H2 ICE – A Solution for a CO2-free Powertrain

- DEUTZ Hydrogen Engine

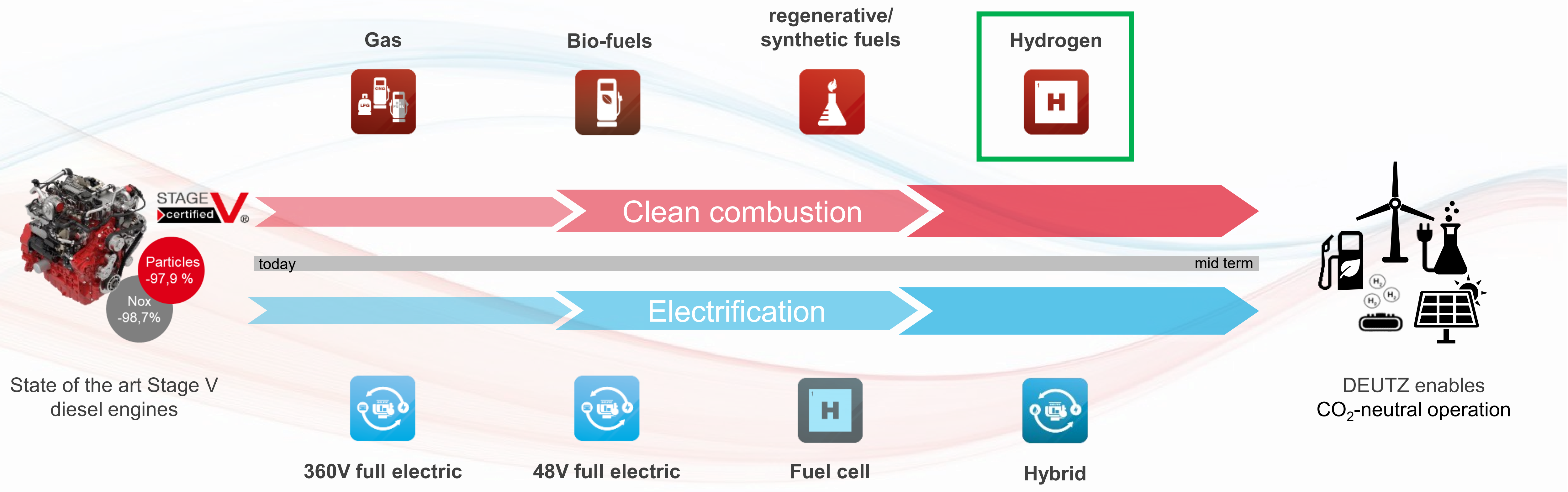
MDEC 2024

Agenda

- DEUTZ Overview
  - Dual Alternative Energy Strategy for CO_2 Neutrality
- H2 Fuels and combustion processes
  - Fuel sourcing and standards
  - Base thermodynamic cycles
- DEUTZ H2 Engine
  - Technical details
  - Emissions summary
- Regulatory Framework (theoretical cycles)
  - EPA and CARB regulatory approach (Current regulations and future Tier 5)
- H2 Safety Standards

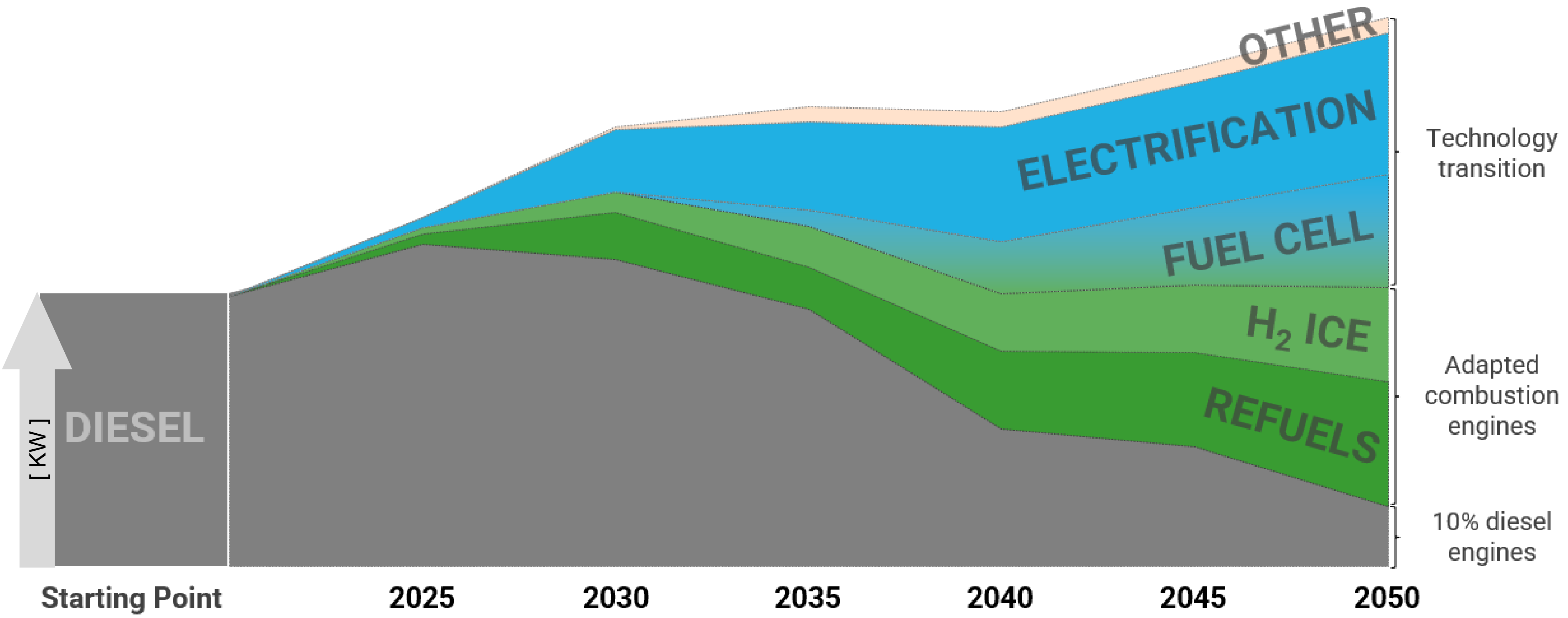
Evolution from Clean towards CO_2-neutral propulsion systems

DEUTZ H2-ICE



Sustainable Drive Portfolio for the Future Construction Site

Projected Technology Allocation Through 2050



Hydrogen Fuels and Combustion Processes

Hydrogen (H_2) Fuels

Procurement Color Palette

- Hydrogen Rainbow – Various color designations are associated with the vast array of hydrogen production processes
- Example H2 Fuel Standards:
  - DIN EN 17124
  - ISO 14687 Type I Grade D

H2 Color Designation		Process	Source
Green	Yellow*	Electrolysis	Renewables (*Solar)
Pink		Electrolysis	Nuclear
Gray	Blue**	Steam Reformation	Natural Gas (** with carbon capture)
Turquoise		Pyrolysis	Natural Gas
Black		Gasification	Coal

- Not all H2 is produced in an environmentally friendly method
- Consideration should be made as to the energy equity of the fuel that is being produced

Hydrogen (H_2) Fuels

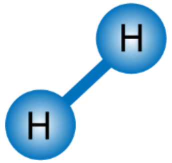
Green (and yellow) hydrogen

CO_2 impact

- Green Hydrogen is generated by electrolysis of water via the use of electricity generated by renewable sources
- Renewable sources include hydroelectric power to produce electricity (abundant in Canada)
- Yellow is a subset being primarily generated by the sun (Solar)

$$2H_2O \rightarrow 2H_2 + O_2$$

Captured Hydrogen

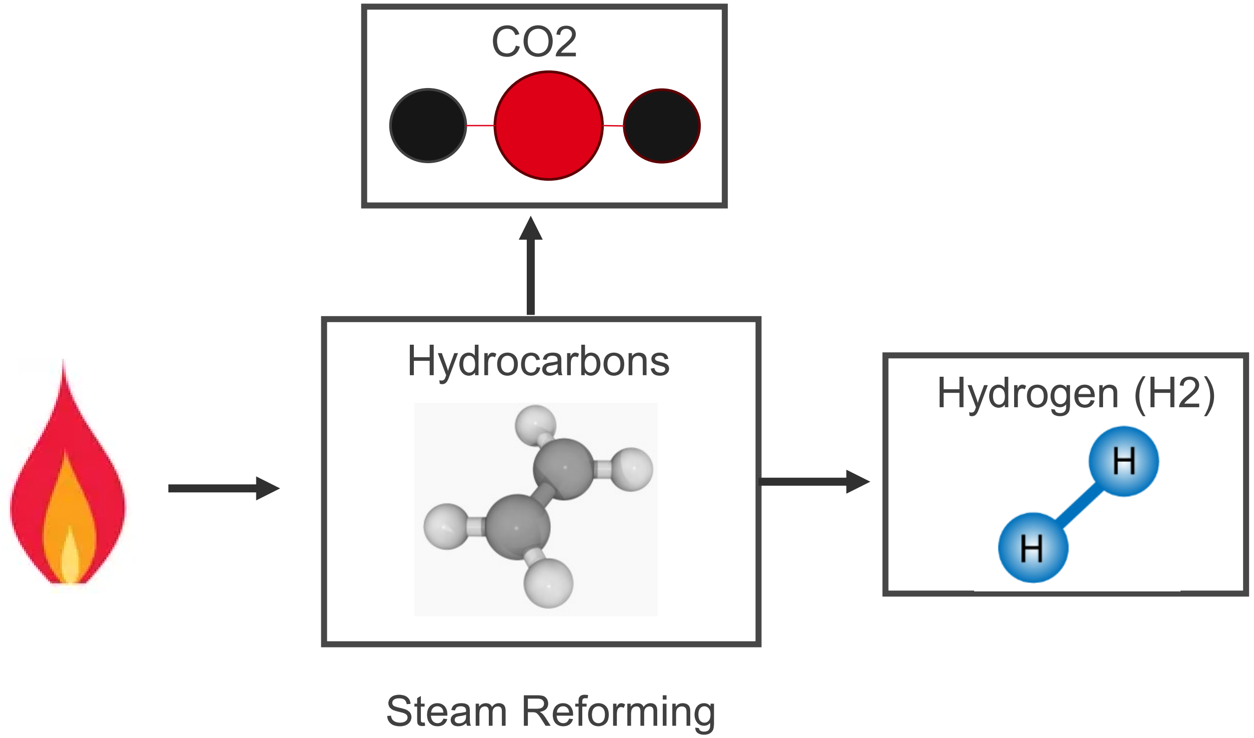


Hydrogen (H_2) Fuels

Grey hydrogen

CO_2 impact

- Grey Hydrogen is generated by processing of fossil fuels. This process is usually the steam reformation of natural gas into H2 and CO2
- Resulting CO2 is released into the atmosphere and compounds the greenhouse effect

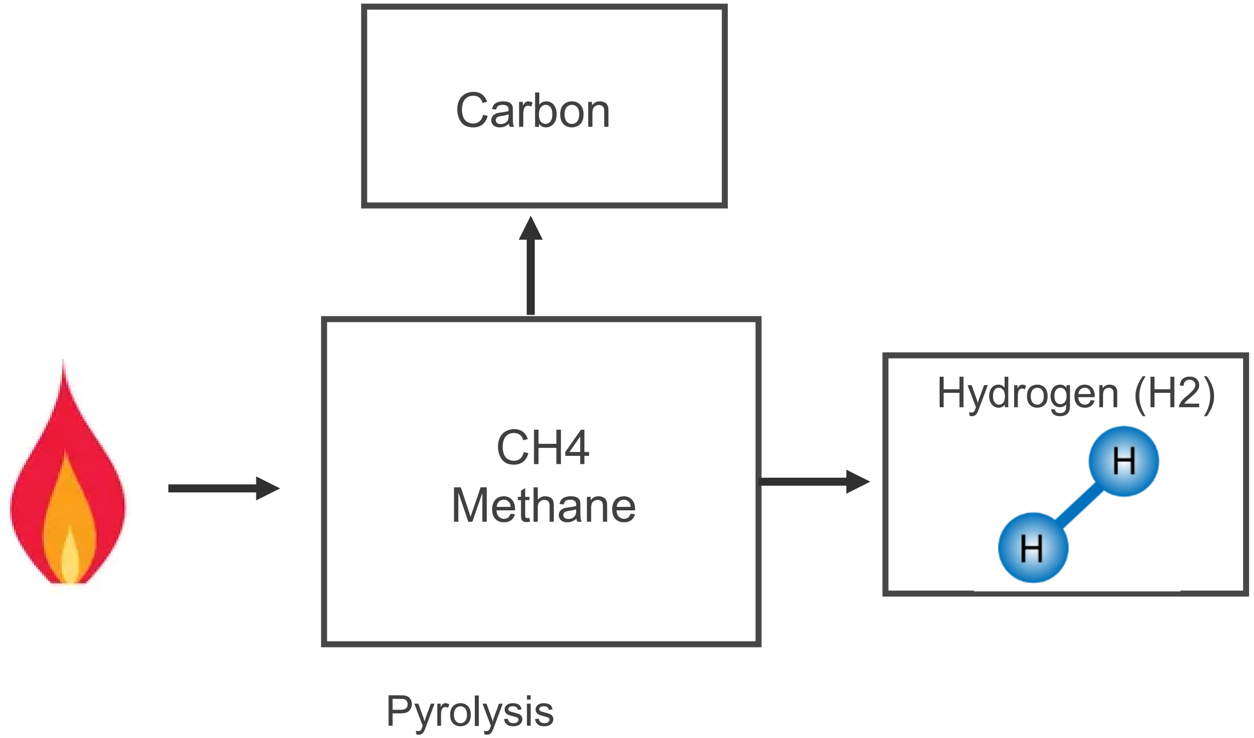


Hydrogen (H_2) Fuels

Turquoise hydrogen

CO_2 impact

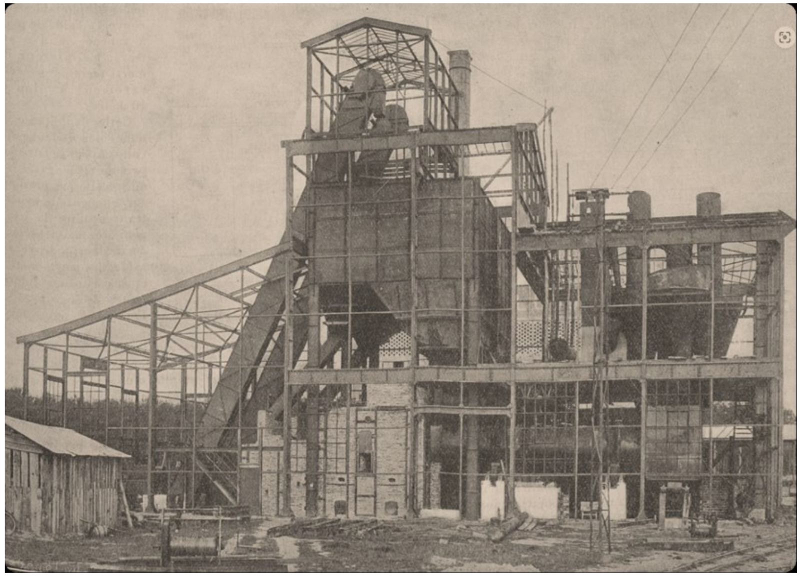
- Turquoise Hydrogen is generated usually by the processing of methane. This process is known as methane pyrolysis.
- In cases where the heat supply for the high-temp machinery involved is renewable, and the methane is not a fossil derived product, the process can have a lower CO2 and environmental impact



Hydrogen (H_2) Fuels

Black hydrogen

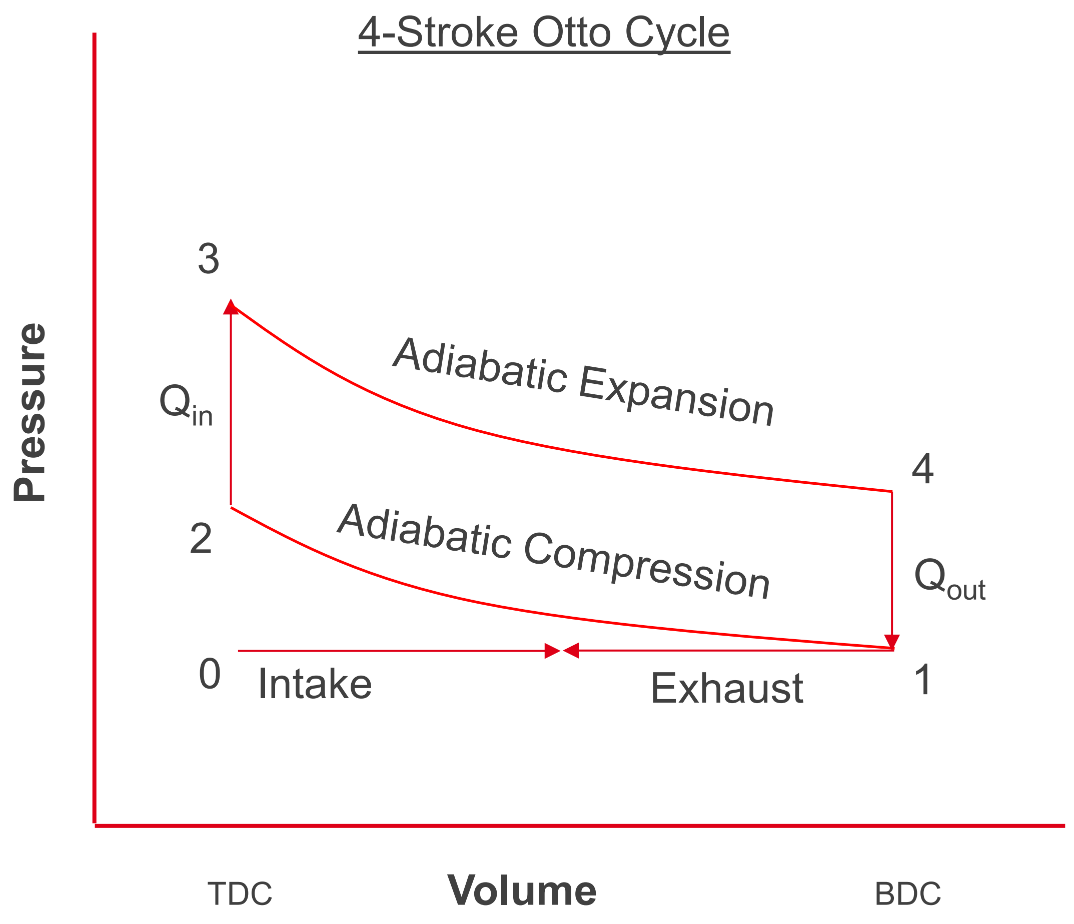
CO_2 impact



- **Black Hydrogen** is generated by **coal gasification**
- Coal is heated red hot and quenched with water vapor

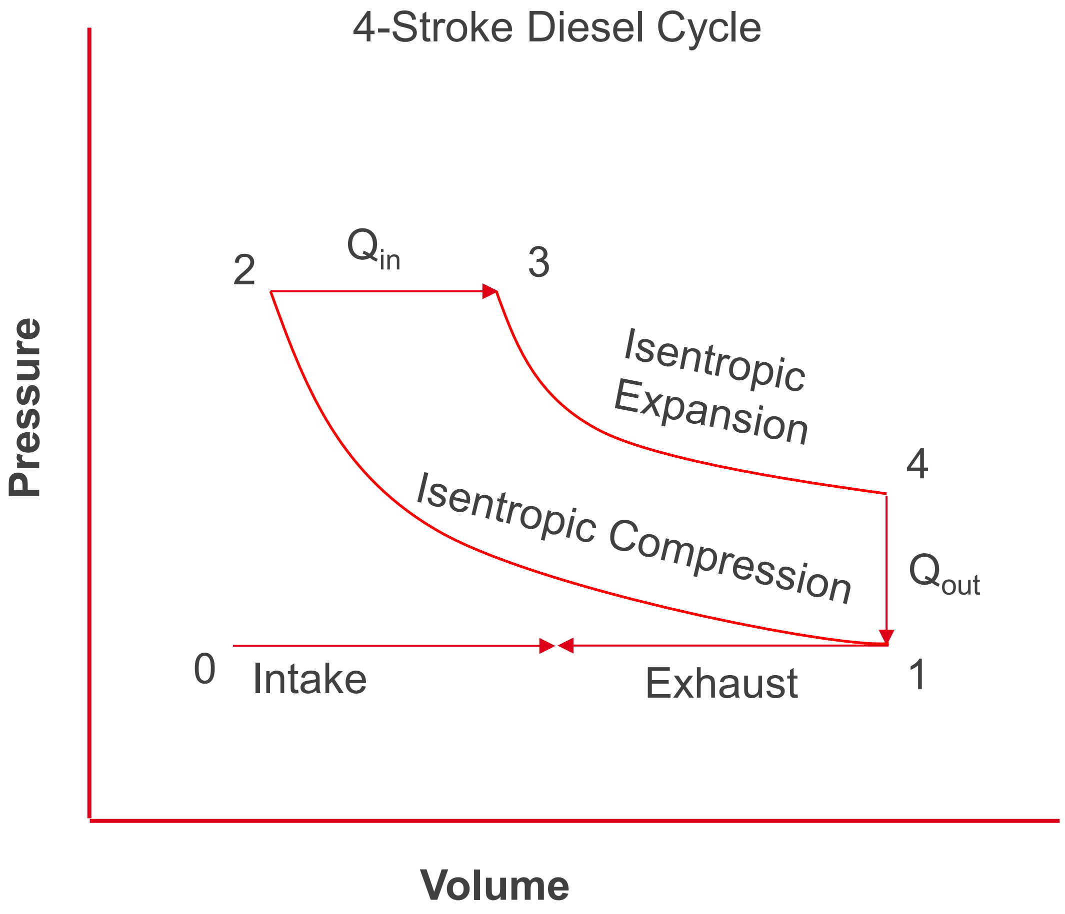
- H2 and CO are released and can be further ‘refined’ if a higher purity of H2 is required
- Purification requires Sulfur base compounds and results in CO2 and more pure H2

Typical SI Combustion Principle



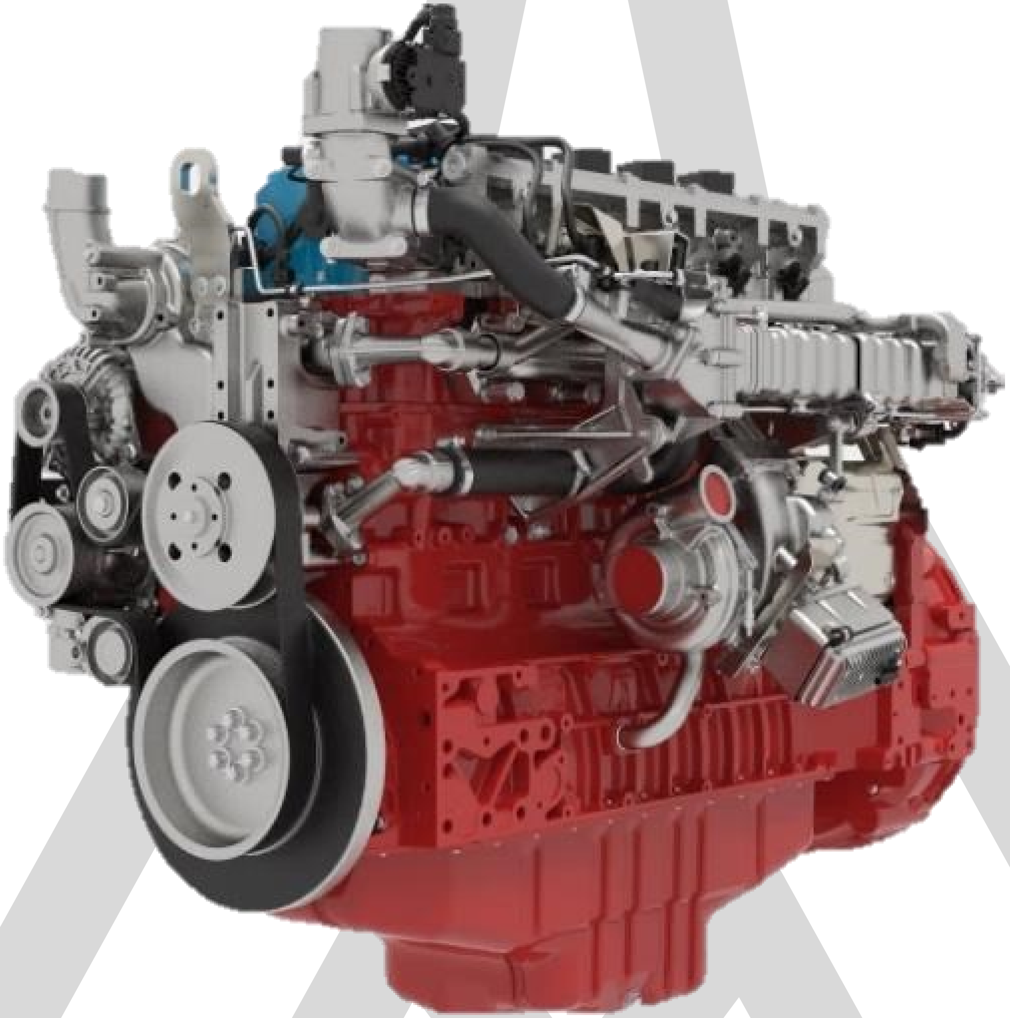
- Idealized Combustion process: $2H_2 + O_2 \rightarrow 2H_2O$*
- Typically combusted in a constant volume process (Otto/Miller cycle)
- Process steps:
  - 0-1 Intake Stroke
  - 1-2 Compression Stroke
  - **2-3 Heat input – (e.g. Spark Plug)**
  - 3-4 Power Stroke
  - 4-1 Heat Rejection
  - 1-0 Exhaust Stroke

Typical CI Combustion Principle



- Typically diesel fuel combusted in a constant Pressure process (diesel cycle)
- Process steps:
  - 0-1 Intake Stroke
  - 1-2 Compression Stroke
  - **2-3 Heat input – (spontaneous combustion)**
  - 3-4 Power Stroke
  - 4-1 Heat Rejection
  - 1-0 Exhaust Stroke

DEUTZ Hydrogen (H_2) Engine

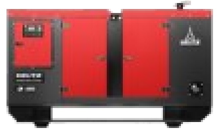


DEUTZ TCG 7.8 H2 Internal Combustion Engine

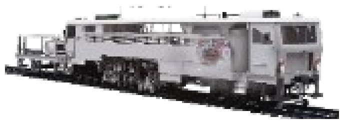
Applications

Off-Road applications

- Excavators
- Tractors & agricultural machinery
- Mining

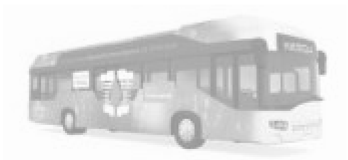


- Generators *(GenSets)*
- Block heat and power plants



Rail applications

- Regional trains
- Special vehicles

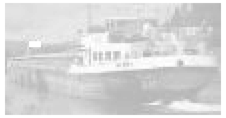


City and intercity buses*

- Medium range buses, 12m
- Complement to BEV city centre fleets

Delivery trucks*

- 16-18t trucks
- delivery traffic



Marine applications**

* On development request
** Possible future development

DEUTZ TCG 7.8 H2

Advantages of a Hydrogen engine

DEUTZ TCG 7.8 H2

- CO_2-free Combustion: $2H_2 + O_2 \rightarrow 2H_2O$*
- Economic alternative to other technologies
  - Attractive overall cost perspective
    (Initial invest is lower than with Fuel Cell drive)
  - Retrofit existing fleets possible (same drive train, additional H2-supply/tank plus safety)
- Could be industrialized in a short time with proven supplier infrastructure and existing production capacities
- Suitable for low H_2-gas qualities (lower costs, less processing than with fuel cells)
- High reliability grounded on proven base engine tech.
- Increasing H_2-infrastructure, available Maintenance-network for combustion engine

**) < 1 g CO_2/kWh*
** Idealized*

DEUTZ TCG 7.8 H2

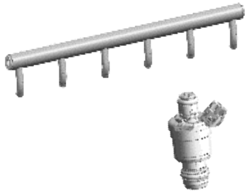
Hydrogen engine Technical changes

Improved Piston

Improved Gas exchange valves and seats

Turbocharger-Matching

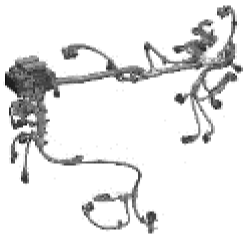
H_2-Injectors (PFI)

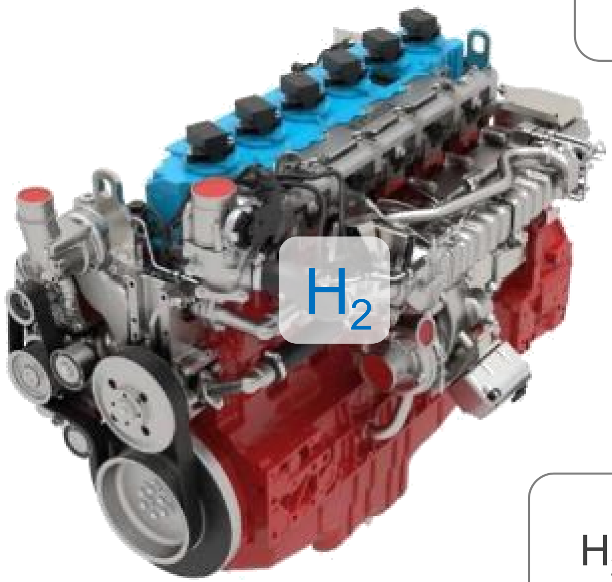


Exhaust-Gas-Recirculation (EGR)

Ignition System for Lean Combustion

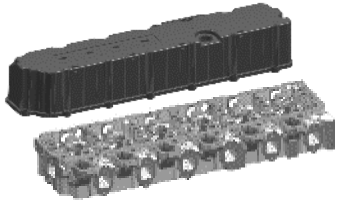
Sensors and actuators



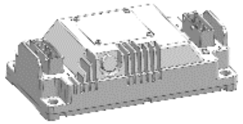


TCG 7.8 H2

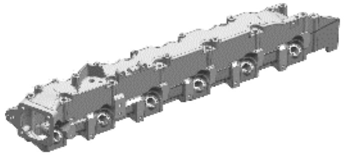
Cylinder head (Integration of ignition system)



H_2-ECU and H_2-Software



Inlet Port (integration of H_2-injectors)



SCR-System *

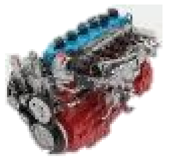
** As needed*

TCG 7.8 H2 – Emission Performance

Preliminary Results from Standard Test Cycles

- C1 and RMC data taken post SCR (tailpipe out), no DPF

			NO	NO2	NOx	HC	CO	PM	CO2	O2	PN
			g/kW-hr								
Power Category (130 - 560kW)	Test Cycle	C1	0.012	0.005	0.017	0	0	0.001	5.0	--	--
		RMC	0.011	0.009	0.020	0	0	0.001	4.9	581	2.22E+09
	US EPA limits (1039, 1048)	Tier 4 - CI	--	--	0.40	0.19	3.5	0.02	--	--	--
		Tier 2 - Large SI	--	--	0.8		20.6	--	--	--	--
	EU ST V Limits	CI	--	--	0.4	0.19	3.5	0.015	--	--	1.00E+12
		SI	--	--	0.4	0.19	3.5	0.015	--	--	1.00E+12



- Ambient air is 0.04% (~421ppm) CO2 which is measured at tailpipe out
- CO2 contribution from DEF (Diesel Exhaust Fluid): $H_2N\text{-}CO\text{-}NH_2 \rightarrow CO_2$

*Emission data presented are preliminary, not part of a certification

Key Message

- **All regulated emissions are within current US and EU**
- **H2 is considered CO2-free since the fuel does not contain Carbon**

TCG 7.8 H2 – Emission Performance

Comparison with Underground Mine Ventilation Requirements

- C1 data

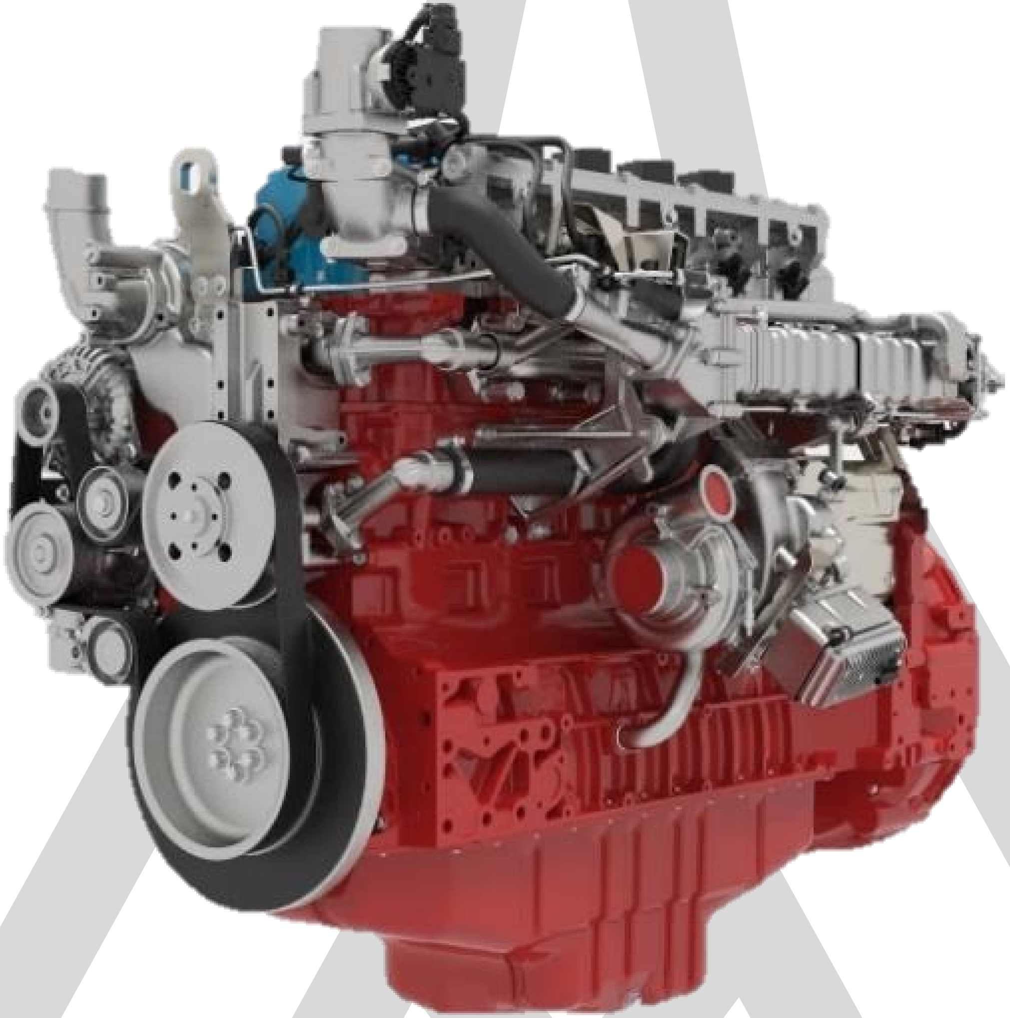
		kW @ RPM	After-treatment	NOx	HC	CO	PM	CO2	Ventilation (cfm)
				g/kW-hr					
CI - Tier 3	**TCD 2013 L06**	190 @ 2300	No	3.8	0.12	0.41	0.097	756	10,700
CI - Tier 4	**TCD 6.1 L6**	180 @ 2300	Post	0.08	0.012	0.01	0.012	773	11,000
SI	**TCD 7.8 H2***	220 @ 2200	Pre	0.51	0	0.023	--	4.3	500
			Post	0.02	0	0	0.001	4.9	500

*Emission data presented are preliminary, not part of a certification or approval

Key Message

- **Hydrogen ICE present opportunity to reduced ventilation rates and compliance to low criteria emissions standards**

H2-ICE Regulatory Framework (U.S.)



Engine Certification Path(s) per Current U.S. Federal Law

Compression Ignition (CI) or Spark Ignition (SI)

DEUTZ®

SI path – 40 CFR 1048

Regulations of part 1048 apply for all new, spark-ignition nonroad engines with maximum engine power above 19 kW

Spark-ignition means relating to a gasoline-fueled engine or any other type of engine with a spark plug (or other sparking device) and with operating characteristics significantly similar to the theoretical Otto combustion cycle. Spark-ignition engines usually use a throttle to regulate intake air flow to control power during normal operation.

Latest standard is Tier 2. No new regulations are expected

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

CI path – 40 CFR 1039

The regulations in this part 1039 apply for all new, compression-ignition nonroad engines

Compression-ignition means relating to a type of reciprocating, internal combustion engine that is not a spark ignition engine.

Latest standard is Tier 4, with CARB Tier 5 expected in 2029+

- **EPA regulations are fuel-agnostic**
- In the EU, all fuel and combustion cycle types within the 56 - 560kW category must meet the same emission standard

CARB Tier 5 Development into Latest Regulation Order

Major Updates from Prior Concept Phases

- California Air Resources Board (CARB) rulemaking mostly applicable to nonroad CI engines (Diesel)
- Increased stringency in criteria emissions (NOx, PM, etc.), diagnostic requirements among others
- However…
- **Includes H2-ICE certification pathway for California**
  - Not considered a Zero Emissions by CARB. Zero Carbon concept is not mentioned (concept may not exist)
  - Proposed CI engine certification and compliance path

1 of 221

9/24/24 DRAFT

Proposed Regulation Order

Amendments to Tier 4 Off-Road Compression-Ignition Engine Emission Standards and Test Procedures and Adoption of New Tier 5 Off-Road Compression-Ignition Engine Emission Standards and Test Procedures

Note: This version of the Proposed Regulation Order complies with Government Code section 11346.2 subdivision (a)(3). The proposed amendments are shown in underline to indicate additions and ~~strikethrough~~ to indicate deletions from the existing regulatory text. Subsections for which no changes are proposed in this rulemaking are indicated with "* * * * *".

Note: Current section 2422 is being deleted in its entirety, and a new section 2422 is being proposed. New sections 2139.1, 2421.1, 2423.1, and 2425.2 are also being proposed. The entire text of new sections 2139.1, 2421.1, 2422, 2423.1, and 2425.2 set forth below is new language and is shown in "normal type" proposed to be added to the California Code of Regulations.

A Table of Contents and page numbers are included in this draft to assist reviewers with navigating the document. These items are not part of the proposed regulation and will not be included in the final Proposed Regulation Order.

Date of Release: September 24, 2024; DRAFT

H2-ICE Certification Pathway

CARB Only (not a Federal EPA Proposal)

- H2-ICE to be subject to CI standards and all requirements if any of the following apply starting MY2029 (Certified to Tier 5):
  1. Engine with boosted air induction (turbochargers, superchargers etc.)
  2. Engine is designed to operate in equipment historically powered by off-road CI engines
- Exception:
  - H2-ICE certified to CI shall not be used in eq. powered by off-road spark ignition (SI) if the eq. is subject to large SI (LSI) forklift phase out requirements
- **H2-ICEs do not meet the CARB's definition of ZE**
- Credits
  - H2-ICE would not generate CO2 credits (CA-ABT or ZE credits)
  - H2-ICE would qualify for CA-ABT credits for criteria pollutants (NOx and PM)

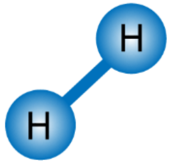
- H2-ICE possibly subject to OBD or extended DF testing

H_2

Tank Standards, Storage, and Safety

Hydrogen Tank Storage and Standards

H2 Physical Properties for Storage



- Mass Basis:
  - Gasoline = 44 MJ/kg vs. H2 = 120 MJ/kg
- Volume basis
  - Gasoline = 32 MJ/L vs. LH2 = 8MJ/L

- LH2: Hydrogen in liquid form requires a temperature of -252.8 deg C at 1 atm
- LH2 has a volumetric density of 71 kg/m^3

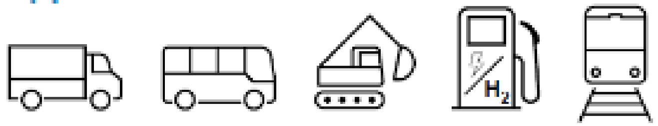
Various storage and transport solutions are necessary for the liquid and gas forms of H2

Hydrogen Tank Storage and Standards

H2 Tank Systems

Type I	All-metal cylinder
Type II	Load-bearing metal liner hoop wrapped with resin-impregnated continuous filament
Type III	Non-load-bearing metal liner axial and hoop wrapped with resin-impregnated continuous filament
Type IV	Non-load-bearing, non-metal liner axial and hoop wrapped with resin-impregnated continuous filament

Application areas



Type I Tank

Type IV Tank

Core-Module Rack

H2 Fuel Storage Tank Requirements

US and EU H2 Tank System Standards

H2 related…	Agency/ Org	Regulation or Standard
General	OSHA	29 CFR 1910.103
	NFPA	NFPA 55
Storage	SAE	SAE J2579
	ANSI, CSA	HGV 2:21
	ISO	ISO 19884-3
		ISO 19881:2018
		ISO 16111
	UN ECE	TRANS/180/Add.13
	NFPA	NFPA 2 – 2023
	ASME	Boiler and Pressure Vessel Code (BPVC)
Safety	ISO	ISO/TR 15916:2015
Transportation by Road	US DOT and CE	UN/ISO 11119-2. CE-PED – Module B and D
H2 refueling connection devises		ISO 17268:2020
Piping, tubing, and fittings	OSHA	ANSI B31.1-1967
	NFPA 2	NFPA 2 – 2023

- Basic collection of standards that relate to H2 tanks and storage
- Standards cover various aspects from tank types, connections, fittings among others

DEUTZ TCG 7.8 H2

Closing Remarks

Zero Emissions vs. Zero Carbon Emission

- H2 ICE can be more efficient than diesel with near zero or zero-carbon emission acceptance
  - Still some carbon emissions from lubricating oil and DEF
  - Emissions of NOx from high temp/press combustion. Emissions control could be needed (SCR)
- Smaller aftertreatment system footprint compared to Diesel

Take-away thoughts

- Fuels Sourcing – Improvements to be made within the fueling infrastructure and sustainable procurement
- H2 derived from Grey/black methods could be worse than diesel when life cycle CO2 (or GHG) emission are concerned
- When considering engine-out criteria pollutants, H2-ICE has lower emission compared to Diesel-ICE
- Gas vs. Liquid H2 storage and safety considerations

Thank you!