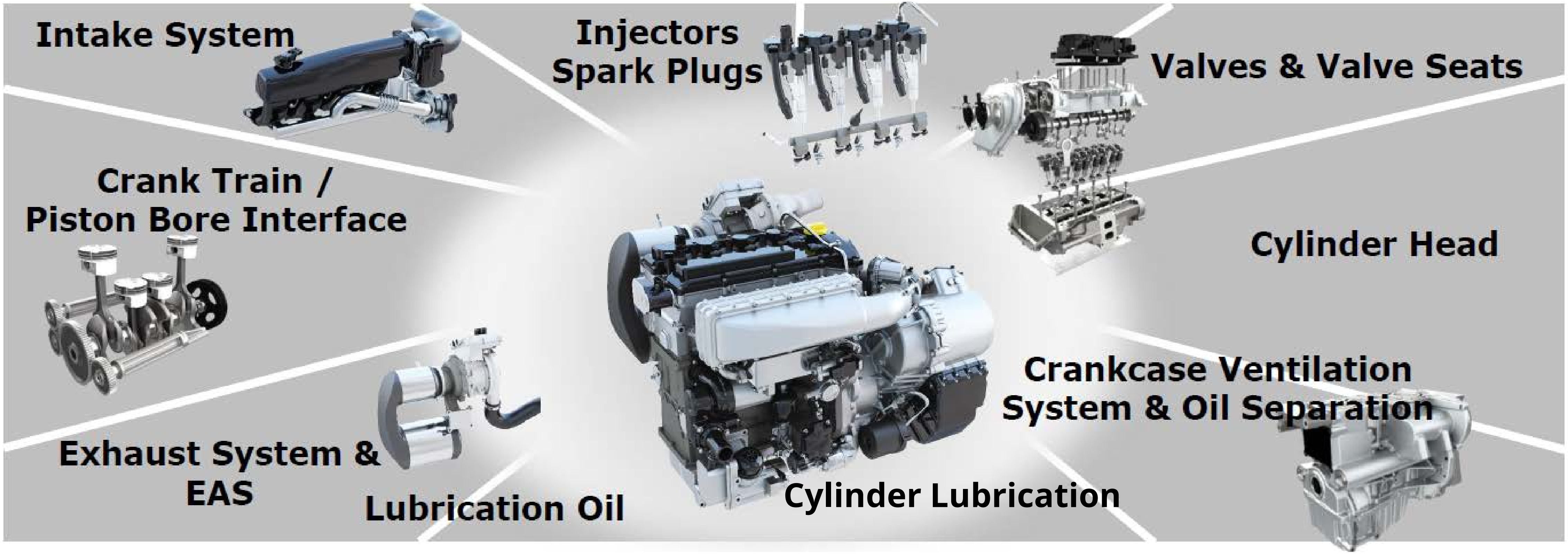
- Option (3) is ready
- (2) and (4) need further research
- **Challenges**:
  - CO_2 emission (3)
  - Potential N_2O emission (2)
  - Durability (1M miles)
  - Noble metal use for (4)

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

Source: https://www.now-gmbh.de/wp-content/uploads/2021/10/NOW_Metastudie_Wasserstoff-Verbrennungsmotor.pdf



CURRENT R&D ACTIVITIES AND TECHNOLOGY GAPS



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

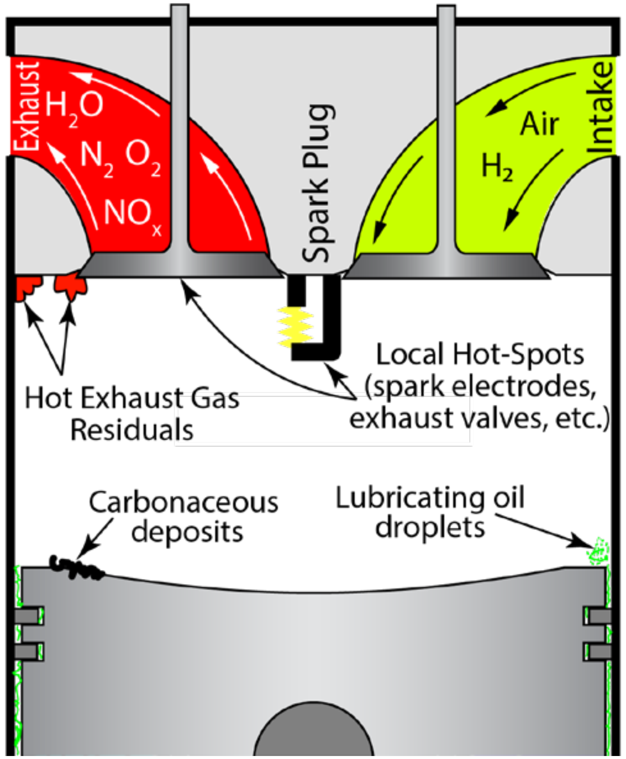
Current OEM perspective:

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"

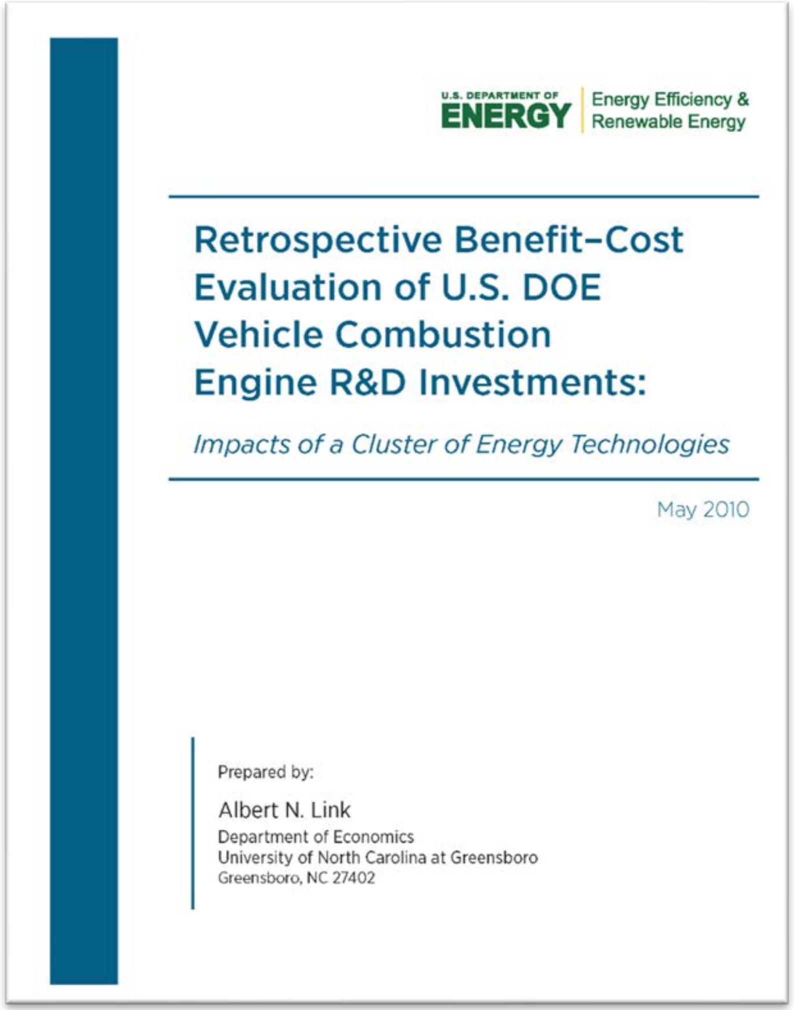


Challenges	Knowledge Gaps
Preignition & knock: mitigation and detection	Phenomenological understanding of key pre-ignition mechanisms
Injection and mixing: full optimization, NOx mitigation	In-cylinder mixing validation data Predictive CFD modelling Injector design guidelines
Flame/wall interactions Heat-loss, material thermal stress	H_2 near-wall quenching/reactions Accurate heat-loss models
Predictive simulations of H2ICE combustion process	Kinetics of H2/NG/renew. diesel fuel blends
Multi-fuel operation using single hardware configuration	Combustion strategies & controls
Reduced power density relative to diesel counterparts, efficiency	Strategies for increasing power density & efficiency
NOx emission in certain operating points	Alternative NO_x mitigation strategies (e.g. H_2O inj.)

Impact
Efficiency, range, emissions, cost, accelerated development

Improvements to existing products through component retrofit

HISTORICALLY LARGE AND RAPID RETURN ON INVESTMENT IN FUNDAMENTAL RESEARCH



U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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 CO_2.
- **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 CO_2 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

CONCLUSIONS

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

- Complementary strengths of H_2ICE and H_2FC will accelerate adoption of H_2 economy
- Robustness, short time-to-market, existing supply chain, low Pt requirements, and HD weight/packaging constraints can favor H_2ICEs
  - Power-generation w/CHP, off-road, certain vocational vehicles, potentially even long-haul trucking
- H_2ICE in small-series production by 2025 and full-scale by 2027-2030
- H_2ICE 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 H_2 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

ACKNOWLEDGEMENTS

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- Paul Miles – Manager, Sandia 8362
- Sandia Center 8300 leadership team
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- 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 Eidhoven
- University of Orleans
- Seoul National University
- Marquette University
- Indian Institute of Technology Kanpur
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- STEMS, Italy
- University of Duisburg-Essen
- University of New South Wales

APPENDIX INDEX:
SUMMARY SLIDES FOR MANY KEY H2ICE PLAYERS WORLDWIDE

Page:

Page:

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.

Daimler Truck & Bus | Mercedes-Benz | FREIGHTLINER | FUSO | DETROIT

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.

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.

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

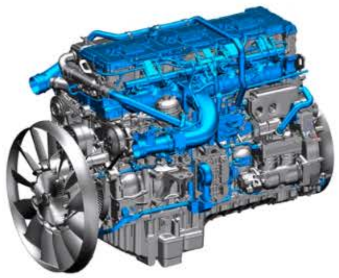
- 44.5% efficiency, Ultra-Low NOx standard achieved with 2020 production ATS
- No specific hardware issues after 450h of operation

ⓘ Main design changes and engine adaptions to realize H2-ICE with state-of-the-art spark ignition technology

Ignition system
- Sparkplugs, ignition coils, adapted cylinder head & cover

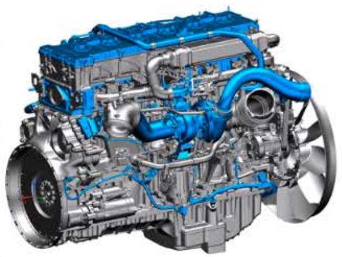
Hydrogen fuel and injection system
- Gas regulator, PFI-valves, common rail, vent line

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



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

+ Ultra low NOx 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

Technical view: Sources of CO_2, when measuring at the tailpipe

1. CO_2 ambient air (ca. 416 ppm)
2. Carbon compounds in fuel (e.g. <100 ppm CH_4)[1)]
3. Lube oil consumption (typ. value 0,05% of diesel[2)] consumption)
4. Carbon content urea (CH_4N_2O)

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 NOx raw < ca. 1g/kWh

Volvo transition to fossil free Heavy Duty transport solutions

Long-term ambition: 100% Safe, Net zero CO_2 and more productive

VOLVO

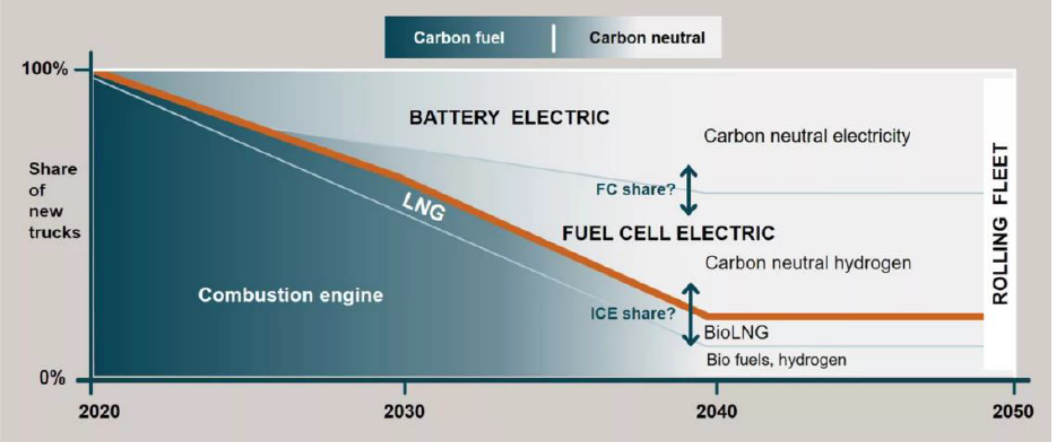
https://www.volvogroup.com/en/future-of-transportation/going-fossil-free.html

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 1,5^0 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:

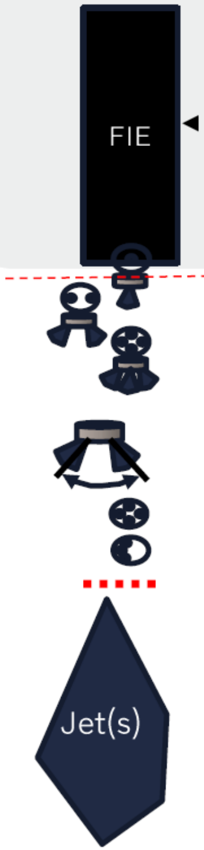
- Example of key development challenges are:
  - Stable combustion and reasonable thermal efficiency in combination with achieving true "zero-emission"
- A key advantage in relation to electric propulsion solutions is a lower production cost and less use of scarce minerals
- We are currently in an AE phase of H_2-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 H_2-ICE exhaust
  - Hydrogen storage and safety, metal hydrogen embrittlement and durability of new components

H_2-ICE research areas

Main Research Question:
Mixing of light fuel gas into a heavy gas ?

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

Pfuel



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
- H_2 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)

Research methods
- Combustion vessel (spray-chamber)
- Single-cylinder engine (SCE)
- Fully optical SCE
- H_2 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

* Of special interest for CFD validation

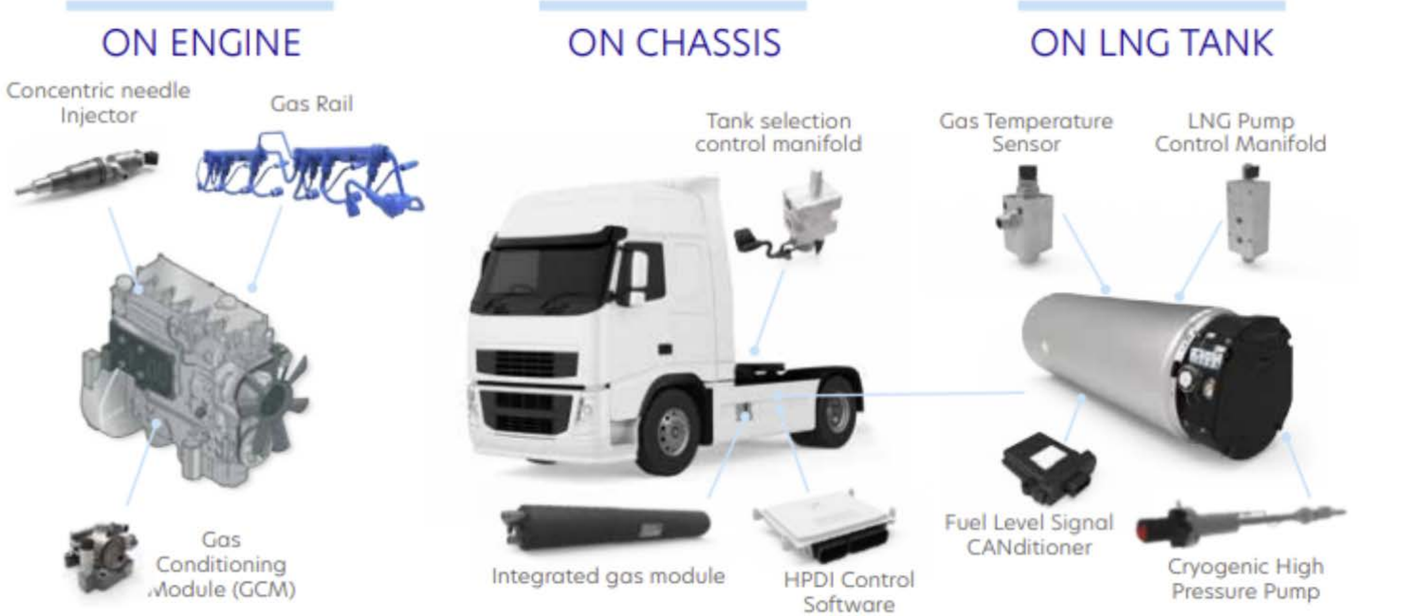
Westport Fuel Systems

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%

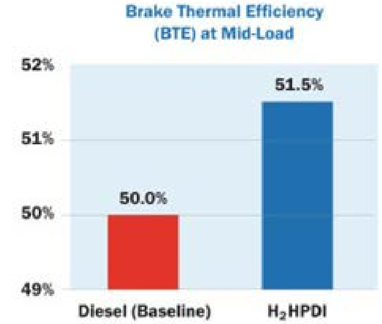
Developed from LNG system with thousands of units readily operational



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

SCANIA

Results of H2-HPDI testing with SCANIA



The engine test results from the Scania 13-Litre CBE platform running with Westport's H_2 HPDI fuel system demonstrates even higher efficiency than the already super-efficient diesel engine.

Modified Scania 13L 6-cylinder engine using Westport HDPI 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

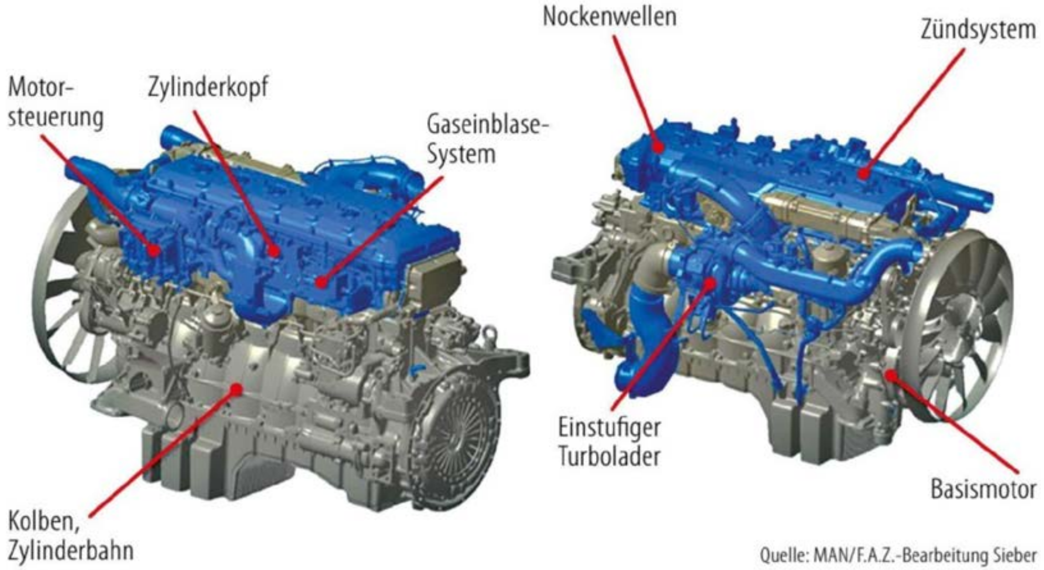
MAN Truck&Bus is developing H2ICE and H2FC in parallel

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 commonnality

Demo vehicle with H2ICE

Required engine modifications in blue



Sources:
Link1
Link2
Link3

£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

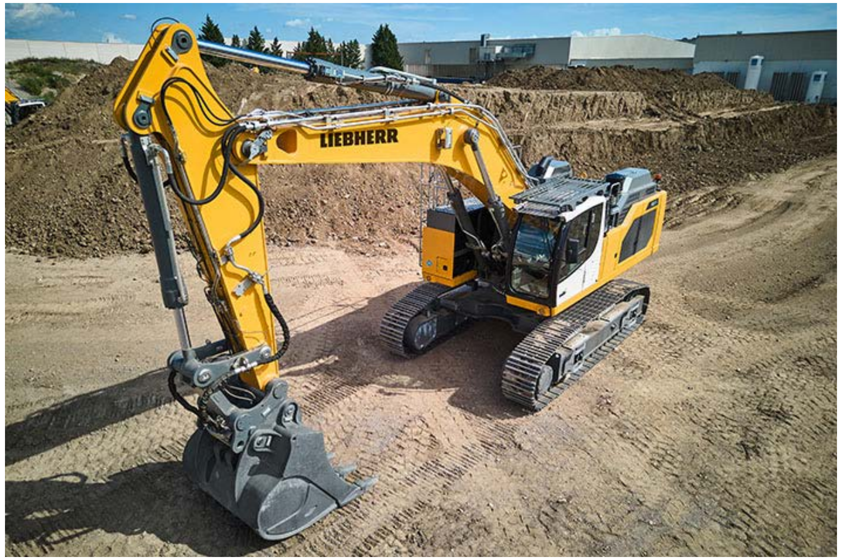
Source:
JCB webpage,
accessed 1/10/2023
Link 1
Link 2
Link 3

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



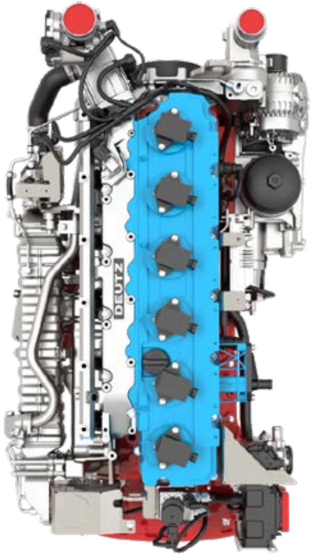
Liebherr H2DI injectors and 964 9L DI H2ICE

Liebherr 966 13.5L PFI H2ICE

Source: https://www.liebherr.com/en/usa/latest-news/news-press-releases/news-press-releases.html

DEUTZ TCG 7.8 Hydrogen ICE

DEUTZ®



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 CO_2/kWh
2. necessary for high power density and dynamic

PROJECT

2021

1st Engine on Test Bench

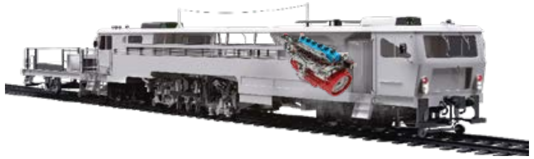
2022

Pilot Operation Genset

2023
Product Industrialization

2024
SoP

FIELD TEST

Rail


Truck
HyCET
Hydrogen Combustion Engine Truck

Hydraulic Excavator


H2 DEUTZ
HYDROGEN TECHNOLOGY

KEYOU

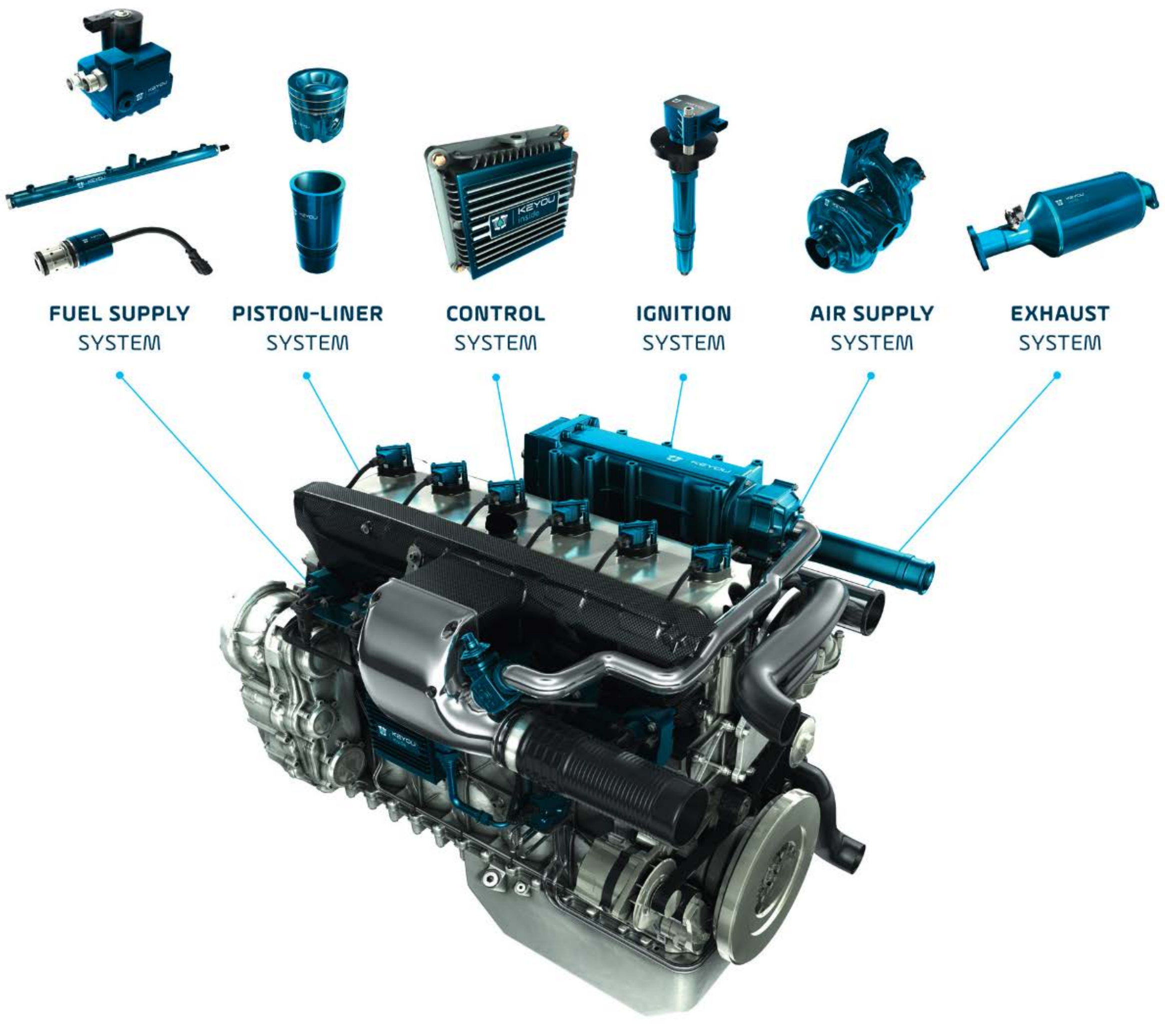
First engine conversion kits in 2017

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

Keyou technology for conversion of diesel engines



Demonstrator vehicles

Source: https://www.keyou.de/

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

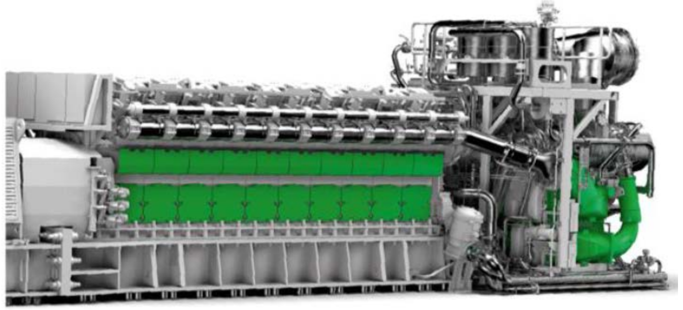
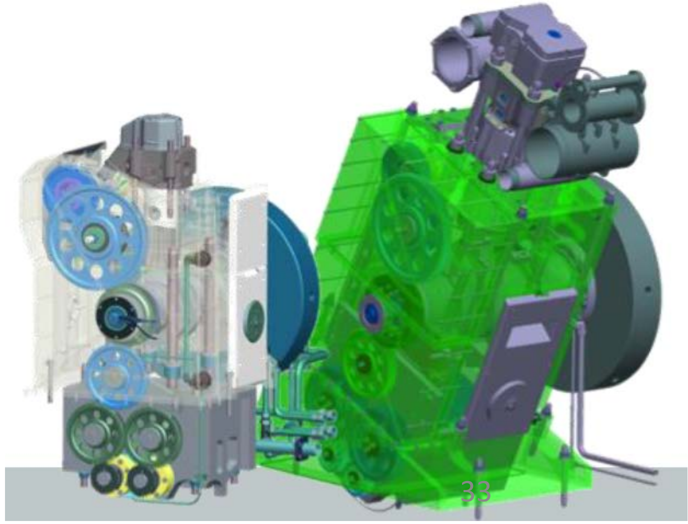
Hydrogen addition (30 v%) to natural gas and pure hydrogen operation in multicylinder engine (~ 6 liters/cylinder)
Investigation of combustion abnormalities and impact of lubricant formulations
Investigation of spark ignition and diesel pilot injection concepts
Investigation of fuel injection concepts
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

"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

achates POWER
MARQUETTE UNIVERSITY BE THE DIFFERENCE.
aramco
ENGINE RESEARCH CENTER UNIVERSITY OF WISCONSIN – MADISON est 1946
SUPERTURBO TECHNOLOGIES
University of Michigan Powertrain Control Laboratory
ALLIANCE for VEHICLE EFFICIENCY
DI2S Duret Innovative 2-Stroke Consulting & Training
Stanadyne
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
ID 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.

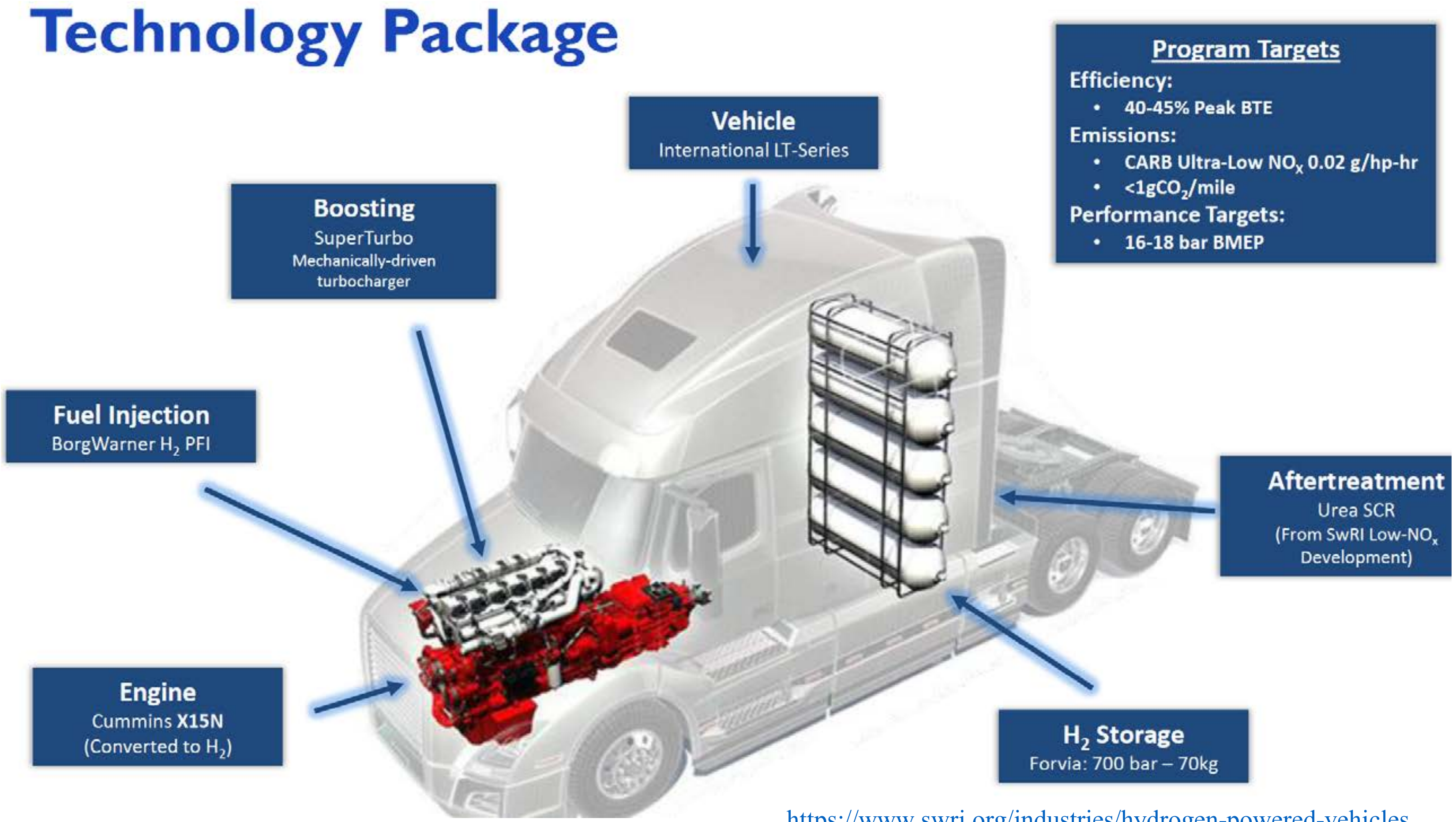
The Truck Innovation Award - which acknowledges the enormous technological changes and energy transition taking place within the automotive sector - has been awarded by the International Truck of the Year (IToY) jury, a group of 25 commercial vehicle editors and senior journalists, representing major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



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

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

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

- Near-zero CO2 and PM
- Ultra-low NOx

- 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

H2 ICE development and demonstration program

Key barriers for H2 ICE development and deployment:
- Unclear legislation creates uncertainty for OEM inverstments: 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

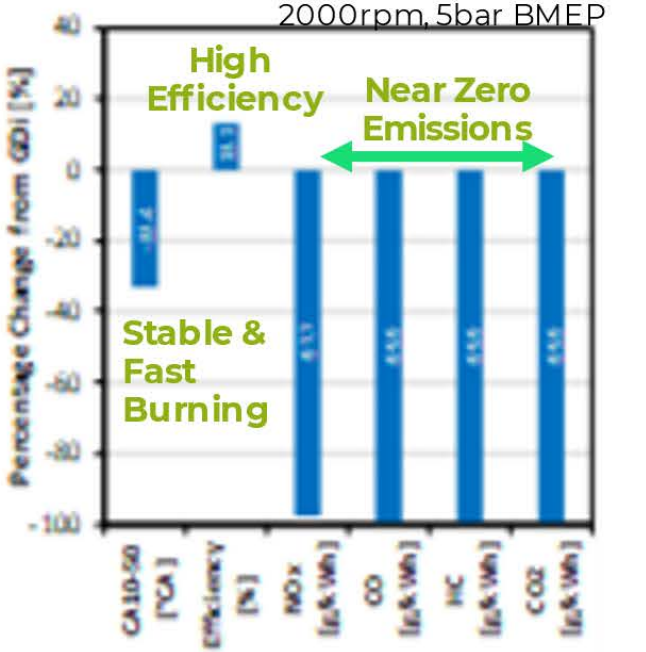
Hydrogen Combustion

Can be an attractive path to CO_2 neutral transportation for PC, CV and Off-road

Historical limitations of H_2ICE are disappearing:

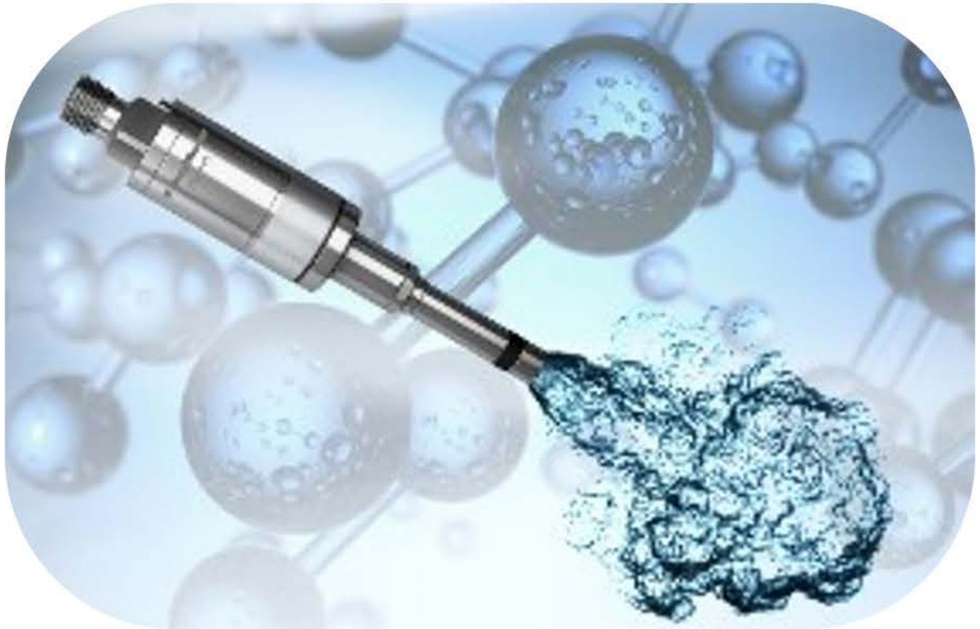
- Motivation→ Push for Zero CO2 solutions
- H_2 supply infrastructure→ USA/EU/Asia support
- Combustion control→ Injection system
- Broad industry commitments

1.5L 4CYL PERFORMANCE



BW H_2 system

H_2, Water & SCR Injectors, Rail, Actuators & Sensors, ECU & SW



- Re use powertrain production assets
- Meet/ Exceed current ICE efficiency
- Cost effective Zero CO_2 solution
- Flexible to hydrogen quality
- Fast to Market at Volume
- High durability capability

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

BorgWarner

H2 Engine Research & Development Topics

MD/HD/OR Applications

Currently, more than 130 worldwide OEMs are interested in, planning or running H_2 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
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- **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)

Hoerbiger injection systems

Full portfolio of injection and ignition products for a range of engine size

Application	Engine size	HOERBIGER portfolio for H2 ICEs		
		H2PFI	H2DI	Ignition
Medium Duty Mobility (on- and off-road)	6-10 litres	GVC10		AH2IS-M
Heavy Duty Mobility (on- and off-road)	10-13 litres	GVC10	GVC7	AH2IS-M
Heavy Duty+ Mobility (on- and off-road)	15+ litres		GVC8	AH2IS-M
Small Stationary Gensets	<1 MW	GVC10	GVC24	AH2IS-S
Midsize Stationary Gensets	2-4 MW	GV40 / GVC40		AH2IS-S
Large Stationary Gensets	>10 MW	GV400		AH2IS-S

PFI small-series fleet demonstrations in 2004

HyperFuel

ePCC DI

H2DI GVC13

H2DI GV7

H2DI GV8

2001 Market Introduction Direct Injection for 2 Stroke Natural Gas Engines

2007-2012 Concept Studies High Pressure Hydrogen DI

2014 Introduction of the ePCC DI - Electronic Pre-Chamber Direct Injection

2018 Start Development Medium/Low Pressure Hydrogen Direct Injection

2019 Introduction Platform H2 DI GVC13

2020 Introduction Platform H2 DI GV7

2021 New Platforms for Medium Duty and Industrial Power Generation

H2DI GVC 24

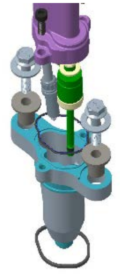
Select reference projects:

- First 1MW H2 engine with Innio Jenbacher
- First H2 off-road engine with Deutz
- First H2 carrier vehicle with Keyou (Unimog)
- Successful upgrades of serial natural gas injectors to 100% H2 opoeration

Component & Combustion system development for H_2 ICE

Combustion process

- MAHLE Jet Ignition (MJI) ® concept
- H_2 ICE pre-chamber ignition to enable ultra lean combustion

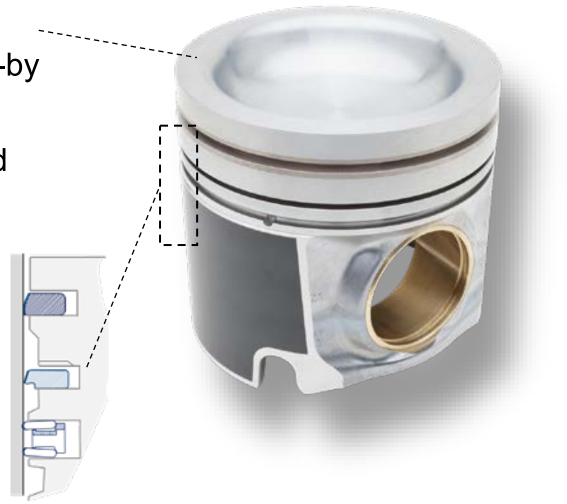


Pistons

- 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

- H_2 compatible material
- Blow-by reduction
- Reduction of oil consumption and related particle formation



Valve set

- H_2 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 H_2 concentration

MAHLE high pressure impactor

Evolutionary development: optimized components for zero CO_2 combustion engine technology

MAHLE Powertrain

Hydrogen-capable injectors as part of newly-lauched 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:

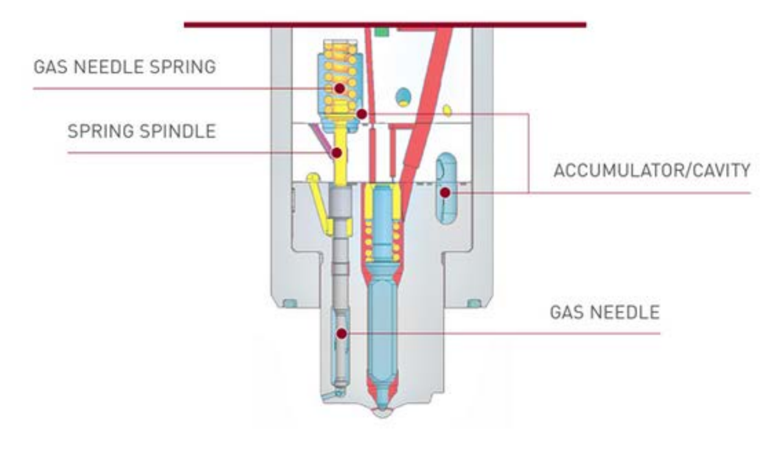
- Up to 30bar injection pressure
- No leakage

Port injection options:

- Modification of existing NG engine products

Direct injector for H2
30bar operating pressure

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

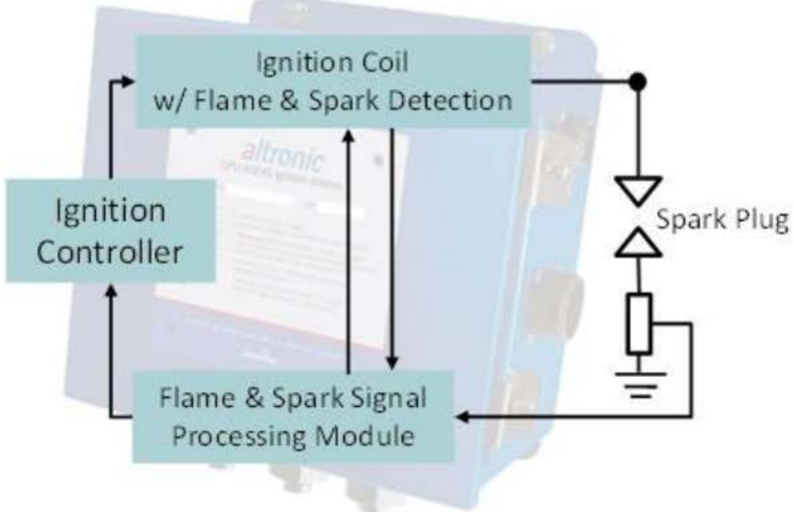


Source: https://www.woodward.com/about/about-woodward/woodward-lorange/produkte/p2x-multi-fuel-injectors

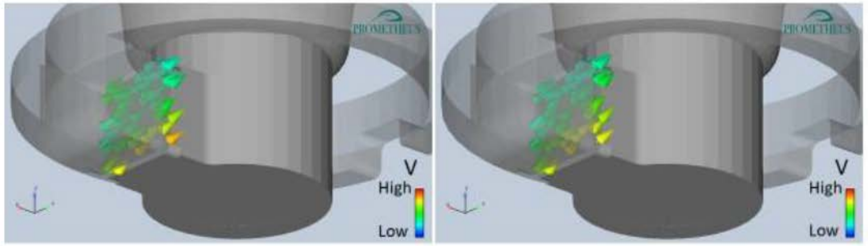
L'orange YOUR POWERFUL INJECTION
WOODWARD Always Innovating for a Better Future

Altronic advanced ignition systems (in collaboration with Prometheus)

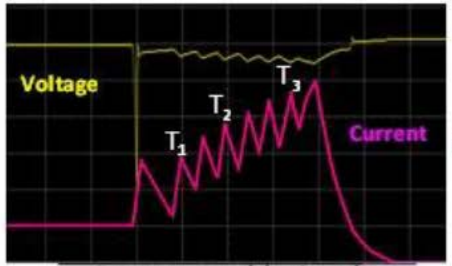
Same-cycle feedback-based ignition control system to minimize cyclic variability and control abnormal combustion



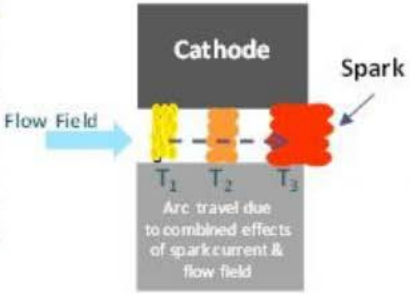
Advanced Prechamber Plug

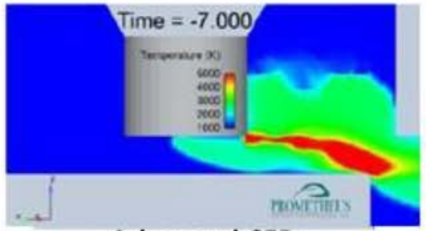


Cycle #1 Cycle #2



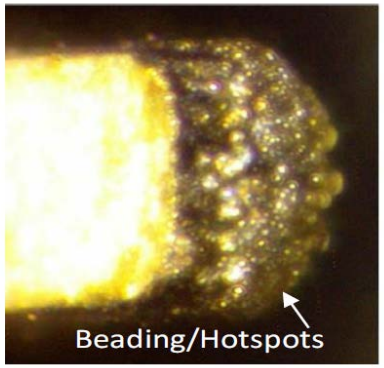
Programmable Spark Current & Voltage

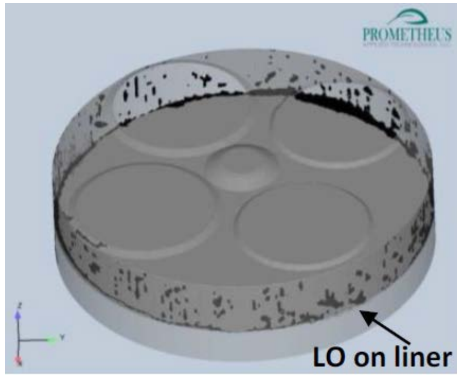




Advanced CFD: Spark (red)/Flame (green)

Mitigation of pre-ignition





altronic PROMETHEUS APPLIED TECHNOLOGIES ADAPT H_2

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.

Accelleron | Albonair | APL Group | AVL | Bendion | BorgWarner | BOSCH | bp | Castrol | CLAAS | Cummins | DAIMLER TRUCK | DEUTZ | Eberspächer | EDAG | FEV | Flexider Automotive | FREUDENBERG | FUCHS | Georgsmarienhütte GMH Gruppe | HELLER | Hirschvogel Group | HJS | IAV | ISUZU | ITAZ GmbH | JWFROEHLICH | Kässbohrer | KIT | KST | LIEBHERR | Linde | MAHLE | MAN | michael rein | MWM | NAGEL | NGK | Poppe+Potthoff | Schaeffler Engineering | Simerics | STADLER | STILL | tmax | TUPY | umicore | Webasto | Westfalia Metal Hoses | Westport Fuel Systems | Witzenmann

Source: https://allianz-wasserstoffmotor.de/en/home.html

Netherlands – Green Transport Delta – Hydrogen consortium

Consortium partners:

DAF, Prins Alternative Fuel Systems, Koedood Dieselservice B.V., Mitsubishi Turbocharger and Engine Europe B.V., NPS Diesel Engine Applications, DENS Dutch Energy Solutions, bosal, GINAF, VDL, Vialle, Circonica, DLS Drive Line Systems, Bronkhorst, KROHNE, hobré Analyzer Solutions, Resato, VSL Dutch Metrology Institute, TNO, TU/e Eindhoven University of Technology, university of groningen

Main objective – develop three technologies:

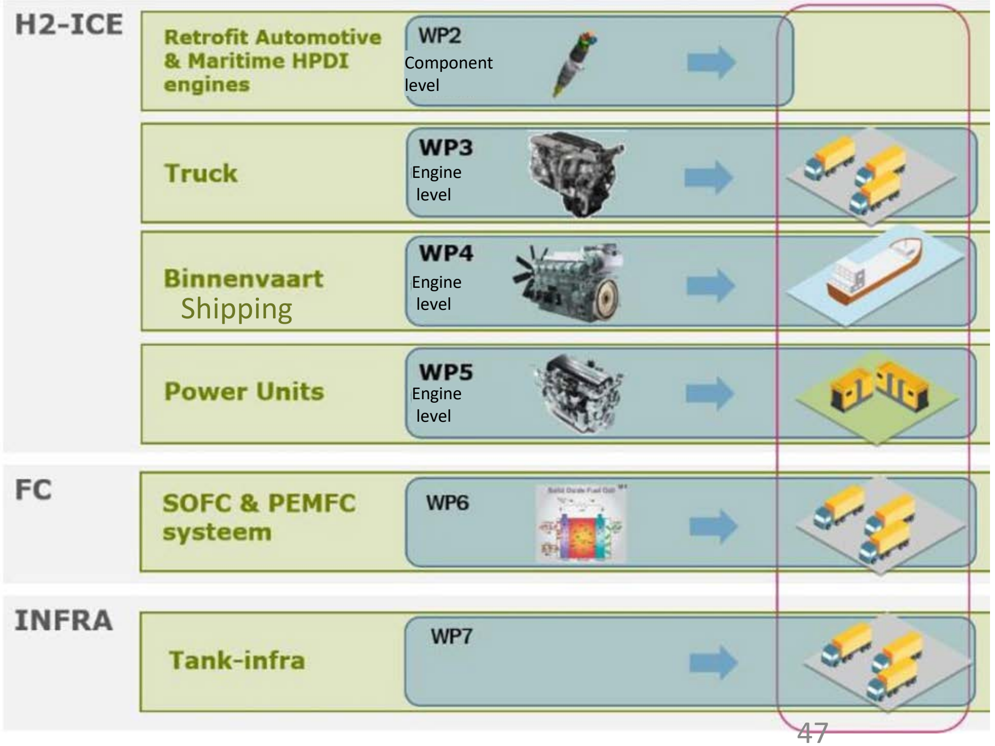
- Hydrogen combustion engines
- Hydrogen fuel cells
- Next-generation H2 refueling technology

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

Specific objectives:

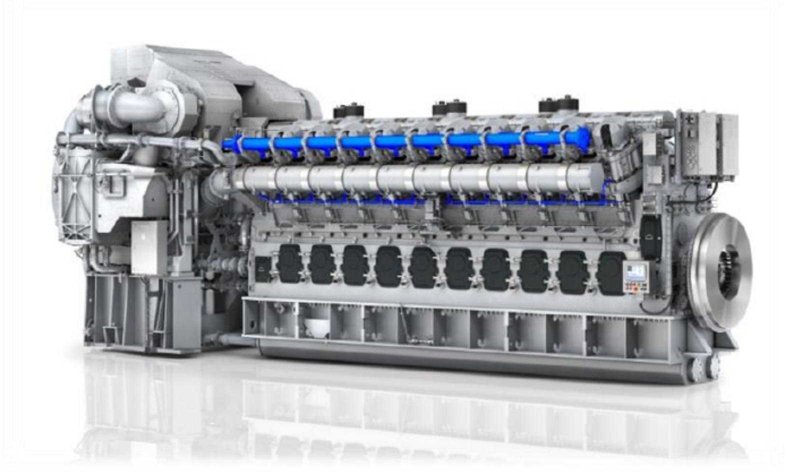
- Flexible hydrogen injection system for retrofit of automotive and marine diesel engines to H2
- Develop efficient H2ICE for trucks, barges and mobile power units
- The development of a modular SOFC fuel cell system and a completed study of dynamic loading of PEMFC fuel cells in relation to degradation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



Source: https://brainporteindhoven.com/en/business-and-innovation/markets/mobility/programme-office-for-smart-and-green-mobility/green-transport-delta-hydrogen

MAN ES - H_2 ICE



- Key barriers to H_2 ICE development and deployment
  - Backfire, (Lube oil) Pre-Ignition, and Fuel availability, Knock, Storage
- Past accomplishments and current activities
  - MAN ES gas engines are H_2-ready up to 25%
  - 100% H_2 is in development, supported by R&D projects (e.g. HydroPoLEn)
- Competitive technologies and motivation for pursuing H_2 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% H_2 : Engine released in 2021, 100% H_2 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

JENBACHER INNIO HYDROGEN ready for H2

Jenbacher J416 H2-ICE genset 710kW electrical power

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)

Source: https://www.innio.com/en/news-media/press-releases/innio-jenbacher-gas-engines-ready-for-hydrogen

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% H_2 in blend of NG

Expecting to have a 100% H_2 engine solution by 2025, active R&D currently on the way

Alternative solution to H_2 is NH_3 – a NH_3 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 H_2 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 H_2 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. H_2 modelling capabilities. Initiated research project with Aalto University and VTT within model development.

Motivation for pursuing H2 ICEs

- H_2 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

- H_2 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 H_2.

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

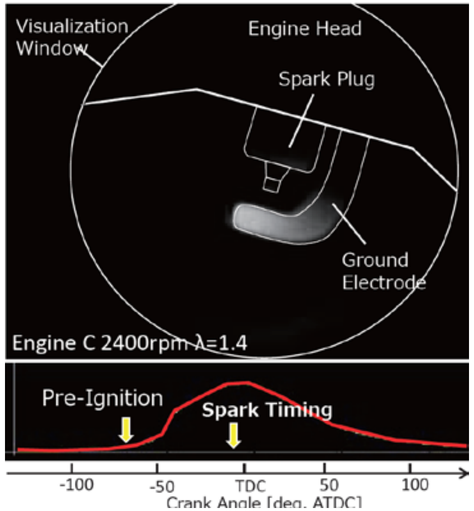
Significant effort invested into understanding and mitigating pre-ignition (presentation JSAE 20224660)

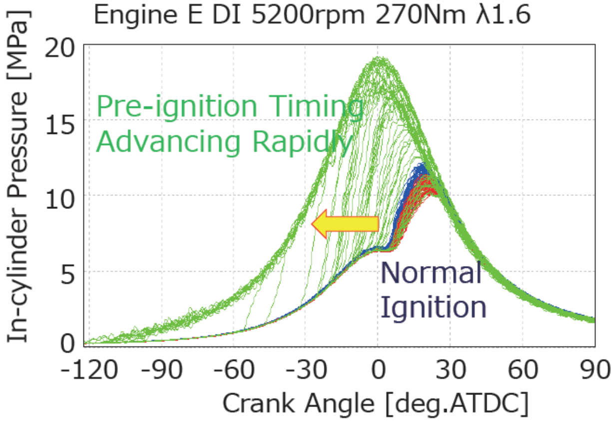
- Tested 4 different engines using H2 DI and PFI to understand the aspects of engine design and load on pre-ignition
- Effort on spark-plug design to minimize pre-ignition tendency
- Visualized hot-spot pre-ignition on a hot spark-plug electrode using endoscopic imaging
- Developed prototype hydrogen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

Toyota Corolla endurance race car

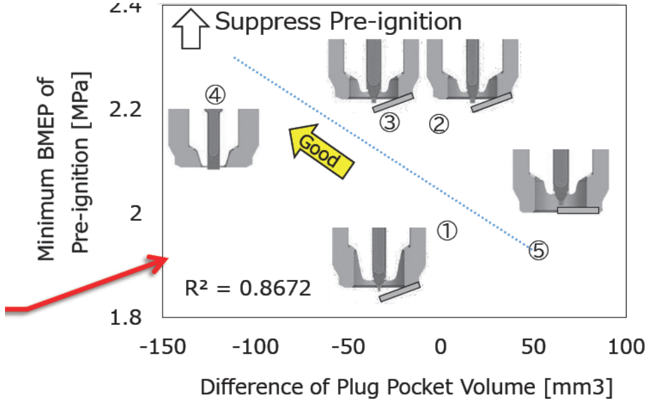
2022 Toyota Cross H2ICE concept

Visualization of hot spark-plug electrode





Pre-ignition tendency of different electrodes



2022 Yamaha 5.0L V8 H2ICE

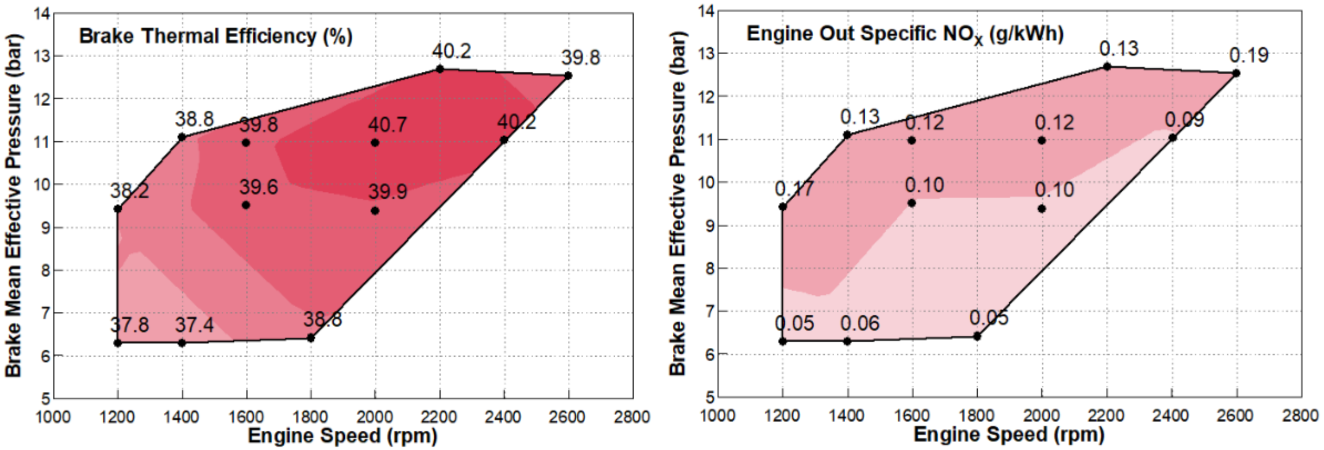
Source: A Study of Abnormal Ignition in Hydrogen Combustion Engine, https://tech.jsae.or.jp/paperinfo/en/search?q[0].id=13&q[0].v=st202205.

- 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

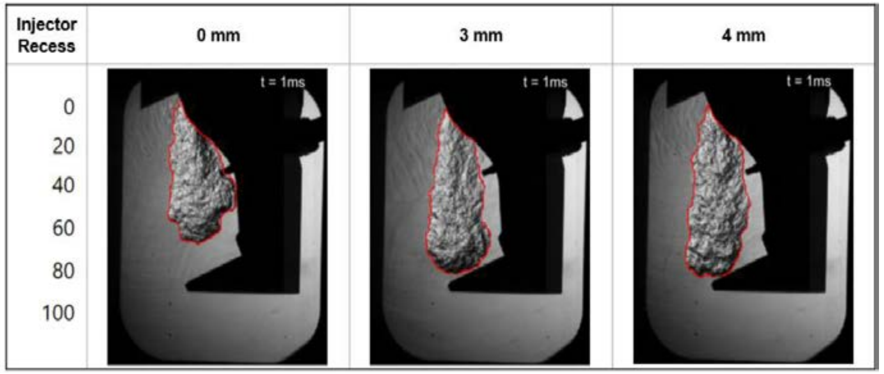
Recent development of H2ICE

- 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

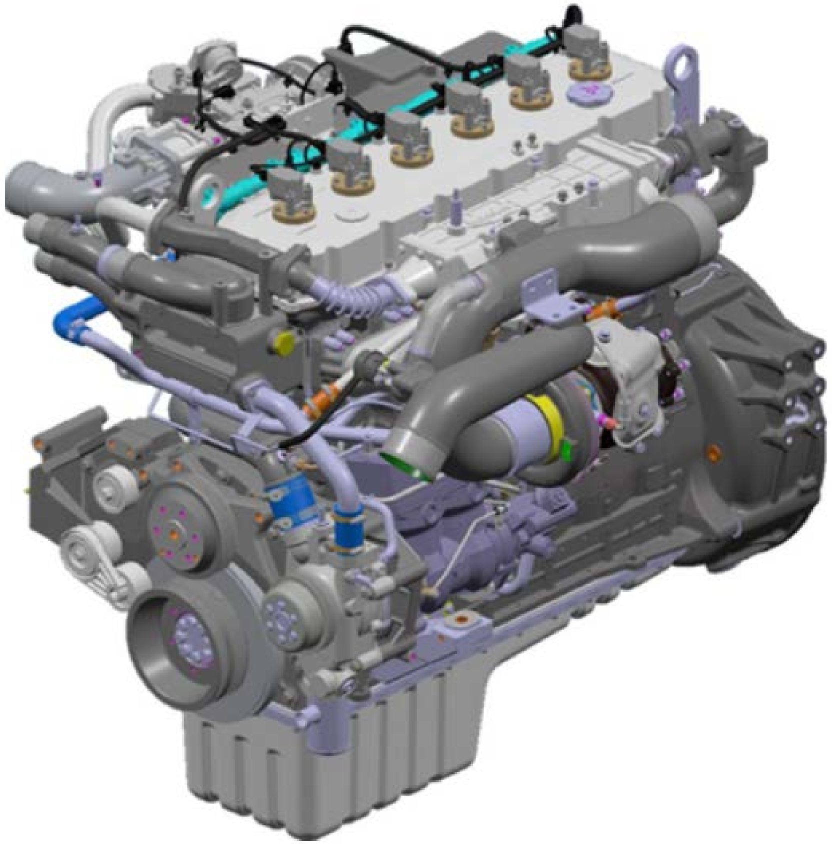


Visualizations of H2DI plume evolution



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 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

Source: https://www.kedglobal.com/hydrogen-economy/newsView/ked202206270011

BEHYDRO CMB.TECH ANGLO BELGIAN CORPORATION We power your future

Joint venture between engine manufacturer (ABC) and ship-owner (CMB, 90 sea-going vessels)

Dual-fuel engine (launched in 2020)

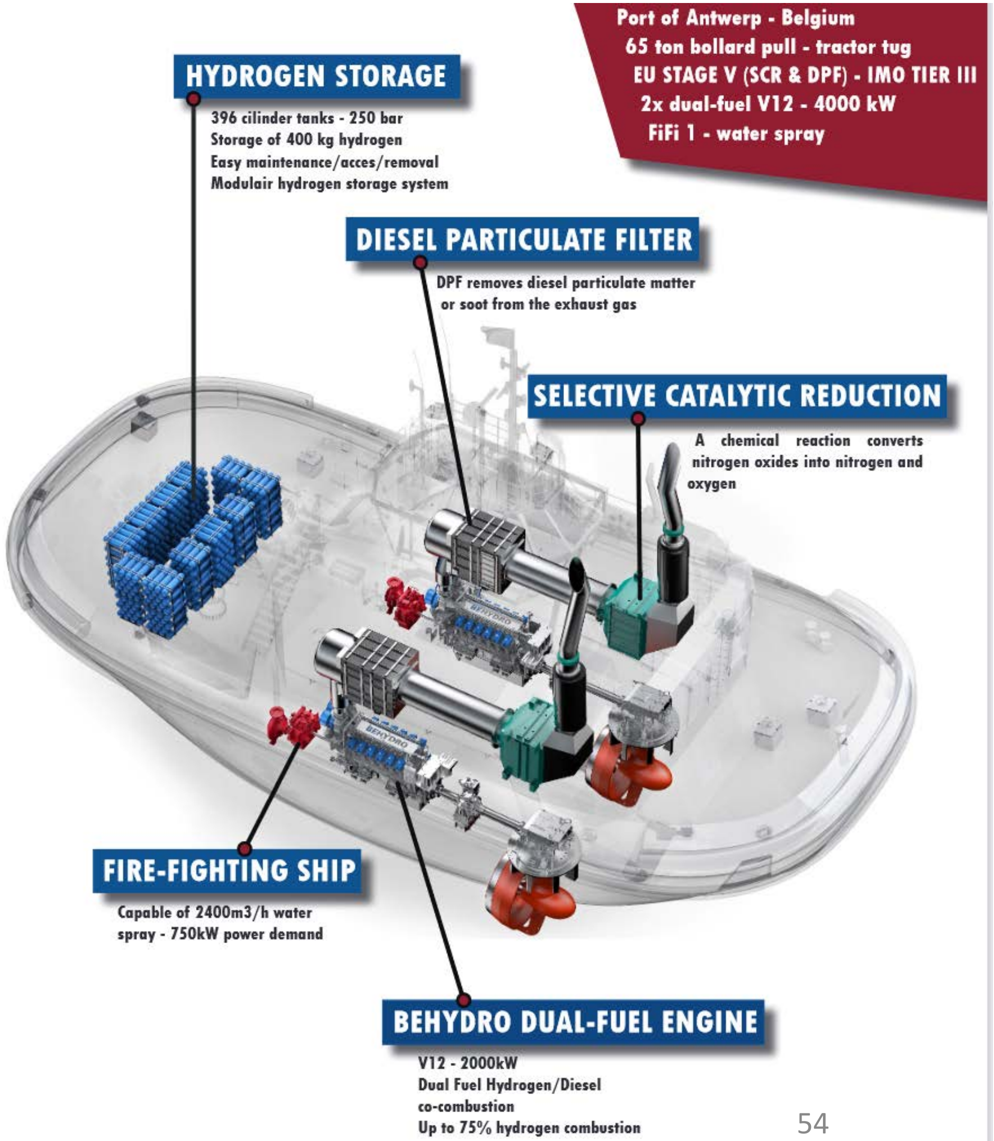
- Modification of existing diesel line to operate on H2 with PFI
- Up to 85% substitution of diesel with H2, 1.0-2.7MW power
- About 30% power-derated from diesel equivalent
- Demonstration vessel fully-operational in Q1 2023
- Back-up operation with diesel possible, reduced requirements for H2 fuel-reserve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



Source: https://www.behydro.be/en/home.html

MISSION NET ZERO

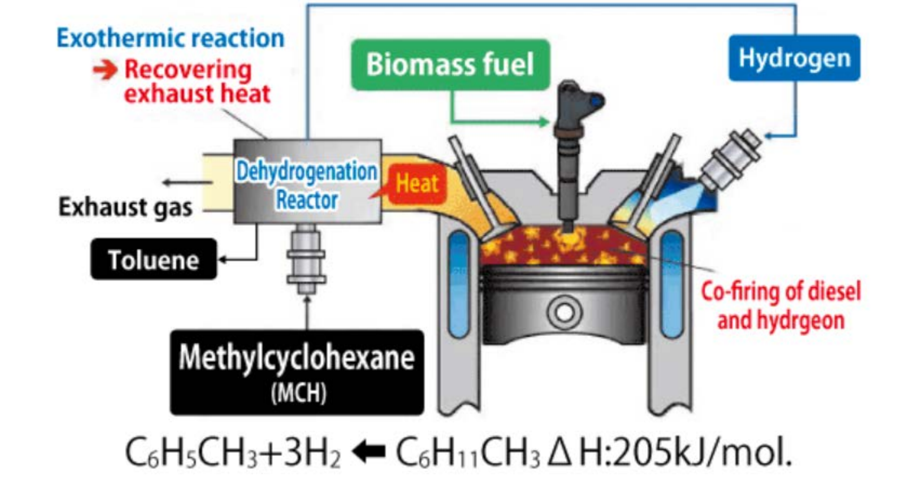
MOVE THE WORLD FORWARD MITSUBISHI HEAVY INDUSTRIES GROUP

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)

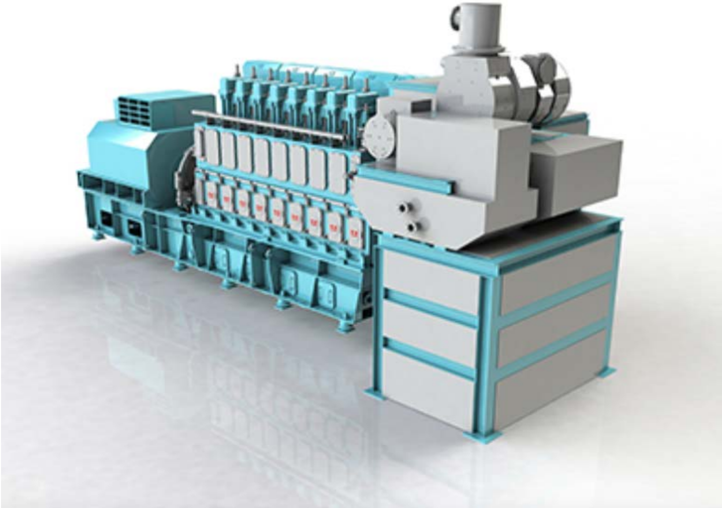
Planned 160,000m3 LH2 carrier (mid 2020s)

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



Source: https://global.kawasaki.com/en/hydrogen/

Kawasaki YANMAR J-ENG

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 CJPT

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 H_2/diesel dual-fuel locomotive engines

Key barriers to H_2 ICE development:
- H_2 preignition leading to backfire or knock
- Maintaining compatibility with diesel fuel while H_2 infrastructure is deployed
- Fuel system hardware (fuel injectors, compressors)
- Engine performance (efficiency, torque, combustion stability) with H_2
- Pollutant emissions (especially NOx)
- Durability of engine components and materials
- H_2 cost, availability, delivery, and storage

Current H_2 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 H_2 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 H_2 ICEs:
- Challenges:
    - H_2 preignition
    - NOx emissions
    - Engine efficiency
- Advantages:
    - Compatibility with diesel fueling infrastructure provides a transition strategy to accelerate H_2 uptake in existing vehicles
    - Near term CO_2 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/H_2 engines
- H_2 fueling infrastructure
- Demonstration programs to prove the technology

Wabtec CORPORATION   CONVERGENT SCIENCE   Argonne NATIONAL LABORATORY   OAK RIDGE National Laboratory

ARGONNE'S H_2 ICE RESEARCH

Past accomplishments:

- Led H_2 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 H_2 injection and mixture formation in ICEs.

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

- HIL capabilities and increased H_2 supply for benchmarking H_2 ICE vs FC.
- Development of advanced CFD models for H_2 injection/mixing.
- Improvement of X-ray diagnostics to account for real H_2 fuel effects.
- Development of best practices for modeling H_2 ICEs for rail/off-road/CHP.

Competitive technologies:

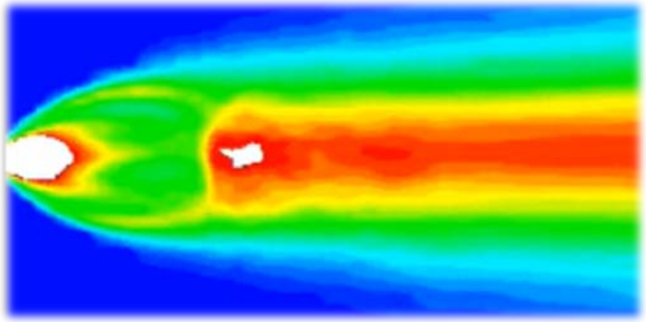
- H_2 FC + net-zero carbon engine technologies (NH_3, MeOH, renewable/bio-fuels)

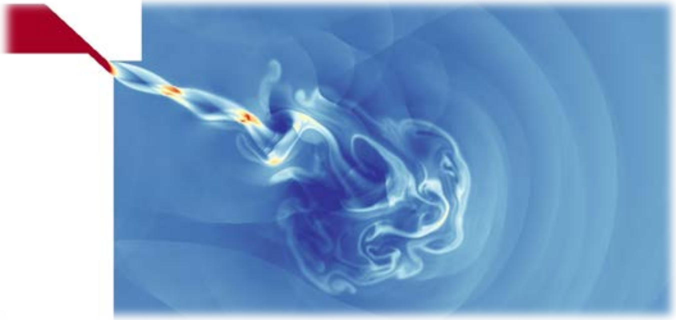
Key barriers to H2 ICE development and deployment:

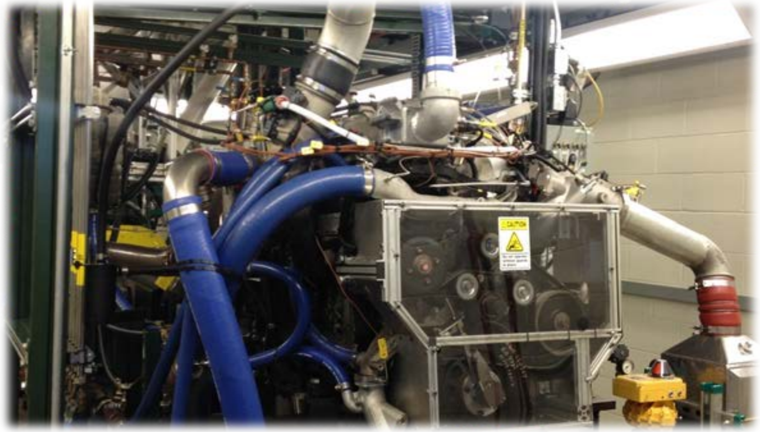
- H_2 injection system development.
- Abnormal combustion detection & risk mitigation.
  - Ignition/combustion system development.

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 H_2 ICE performance.







H2 INTERNAL COMBUSTION ENGINE
MAIN CHALLENGES ADDRESSED BY IFPEN

Sustainable mobility

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

Challenges:
- Preventing abnormal combustion
- Efficiency
- NOx control
- Performance
- Durability

Research focus:
- Characterization of Hydrogen combustion
- Combustion system design
- After treatment System
- Air loop design
- Control algorithms
- Materials compatibility

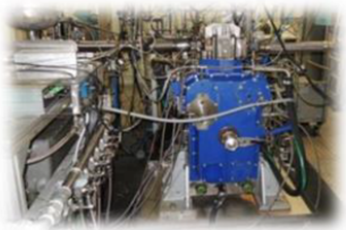
Challenges | Research focus

Focus : Hydrogen combustion R&I @ IFPEN

Development of a SCE dedicated to Hydrogen combustion research

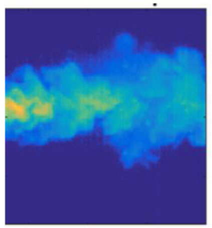
HD application – single cylinder 2.2L

Port Fuel and/or direct Hydrogen injection

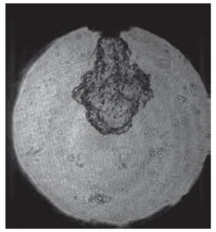


Development of advanced diagnostics to support the improvement and validation of 3D CFD modeling and the development of H2 ICEs

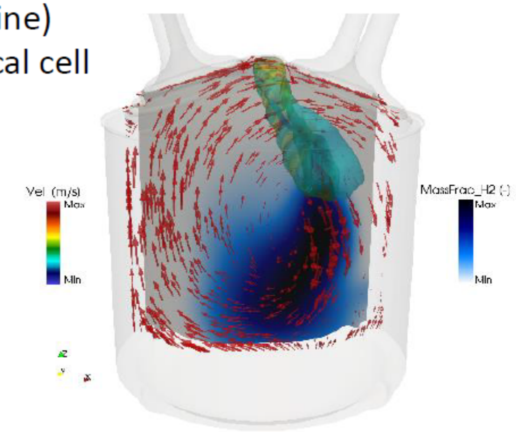
- Identification of the origin of **abnormal combustions** within in situ visualization (optical access on full metal engine)
- In situ heat flux measurement to characterize **transient wall temperature and heat losses** (optical cell and full metal engine)
- **Injection and mixture characterization**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

H2-ICE activities at KAUST

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

TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY

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 experiements
- 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

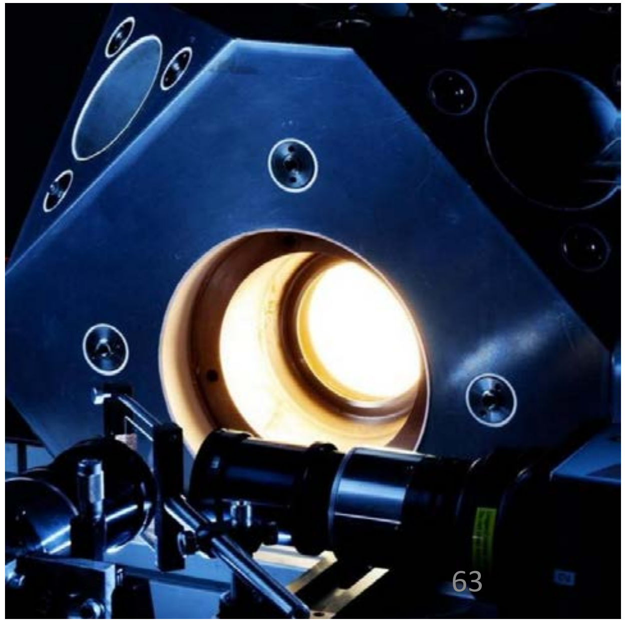
- Argon power cycle is targeted at stationary applications
- Long-term plan will focus on heavy-duty long-haul truck applications

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

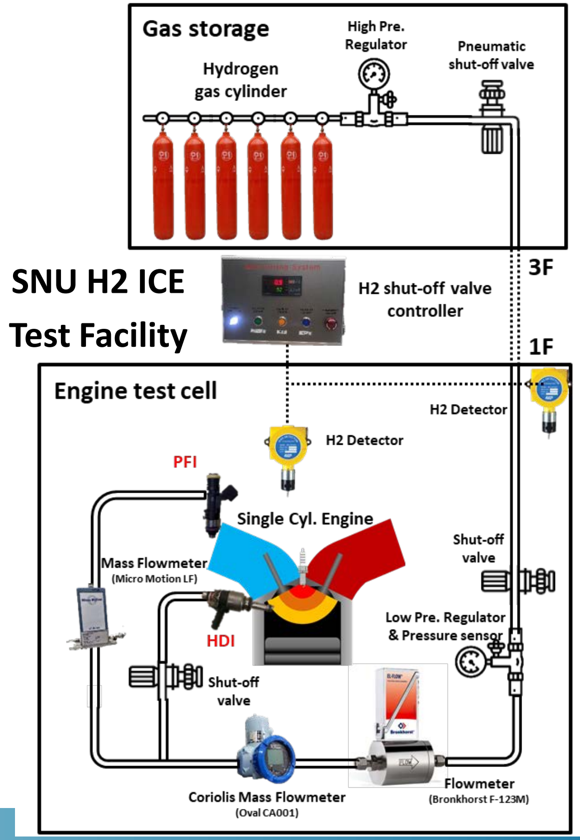
Abnormal Combustion
- Direct injection (high/low pressure)
- Mixture quality, air dilution

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

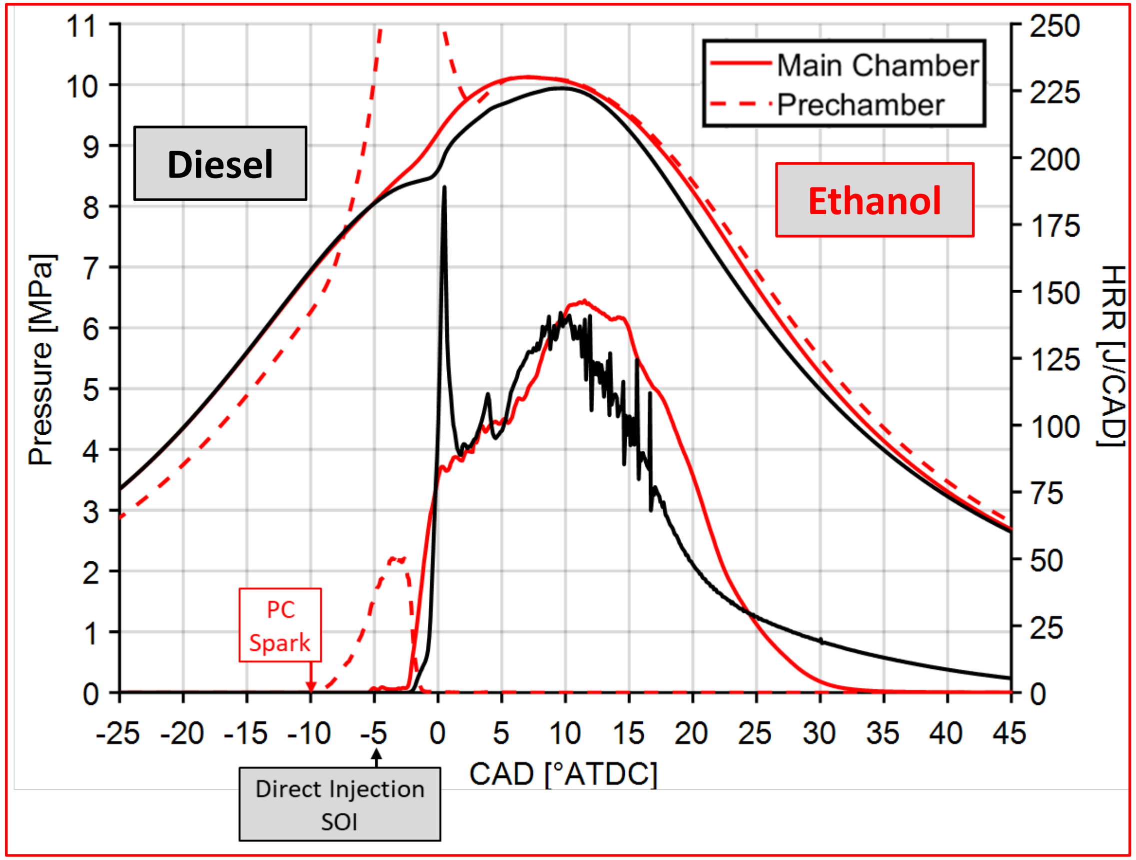
- **To maximize thermal efficiency and to reach near zero emission by optimizing the hydrogen combustion systems**
  - Injection strategy → mixture formation (Homogeneous / stratified charge)
  - Stroke-bore ratio → heat transfer, in-cylinder flow, mixture formation
  - Compression ratio → thermal efficiency, 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.**

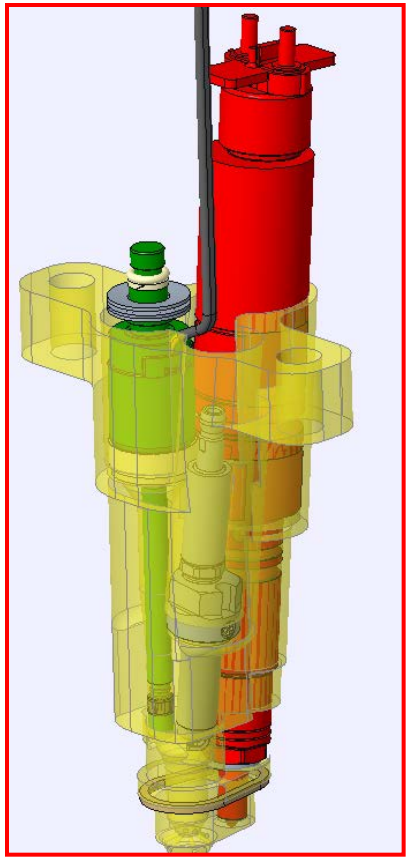


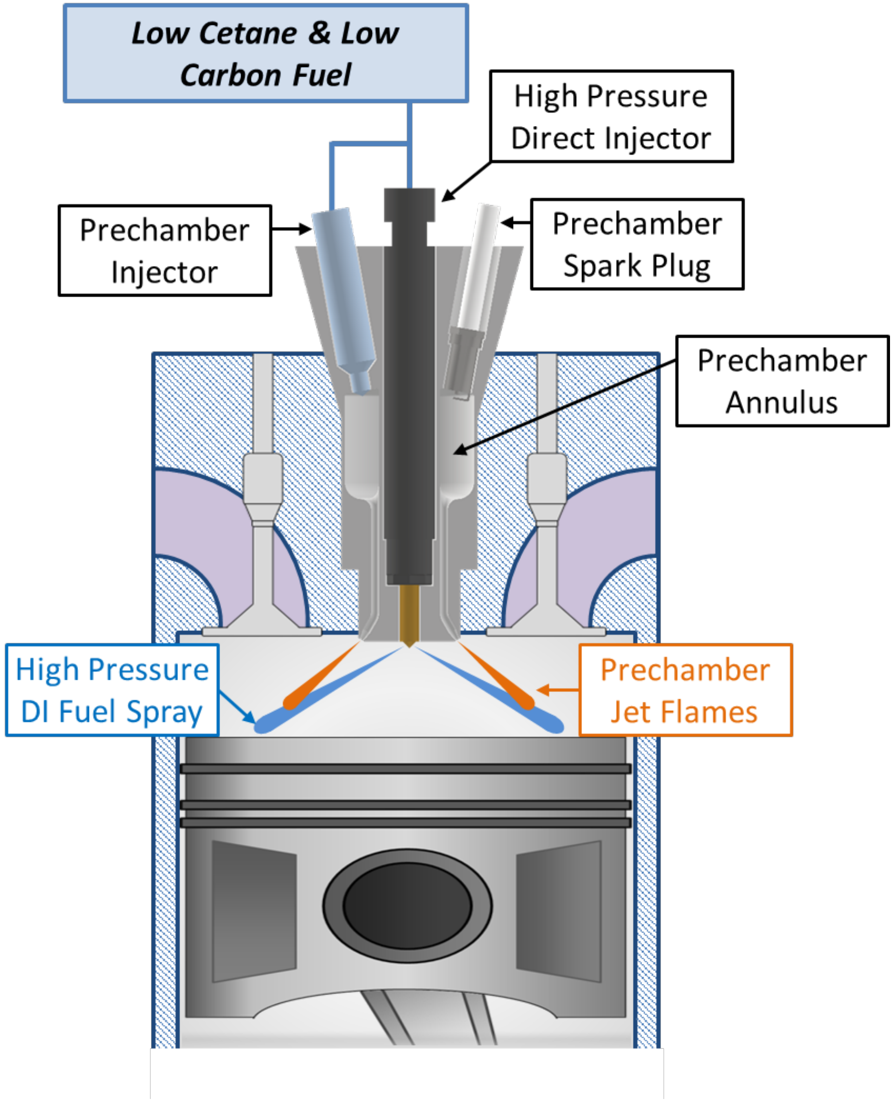
Fuel Agnostic Combustion Strategy for Low Carbon Heavy-Duty Engines

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 H_2 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

Source: https://www.ivtinternational.com/news/hydrogen/fpt-industrial-powers-worlds-first-hydrogen-snow-groome

Consiglio Nazionale delle Ricerche

STEMS

Istituto di Scienze e Tecnologie per l'Energia e la Mobilità Sostenibili

• 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 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/m³) due to its low density

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

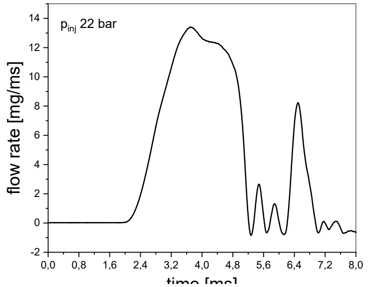
Flame backfiring in the intake manifold for PFI config

NO_x formation if not in lean operations or high EGR level

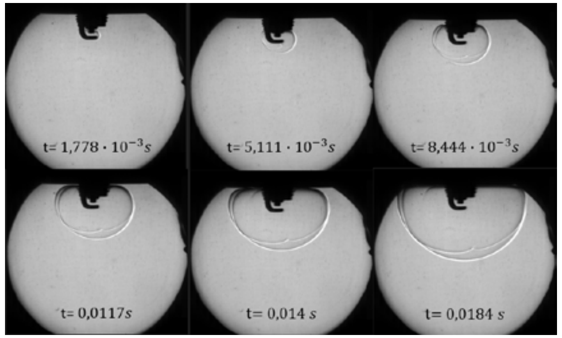
Safety concerns and tank capacity

• Past achievements

Spray Imaging

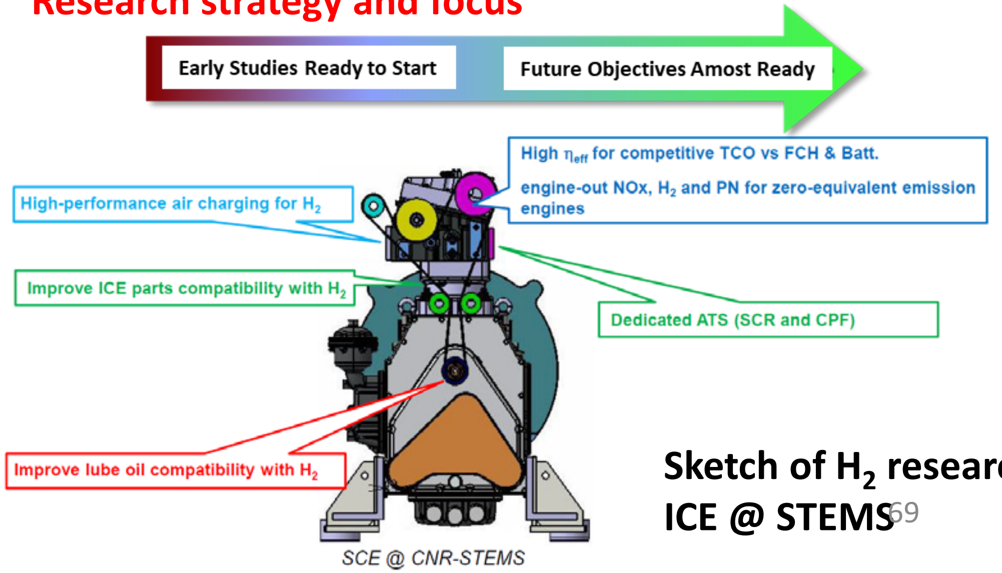


Flow rate



Gaseous mixture combustion

• Research strategy and focus



Sketch of H_2 research ICE @ STEMS

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
- H_2 jet autoignition displays considerable run-to-run variation at temperature and pressure conditions typical of conventional compression-ignition engines.
- H_2 jet flame recesses upstream to stabilise close to the nozzle after ignition. The stabilisation position of the H_2 jet flame raises concerns about the potential emission and thermal stress effect on the nozzle.
- World-first demonstration of an H_2-diesel dual-fuel direct-injection engine at UNSW that can operate up to 90% hydrogen substitution by energy, with a significant reduction in CO_2 emission (more than 80%).

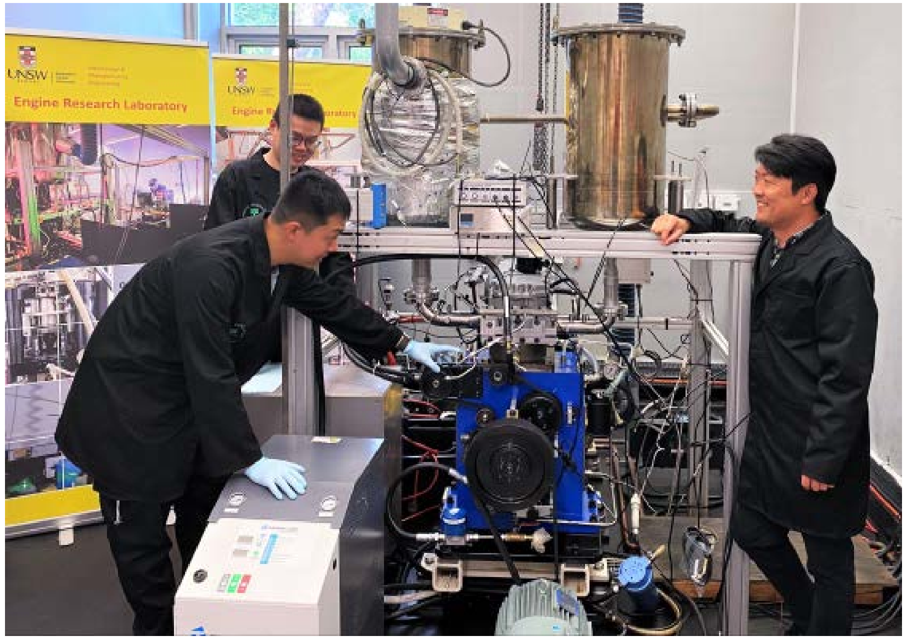
Competitive technologies and motivation for pursuing H2 ICEs (highlighting both H2ICE challenges and advantages)

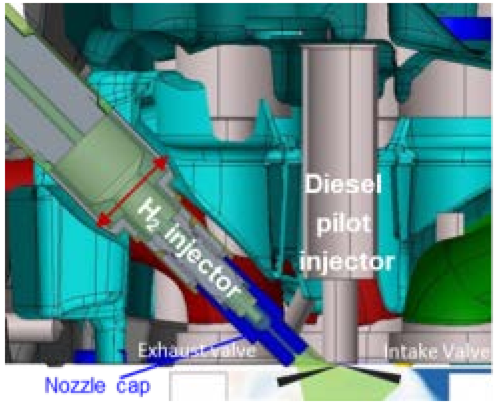
H_2-fuelled reciprocating engines have several competitive advantages over H_2-fuelled gas turbines and fuel cells stemming from their lower capital costs, better dynamic response, greater robustness to fuel impurities and inherent higher efficiency than gas turbines. If minor modifications to existing engines are only required to incorporate H_2, this implies that H_2-fuelled engines can have the same capital and non-fuel operating costs as conventional engines, with higher efficiency potential because of H_2 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:

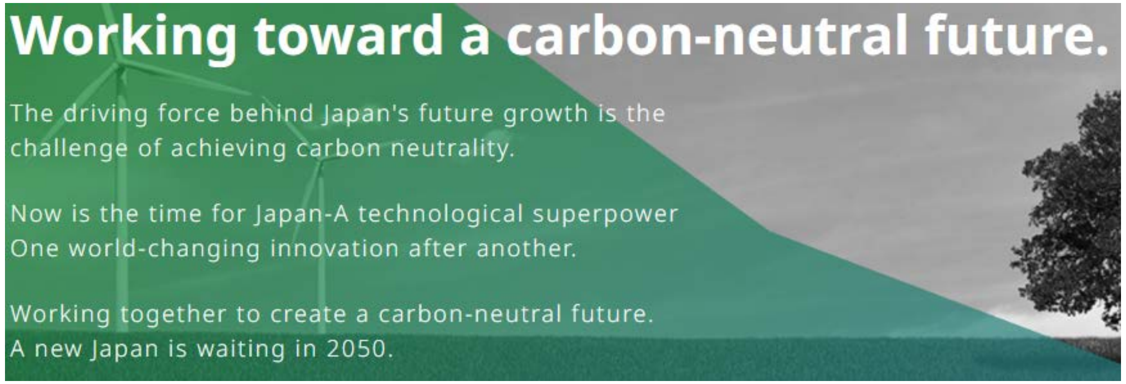
- Control of abnormal combustion for highly-boosted gasoline engines
- Direct injector development with DENSO
- Heat loss minimization through in-cylinder flow and DI
- Evaluation of CFD simulation accuracy and H2 fuel diffusion

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

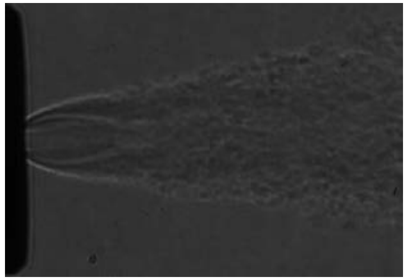
Target applications of H2ICE

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

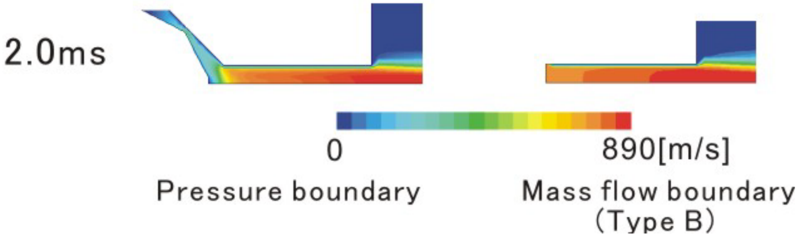


NEDO(Ministry of Economy, Trade and Industry), Ministry of Land, Infrastructure, Transport and Tourism, Ministry of the Environment have much budget for carbon neutral society by 2050

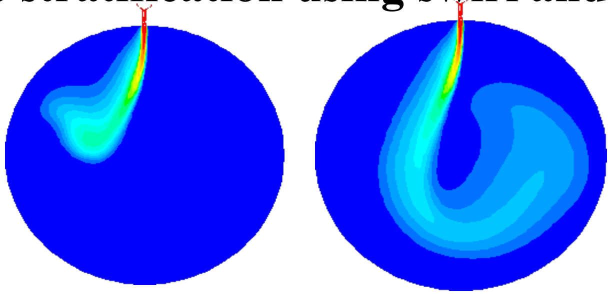
H_2 jet visualization



In-nozzle flow simulation



Mixture stratification using swirl and DI



千葉大学
Chiba University

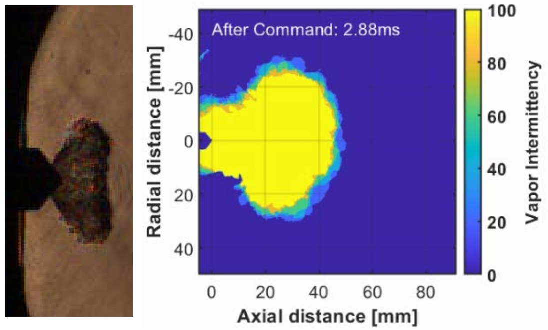
H2 ICE Works in KAIST

Hydrogen Jet analysis

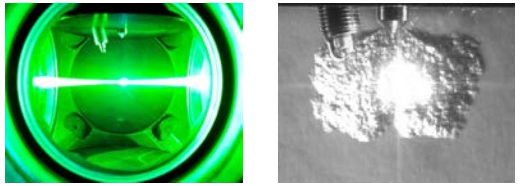
Jet Characteristics

@ Constant Volume Vessel

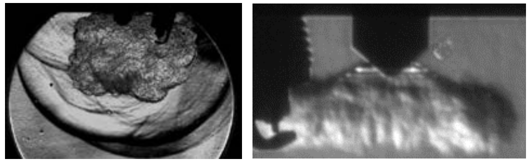
- **(10 MPa) Jet visualization**



<High-speed Schlieren imaging>



<LIBs Equivalence ratio Measurement>



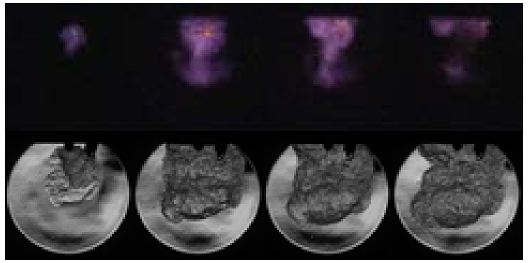
<Shock analysis>

Combustion Visualization

Hydrogen combustion

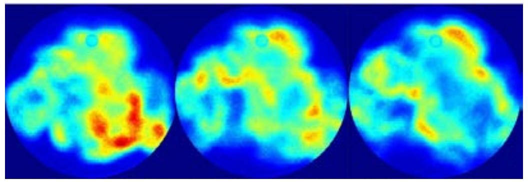
@ Constant Volume Vessel

- **Energy Conversion analysis**



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

- **Measurement of high temperature heat release location**



<OH* Chemiluminescence>

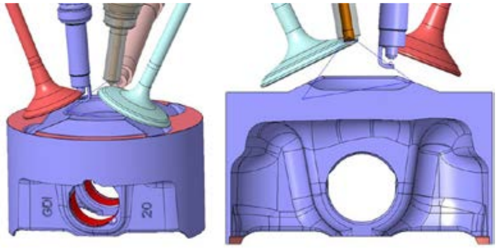
- Energy conversion **efficiency**

H_2ICE Single-cylinder

Performance & Emission

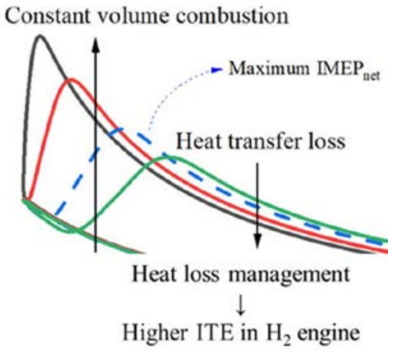
@ Single-cylinder research engine

- **Evaluation of hydrogen lean stratified combustion engine**



<Jet-guided DISI engine heat schematic>

- **CO_2 & PM emission analysis**
- **Local rich-hydrogen ➔ NO_x emission measurement**



- **Heat loss analysis**

German Research Foundation – Research Unit 2687
Cyclic variability in H2 ICE, start in 2023

Focus – Light-Duty H2 engines
Topics and methodology

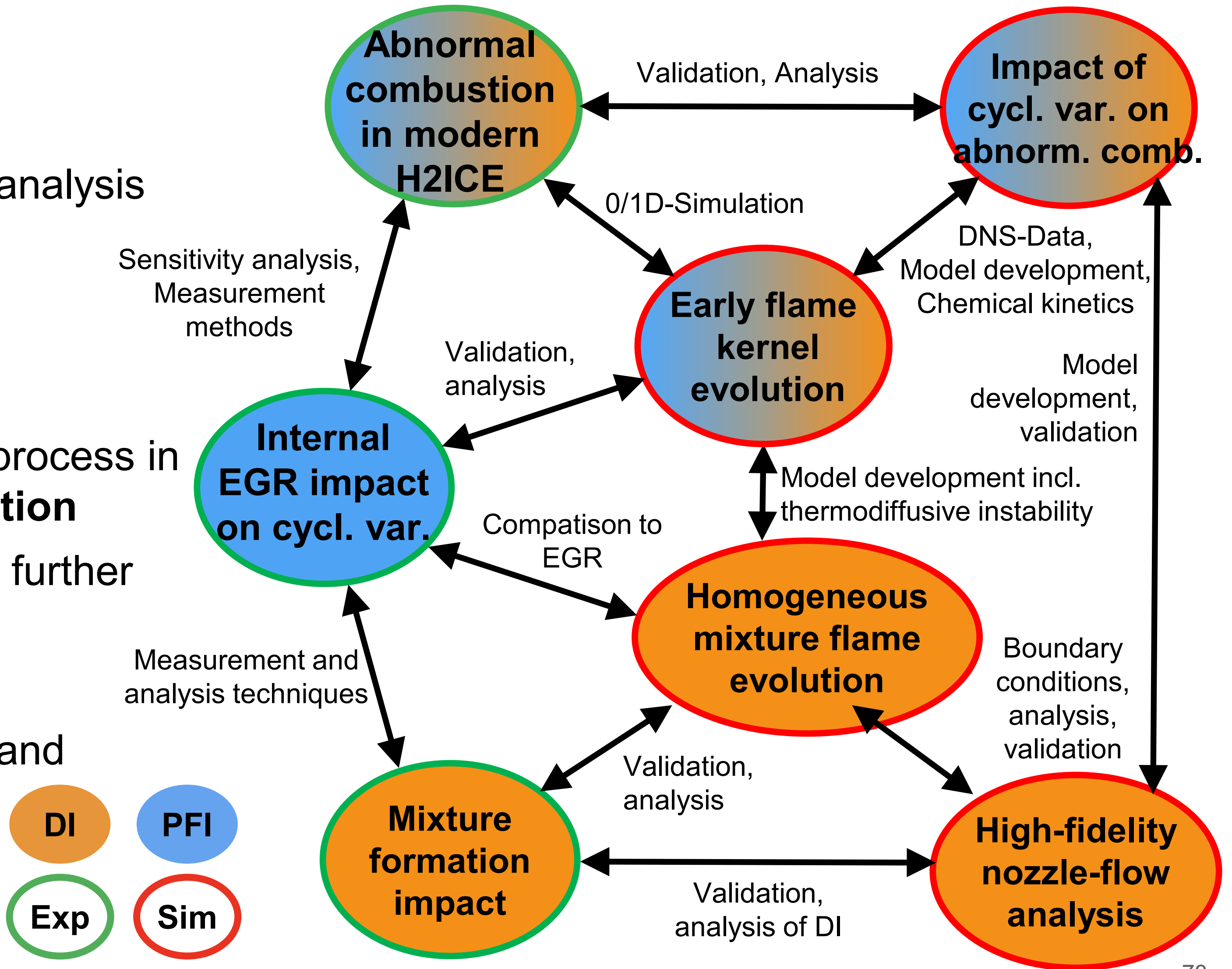
- **Experiment, Simulation**, Modelling and Data analysis
- Homogenous and stratified mixture (H_2 PFI or DI)

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

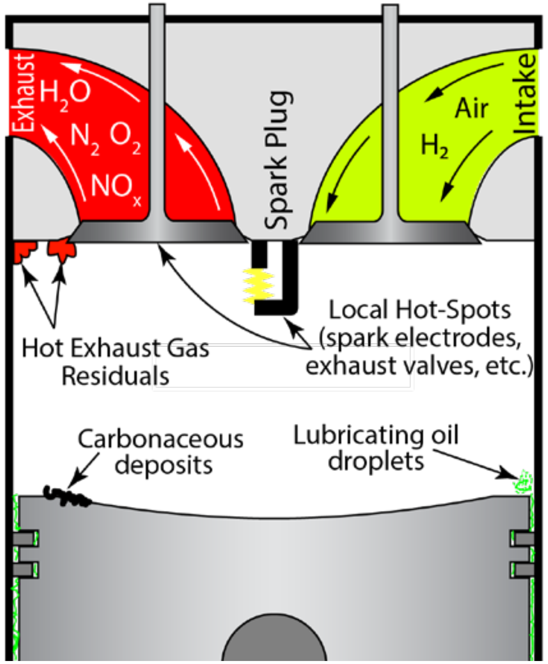
→ Main scientific task for the unit:

Synthesis of individual findings

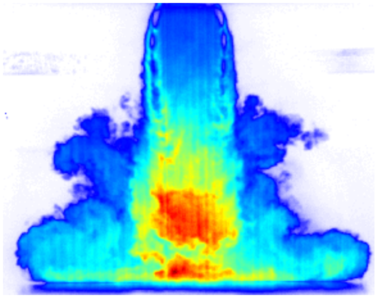


SANDIA IS ADDRESSING KEY KNOWLEDGE GAPS IN DEVELOPMENT OF HIGHLY-EFFICIENT H2ICE

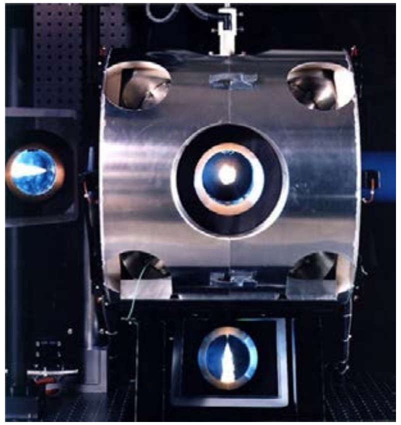
Pre-ignition mechanisms



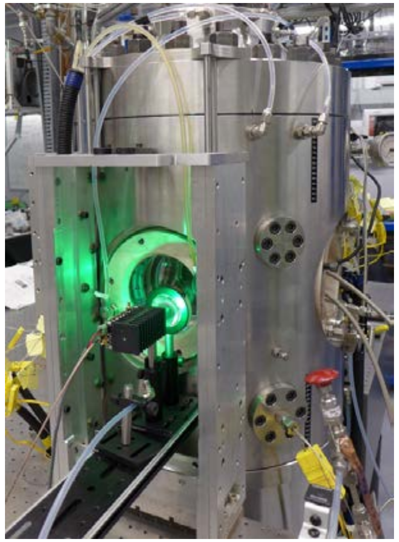
H2 DI jet visualization
In-cylinder mixing



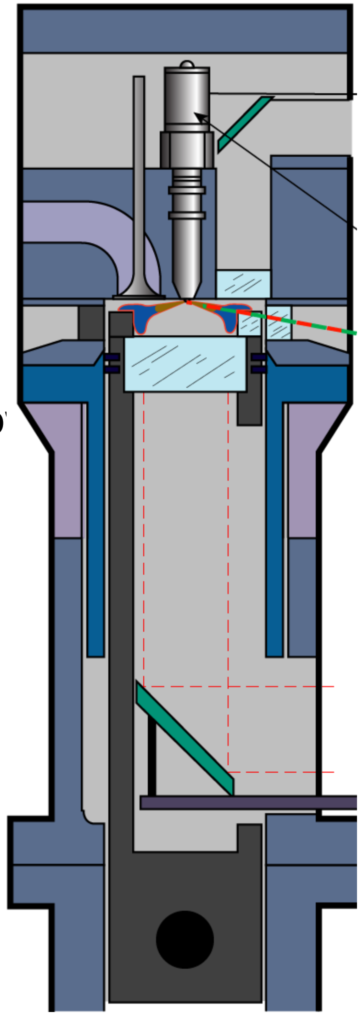
Pre-burn spray vessel



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 it's effects on performance, ignition, and NOx
- 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 NOx
- Visualization of NOx 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

H_2ICE 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 H_2ICE evaluation for trucks

Executive Summary

H_2ICEs De-risk H_2 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 H_2ICE vehicles.
- Freight decarbonization solutions remain highly uncertain:
  Energy cost (diesel, electricity, H_2), powertrain requirements, component durability, thermal management, performance degradation, fueling/charging infrastructure, CAPEX…
- Hydrogen Earth Shot is critical for any H_2 fueled vehicle competitiveness.

While meeting HFTO H_2 cost targets remain critical, H_2ICEs could de-risk some of the investments, jump-starting the H_2 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_2ICE engine test data is not readily available. H_2ICE potential was evaluated using information from publications and inputs from industry partners

- **Questions**
  - Under which conditions can H_2ICE 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

Timeframes

2021

2030

×

Vehicles

	Class	Purpose
Medium Duty	2	Van
	3	Box
	3	Van
	3	School
	3	Pickup
	4	Box
	4	StepVan
	4	Service
	5	Utility
	6	StepVan
	6	Box
	6	Construction
Heavy Duty	7	Tractor
	7	Vocational
	7	Box
	7	School
	8	Longhaul
	8	Beverage
	8	Drayage
	8	Vocational
	8	Transit
	8	Refuse
	8	Regional

×

Powertrains

Conventional

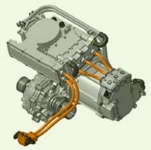
H_2ICE

ICE HEV

H_2ICE HEV

Fuel Cell

Electric



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Fuels

Diesel

Hydrogen

Electricity

×

Technology Progress

(risk analysis)

LOW
Business-as-usual

HIGH
DOE Targets

=

Output

- Energy consumption
- Component size
- Manufacturing cost
- Purchase cost parity
- TCO parity
- GHG impact

- 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.
- H_2ICE evaluation was done for StepVans, Box, Refuse, Drayage and Longhaul trucks

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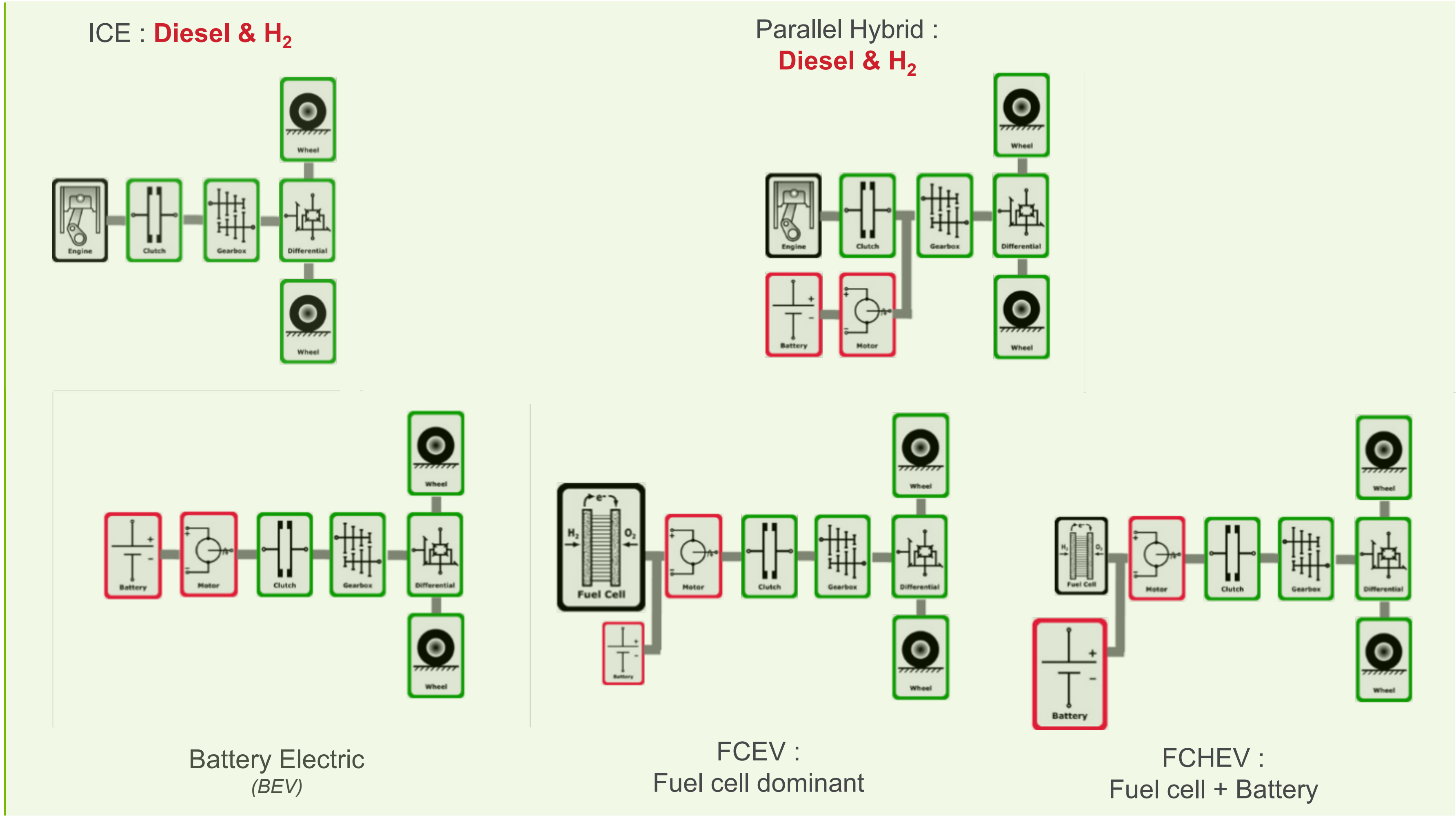
Powertrain Configurations and Fuels Considered

New technologies (H_2ICE, 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 & H_2ICE systems.



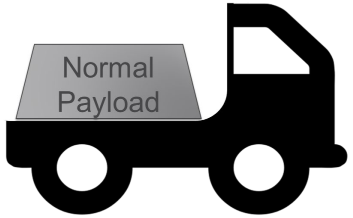
More details are at : https://vms.taps.anl.gov/research-highlights/u-s-doe-vto-hfto-r-d-benefits/

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 → **Analysis**



- 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

- 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

More details are at : https://vms.taps.anl.gov/research-highlights/u-s-doe-vto-hfto-r-d-benefits/

Class8 Long haul Truck Evaluation as a Potential Candidate for H_2ICE

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_2ICE 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

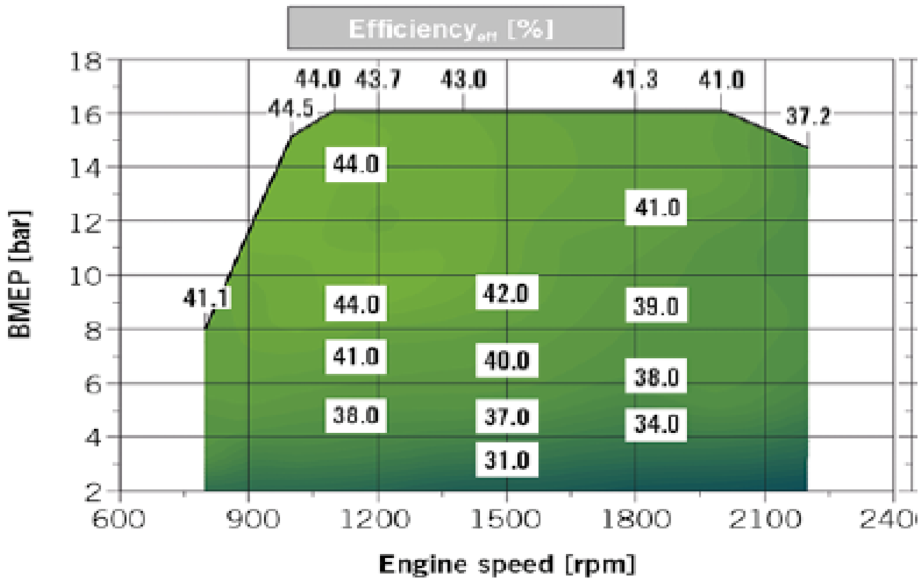
- A simplified TCO calculation provides the costs associated with vehicle and fuel use.
  (please see backup slide for simplified TCO calculation assumptions)

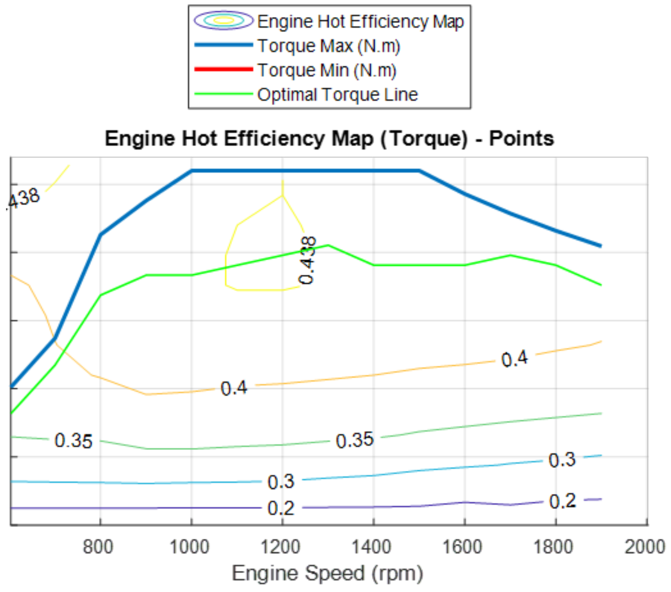
More details are at : https://vms.taps.anl.gov/research-highlights/u-s-doe-vto-hfto-r-d-benefits/

Heavy Duty Truck H_2ICE 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 NOx targets can be achieved with H_2ICE.

- Engine map modified for Class 8 longhaul and vocational applications based on inputs from industry partners.





* H_2 ICE map developed based on work by Koch et. al

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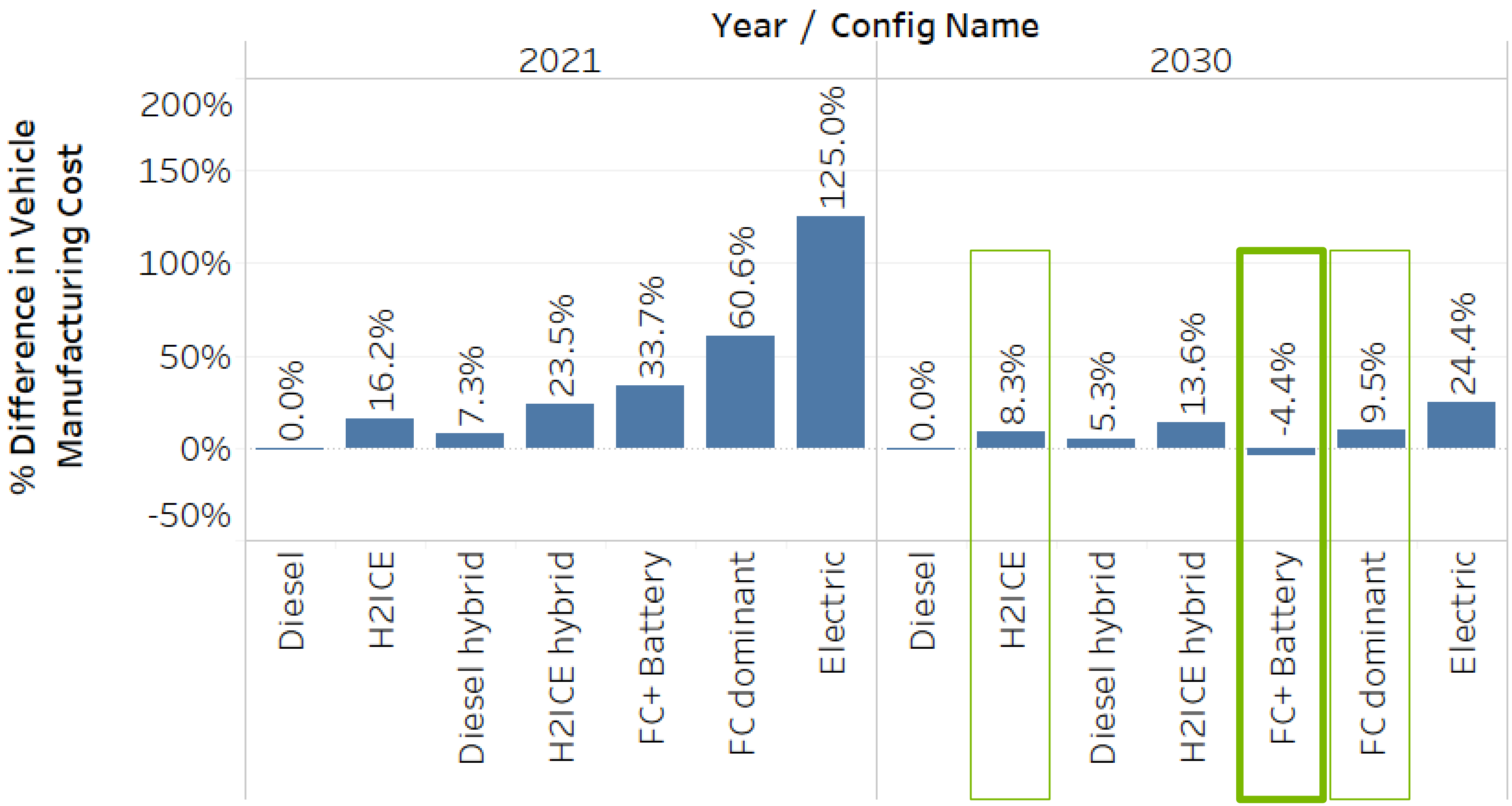
Considering 2030 HFTO and VTO Targets, FCHEV Manufacturing Costs are Lower than Diesel and H_2ICE Vehicles



- 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.
  - H_2ICE option has lower uncertainty.

* Assuming high volume production for fuel cell systems.
** No oversizing is assumed.

Class 8 Long Haul

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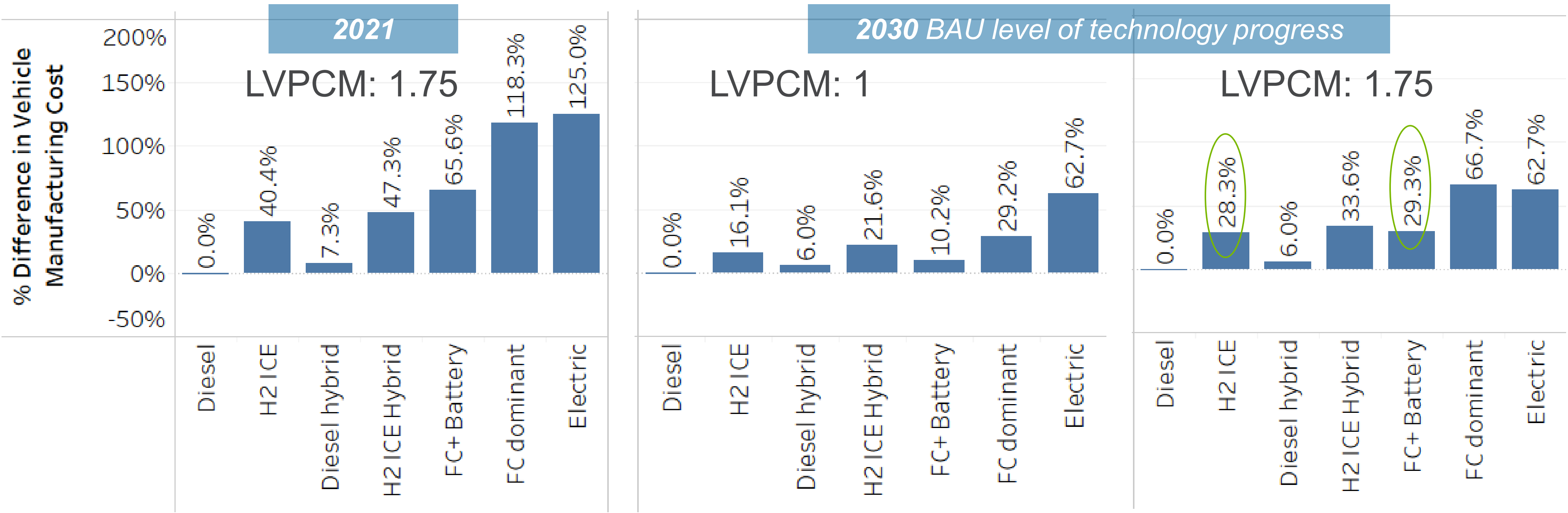
BAU Scenario: H_2ICE Vehicles & FCHEVs have Comparable Vehicle Costs. Both are ~30% Costlier than Diesel Baseline Vehicles.

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



Class 8 Long Haul

Same LVPCM is used for FC & storage.

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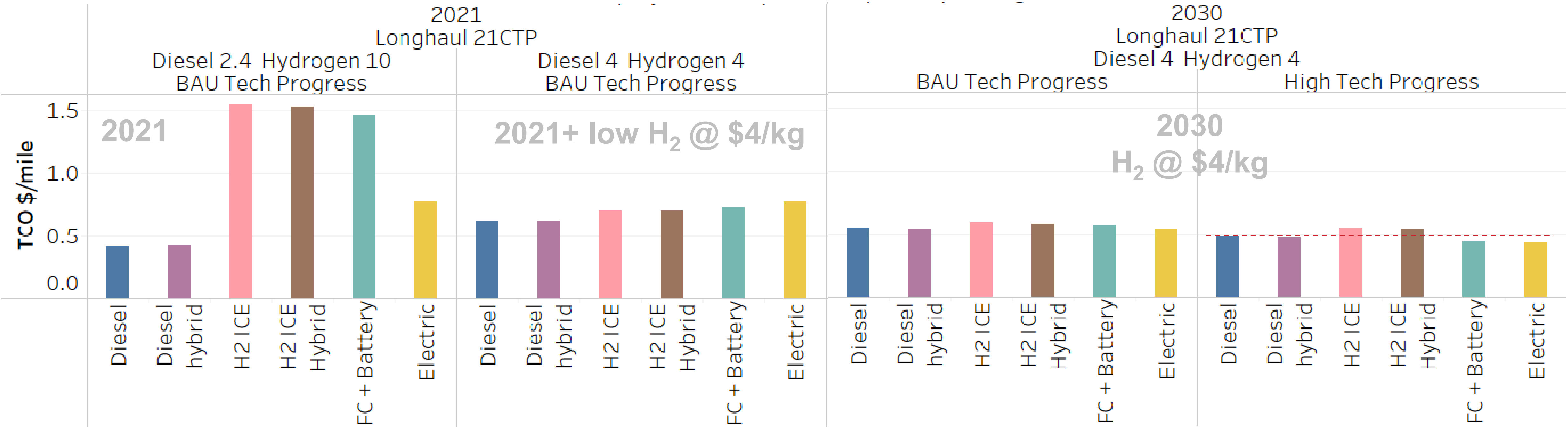
Fuel Cost is Critical to Vehicle Technology Assessment

Long term H_2 cost target from HFTO is $4/kg.

H_2ICE approaches operating cost parity with diesel vehicles at this cost level.



Class 8 Long Haul

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 H_2ICE even further.

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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%

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Overall GHG Impact

Results from GREET: Assuming NG-SMR for H_2 pathways, both current and future

WTW CO2e g/mile	Diesel	H_2ICE	H_2ICE Hybrid	FCHEV
2021	1,724	2,009	1,903	**1,691**
2030 high	1,365	1,644	1,438	**1,177**

Cleaner H_2 production is necessary to further reduce the overall CO_2 emission for FCHEVs and H_2ICE.

Compared to Diesel Engines, H_2ICE Offer Significant NOx Emission Benefits

H_2ICEs have comparable NOx output as diesel for higher loads and are significantly cleaner at low loads.

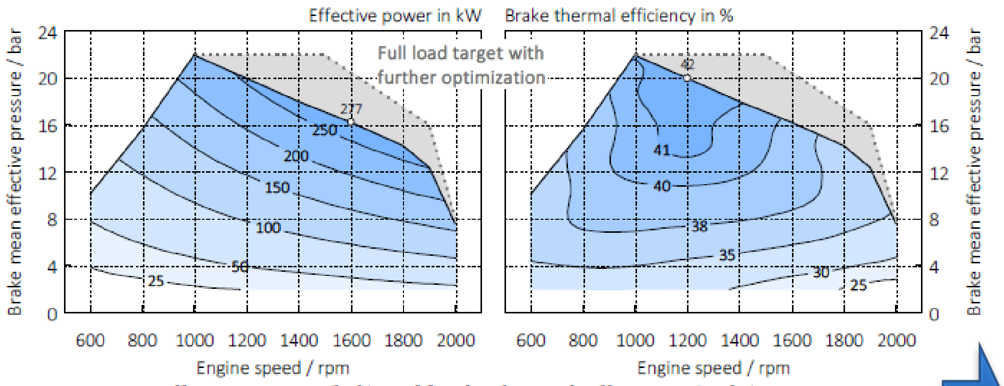


Figure 6: Effective power (left) and brake thermal efficiency (right) in MPI operation

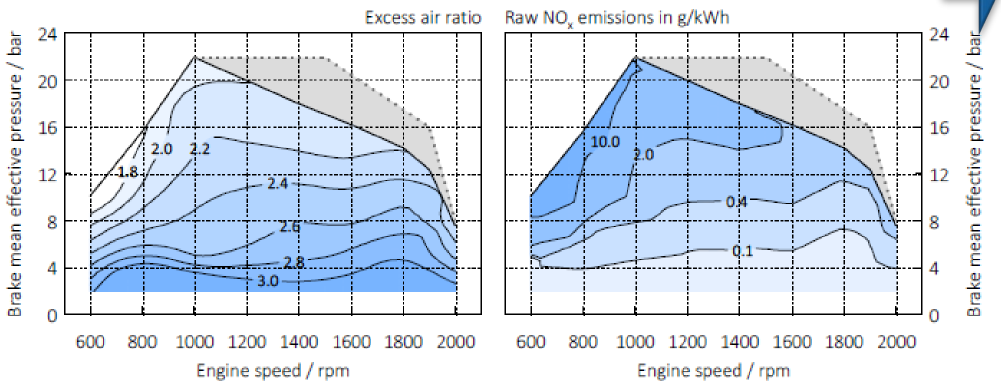
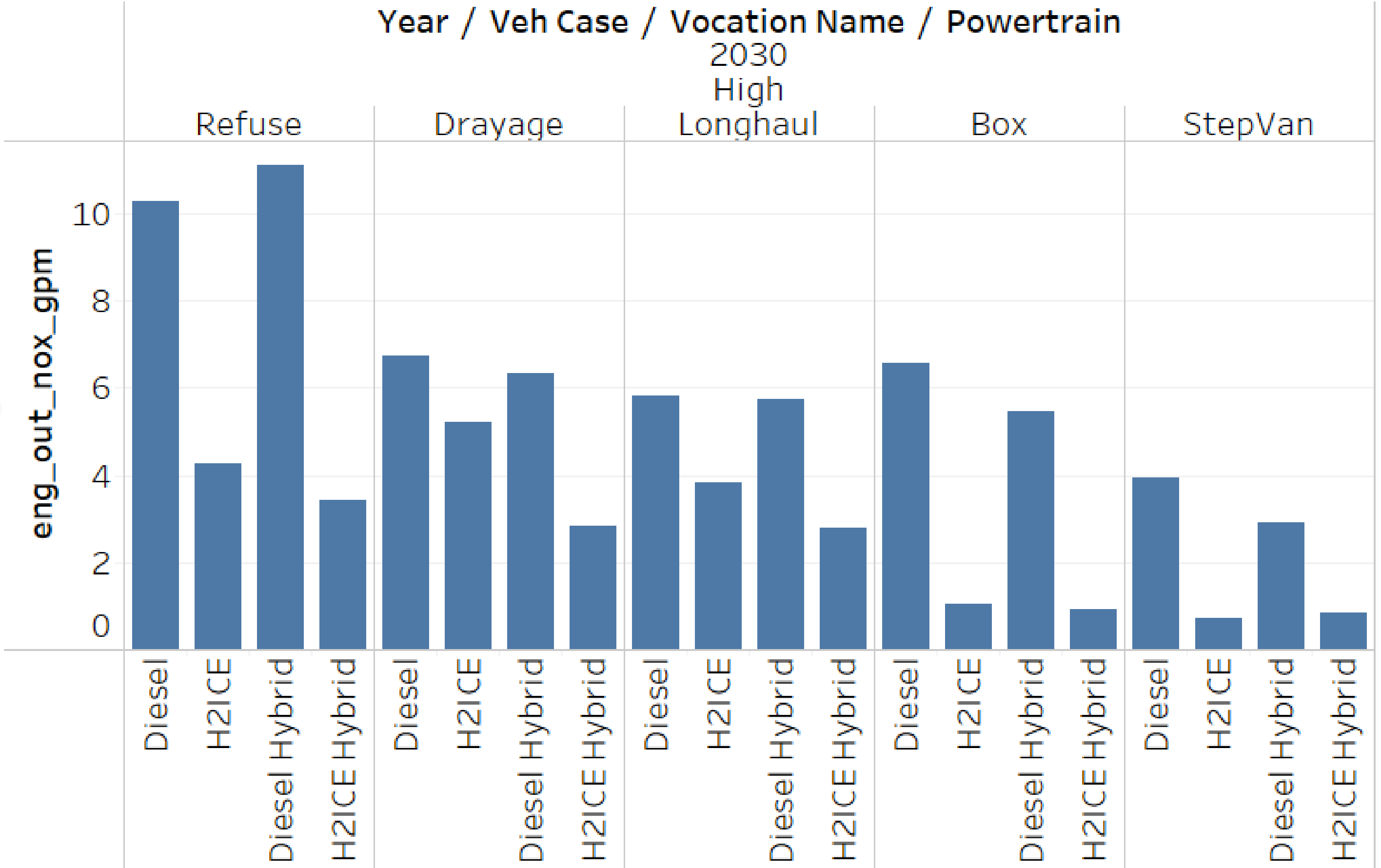


Figure 7: Excess air ratio (left) and raw NO_x emissions (right) in MPI operation



Based on AVL's work on a 12.8L engine

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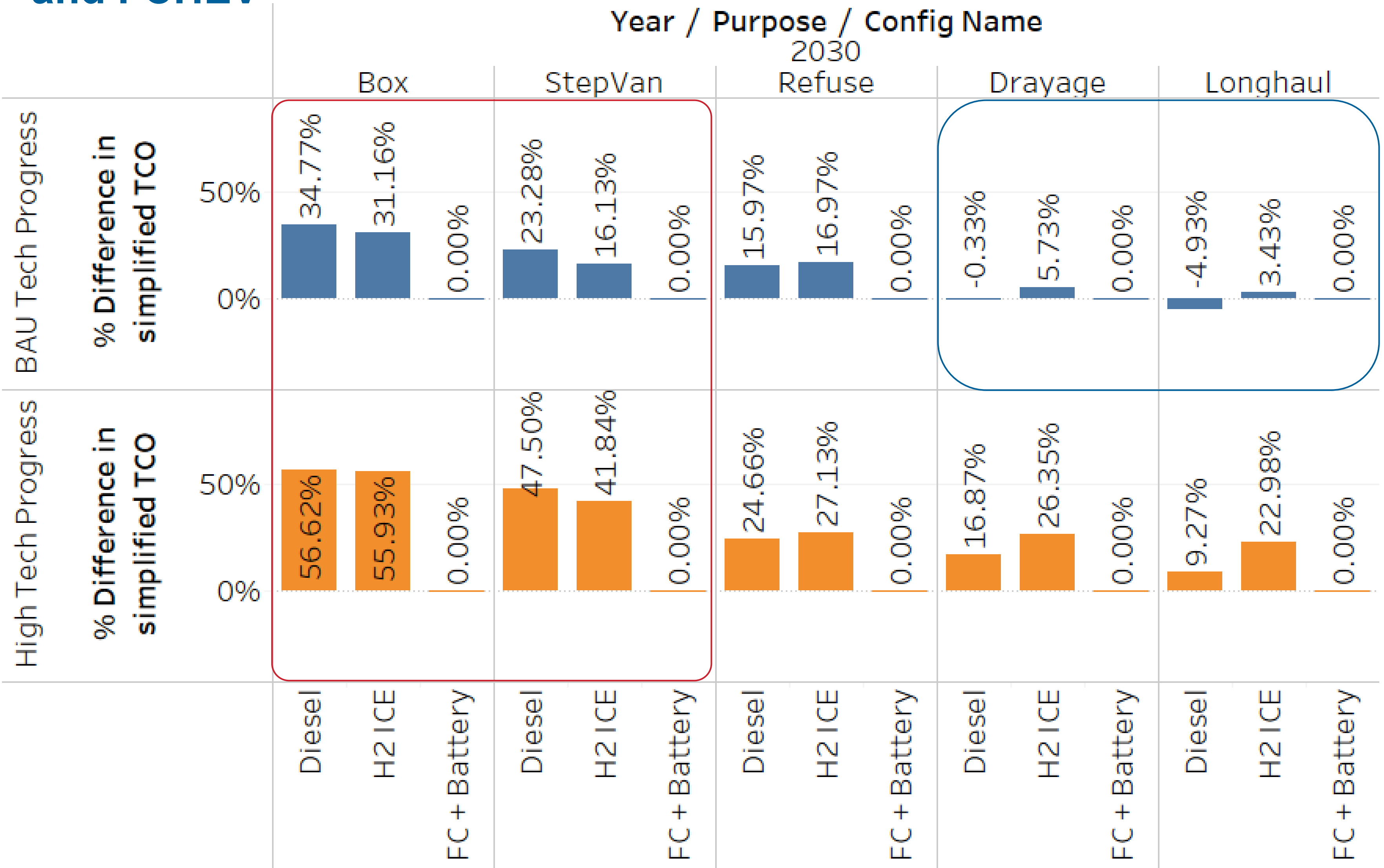
Under BAU scenario, FCHEV & H_2ICE has comparable ownership costs for heavy duty vehicles.

H_2 is assumed to be $4/kg. Cheaper hydrogen can reduce the TCO difference between H2ICE and FCHEV



- Under a low technology progress assumption, H_2ICE can be a viable backup
- H_2ICE can provide an economically attractive alternative to Diesels in medium duty applications

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Summary

H_2ICEs have the potential to be a bridge technology until HFTO interim targets are met

- **H_2ICE** de-risk H_2 infrastructure investments while offering a viable option for freight decarbonization.
  - H_2ICEs can provide an immediate switch to H_2 as fuel.
  - Help improve the demand and user base for hydrogen infrastructure.
  - DOE funded research can further improve H_2ICE.

- If **HFTO targets & VTO battery targets** are met, FCHEVs will be economically competitive by 2030.

- Hydrogen earth shot is critical for any H_2 fueled vehicle competitiveness

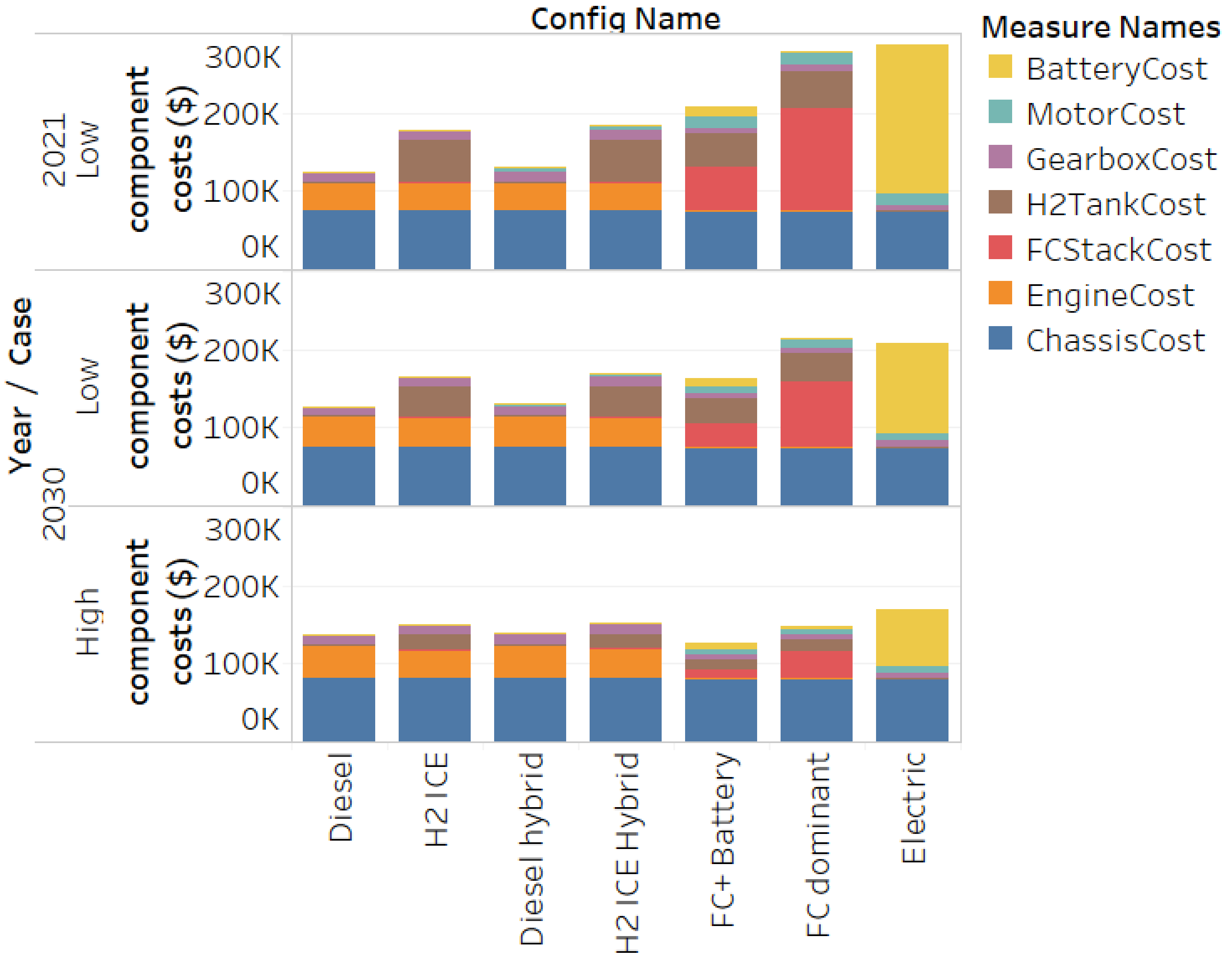
Potential Next Steps

- Include H_2ICE as part of a larger analysis to quantify the potential benefits across more modes of freight transportation and non-road applications.

Thank you!

Contact:
Ram Vijayagopal (ram@anl.gov)
Vehicle System Analysis Group
Vehicle and Mobility Systems Department
TAPS Division
Argonne National Laboratory

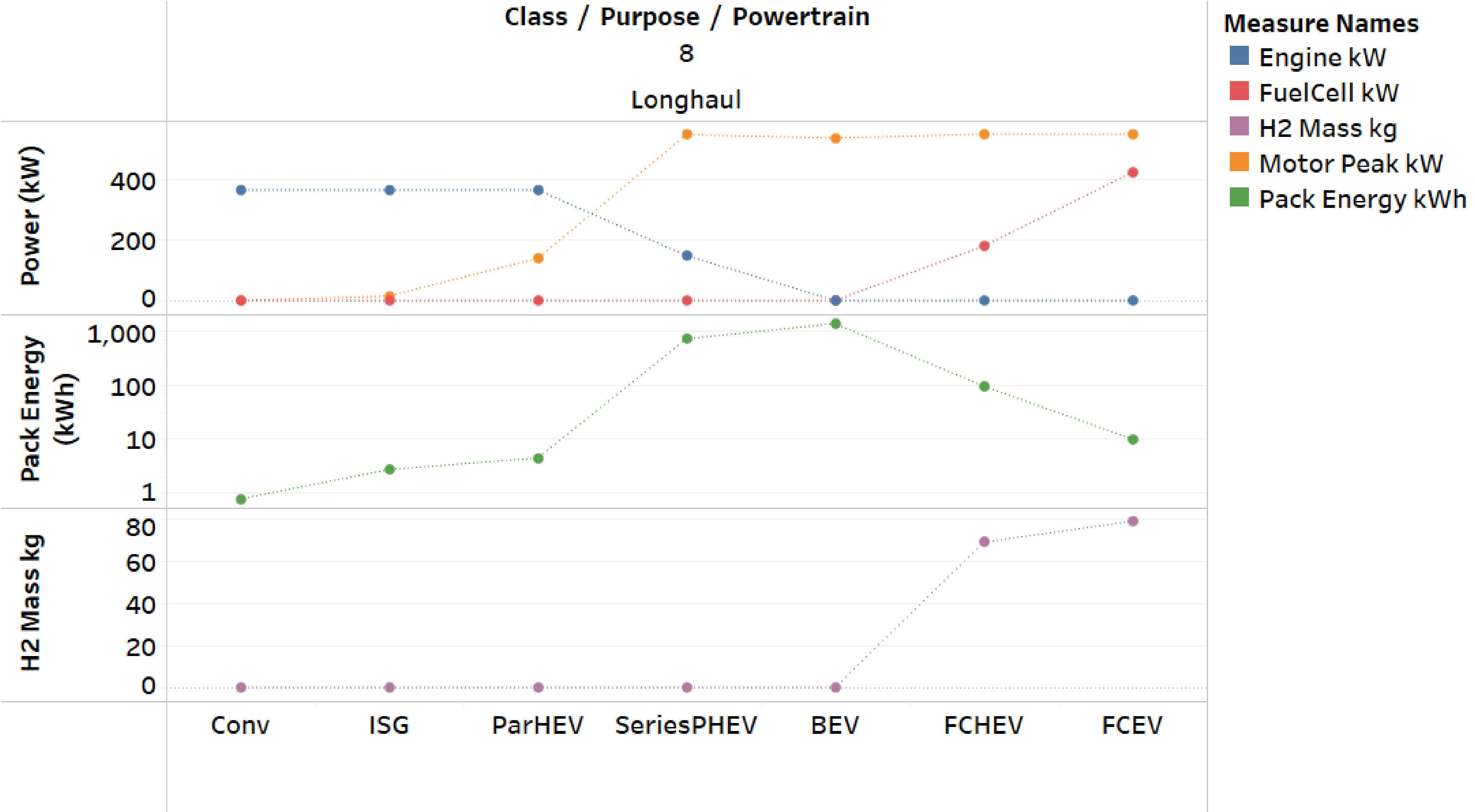
Cost of major components. Evolution over 2021-2030



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



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Factors considered for Simplified TCO calculation

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

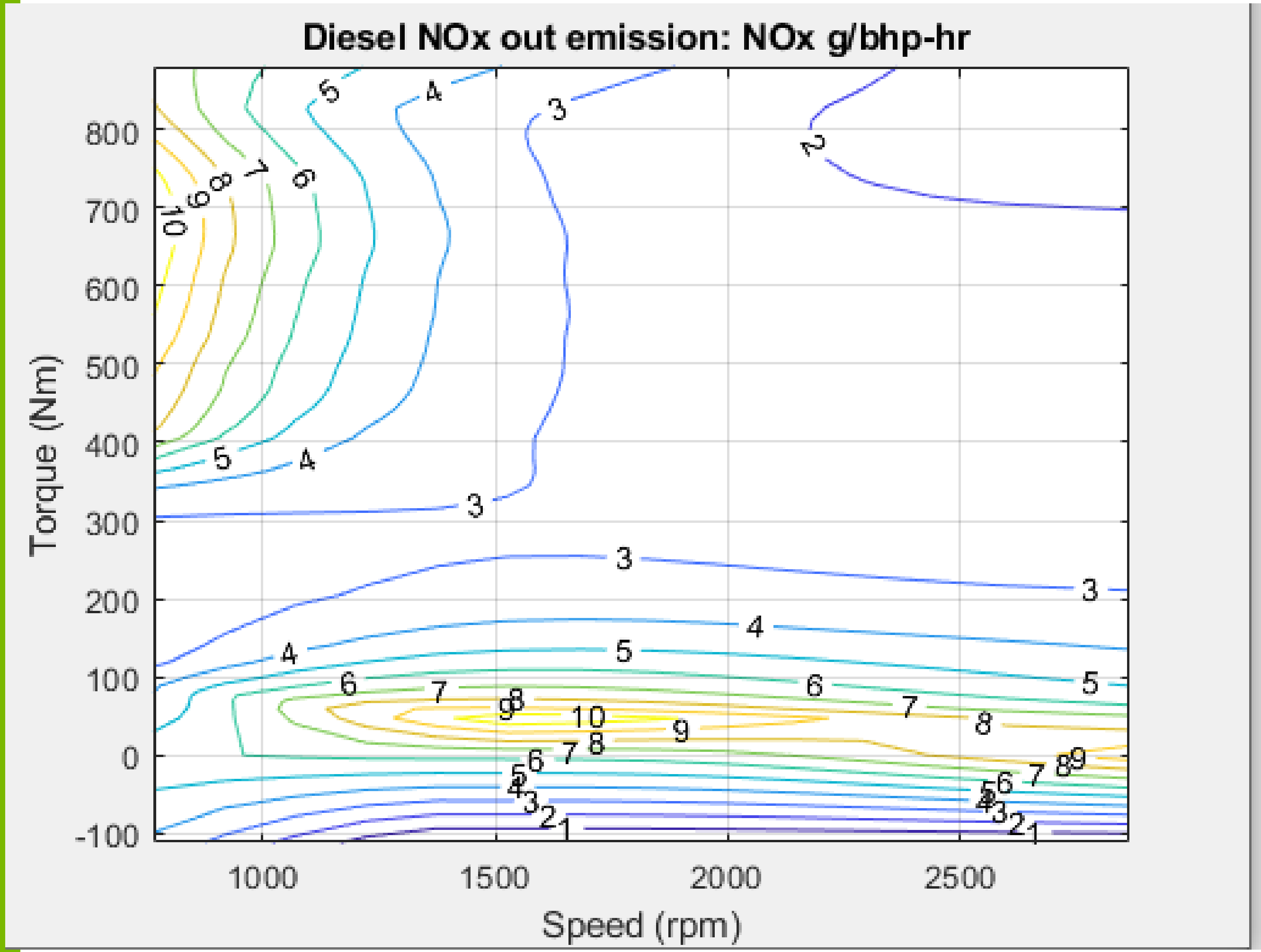
	Parameters	Simplified TCO
Capital expenses	Vehicle purchase price	yes
	Resale value	yes
	Financing costs	no
	Insurance	no
	Registration	no
	Taxes & Incentives	no
Operating expenses	Fuel cost	yes
	Driver Wage	no
	Maintenance	no
	Tolls	no
	Charging time penalty	no
	Cargo limit penalty	no

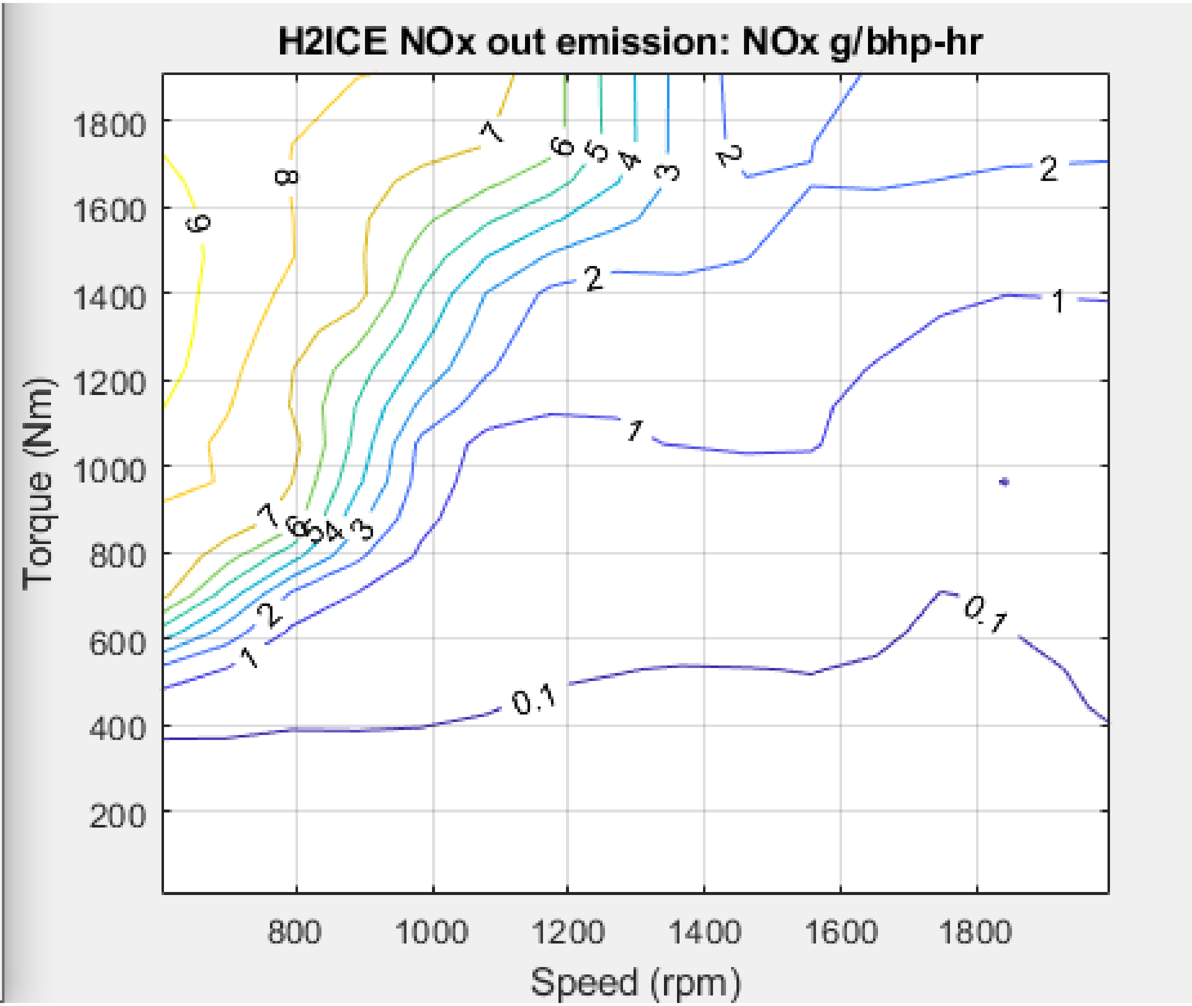
Parameters	Vocational/Longhaul
Vehicle lifetime	15 years
Service time for TCO	15/5 years
Discount rate	5%
Miles travelled	22k/100k per year

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

H2ICE has comparable NOx output as diesel for higher loads and significantly cleaner at low loads.

HEV/PHEV control can be adapted to improve NOx emissions





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