ASHOK LEYLAND
No Dream Too Far

Technical Session – 2B

Hydrogen in Mobility

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HINDUJA GROUP

EVOLUTION FROM TRANSPORTATION TO MOBILITY

ELECTRIC

CONNECTED

SHARED

AUTONOMOUS

"The future we've been saying is coming so fast – is already upon us"

ZERO CRASHES

ZERO EMISSIONS

ZERO CONGESTION

Pollution

Global Warming

Economy & Productivity

Can we Predict Future ? Are we fortune tellers ?

"Carbon is our enemy, not the internal combustion engine," says Akio Toyoda , Chief Toyota Motors.

- No one can predict the future. The best that humans can do is forecast.
- What if EVs aren’t the future we were hoping for?
- By not putting all of its eggs in one basket, (Toyota’s or AL’s) diversity will enable to not just **be flexible to what the future will be**, but to be able to **address carbon neutrality** in a much swifter manner.
- It’s not the internal combustion engine is our problem, but rather, **it’s carbon dioxide emissions.**
- **CNG,LNG, Bio fuels , Methanol , Ethanol , Hydrogen combustion engine, hydrogen fuel cell electric vehicle (FCEV), and other potential new technologies to co-exist.**

- ***I Believe That Water Will One Day Be Employed As Fuel, That Hydrogen And Oxygen Which Constitute It, Used Singly Or Together, Will Furnish An Inexhaustible Source Of Heat And Light (Energy), Of An Intensity Of Which Coal (Hydrocarbon) Is Not Capable. – Jules Verne (1874)***

Market Dynamics

- CO_2 commitments not just by Government, but also by large customers such as Amazon, Flipkart, Jio, Shell etc.
- Large Investments in Green Energy > 10B by Reliance, investments by Public Sector firms like IOCL, GAIL etc.
- PLI schemes relevant to Automotive Industry – Battery cell ecosystem, Focus on BEV, Fuel Cell etc.
- CNG/LNG Pricing Policy by government (revised once in 6 months) and its implications.
- Investments in CNG/LNG by Governments and Private players, resulting distribution / availability etc.
- Vehicle scrappage policy.
- Shift of Market from Retail Customers to Fleet Customers (Key accounts).
- Regulations & Policy - Flex Fuels, Bio-Fuels, Fuel Economy, Safety (ADAS for example) etc.
- Customer Requirement - Bio Fuels, Increased Warranty etc.
- Increased Use of Railways for freight will compete with us (last mile connectivity is a challenge).
- Supplier/OEM partnership for value added services, customer oriented in New Technology Products like BEV, FCEV, etc.
- Market moving from Buying Product to Subscription model (Pay / km) (Different sales model)
- Price sensitive (value for money products) – Better service support.

where are we now

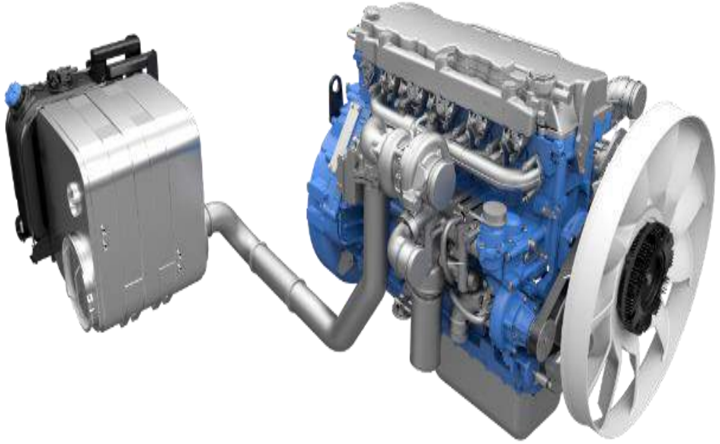
- removes the harmful gases produced in engine,
- control noise
- treating gases and sending less harmful ones (Combustion time is less)
- improves engine performance and fuel consumption , by breathing
  (If quicker exhaust leaves , engine is free to take in more, fresh oxygen)

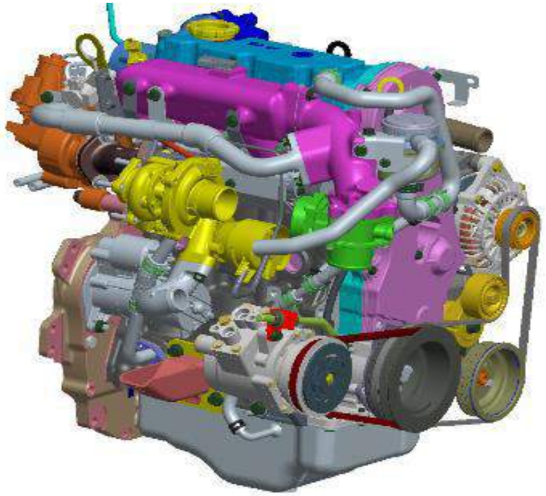
Road & infrastructure : Challenging

Maintenance practices : Rudimentary.

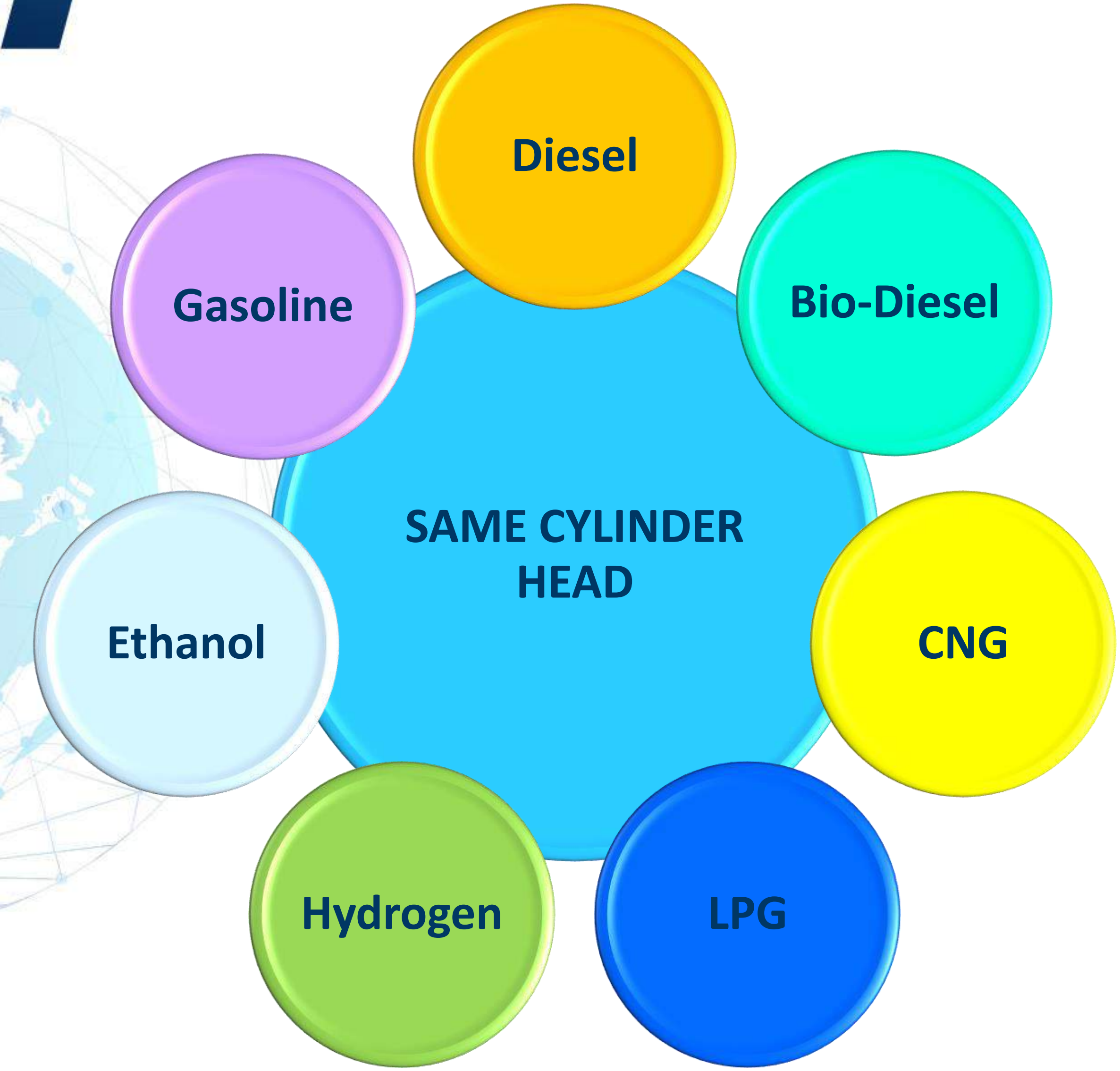
Challenging environmental conditions: Vibration, Cleanliness, fuel/ lubrication quality.

UNDERSTANDING EMISSIONS





IC Engines to be made Fuel Agnostic



SAME CYLINDER HEAD

Diesel

Bio-Diesel

CNG

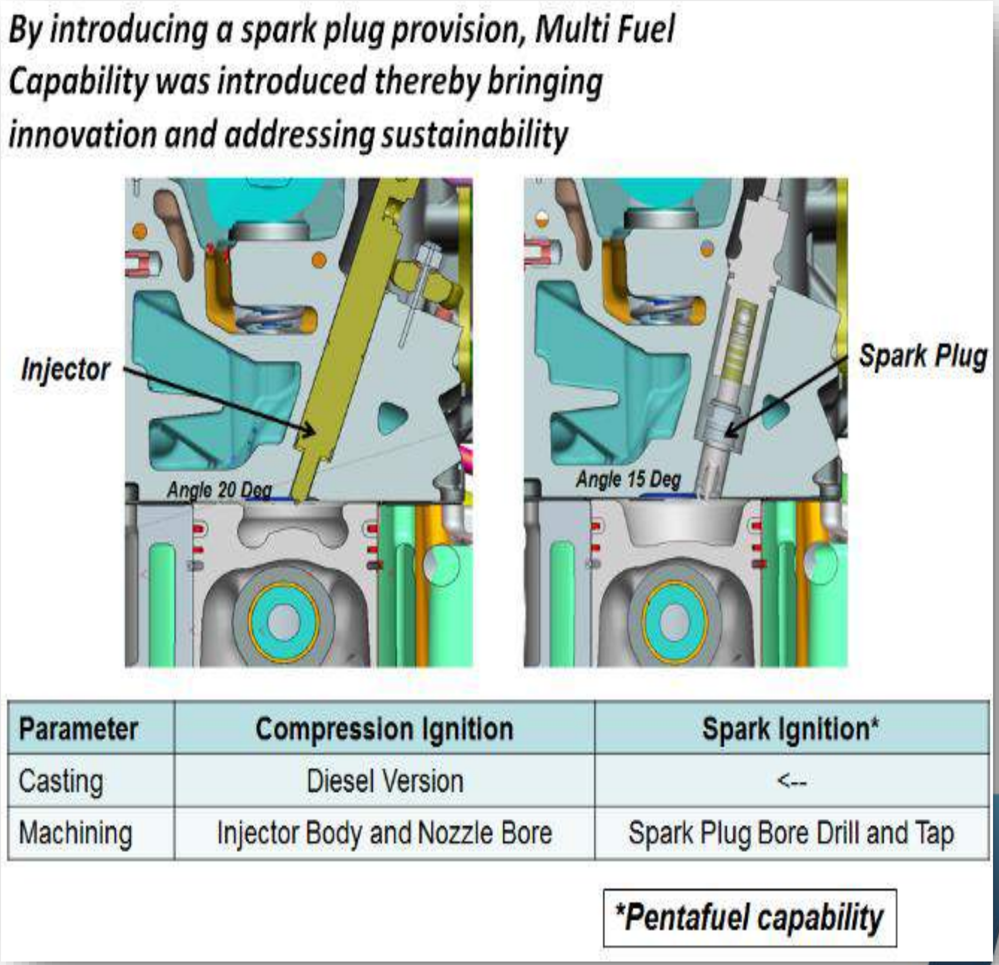
LPG

Hydrogen

Ethanol

Gasoline

- Engine Design for Multi-Fuel configuration.
- All component below cylinder head remains same.



By introducing a spark plug provision, Multi Fuel Capability was introduced thereby bringing innovation and addressing sustainability

Parameter	Compression Ignition	Spark Ignition*
Casting	Diesel Version	<--
Machining	Injector Body and Nozzle Bore	Spark Plug Bore Drill and Tap

**Pentafuel capability*

Non fossil fuels and electric vehicles for future

- Consumption of hydrocarbons is increasing exponentially on use of HC fuels , their impact is
  - environmental degradation
  - fall in AQI (Air Quality Index)
  - fluctuating climatic conditions
  - falling human health as well as global warming, rising sea levels, air pollution, acid rains, damage to marine life due to oil spills and ocean acidification.

- In Hydro carbon , Hydrogen being focused now as it is "THE SIMPLEST AND MOST ABUNDANT ELEMENT ON EARTH".. Hydrogen energy , denser, Better & cleaner contender for energy generation.

- Hydrogen is now being considered for replacement of gasoline, heating oil, natural gas, and other carbon fuels in both transportation and non-transportation applications , can be produced on site or transported, efforts are being thought off.

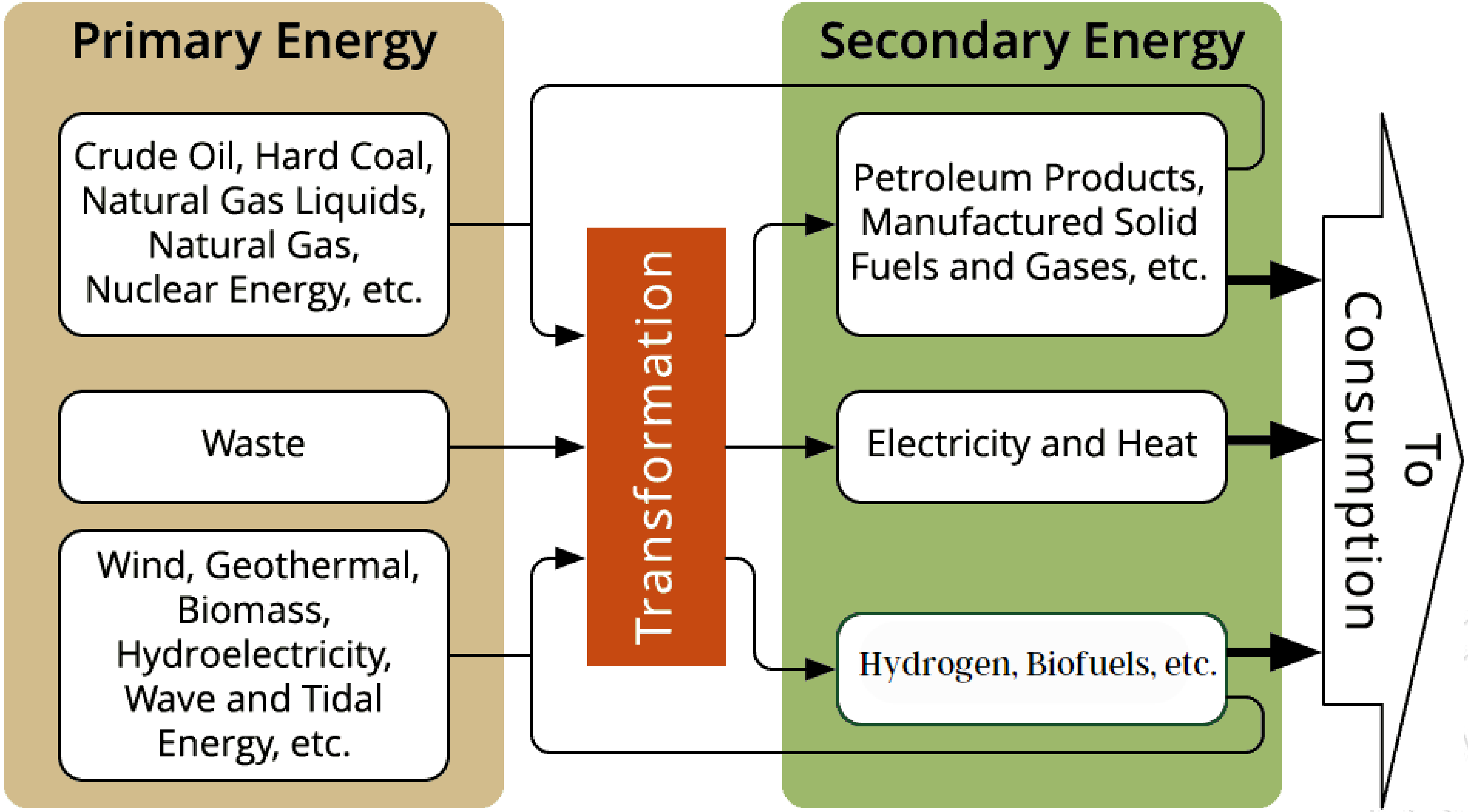
- Similar to electricity, Hydrogen is a high-quality energy carrier, which can be used with excellent efficiency and near-zero emissions at the point of use.

- Hydrogen usage as fuel for transportation, heating, and power generation being considered now.

ICE is NICE…New Ice ..what is new ? Why ? How relevant ?

- Affordable energy has been instrumental in raising the standard of living across the world. Burning of fossil fuel or bio-derived fuel has been the only reliable source of energy.
- Entire planet is linked by a massive transportation infrastructure that is based on ICE. This requires decades and tremendous expense to replace.
- Dramatic advancements in ICE in the past decade that have brought emission levels down and now tire and brake wear particulate emissions are more significant (applicable to EV too).
- Proposed alternatives like EV have major challenges in battery due to cost, weight and other limitations. Renewables for these alternatives are only a miniscule fraction of world’s energy.
- Impact of ICE on climate change being assessed and alternative fuels getting evolved
- Data and science driven our policies for a realistic transition to sustainable future energy systems.
- Future of road and off-road transport sector would be characterized by a mix of solutions involving battery and hybrid electric as well as conventional vehicles powered by IC engines. Need for brightest young minds to engage in this effort!
- Lot of scope to improve ICE further by combining with electrification (Toyota effort on hybridization).

Ref.: Reitz, 2019 – Future of ICE, IJER editorial



Primary Energy

Crude Oil, Hard Coal, Natural Gas Liquids, Natural Gas, Nuclear Energy, etc.

Waste

Wind, Geothermal, Biomass, Hydroelectricity, Wave and Tidal Energy, etc.

Transformation

Secondary Energy

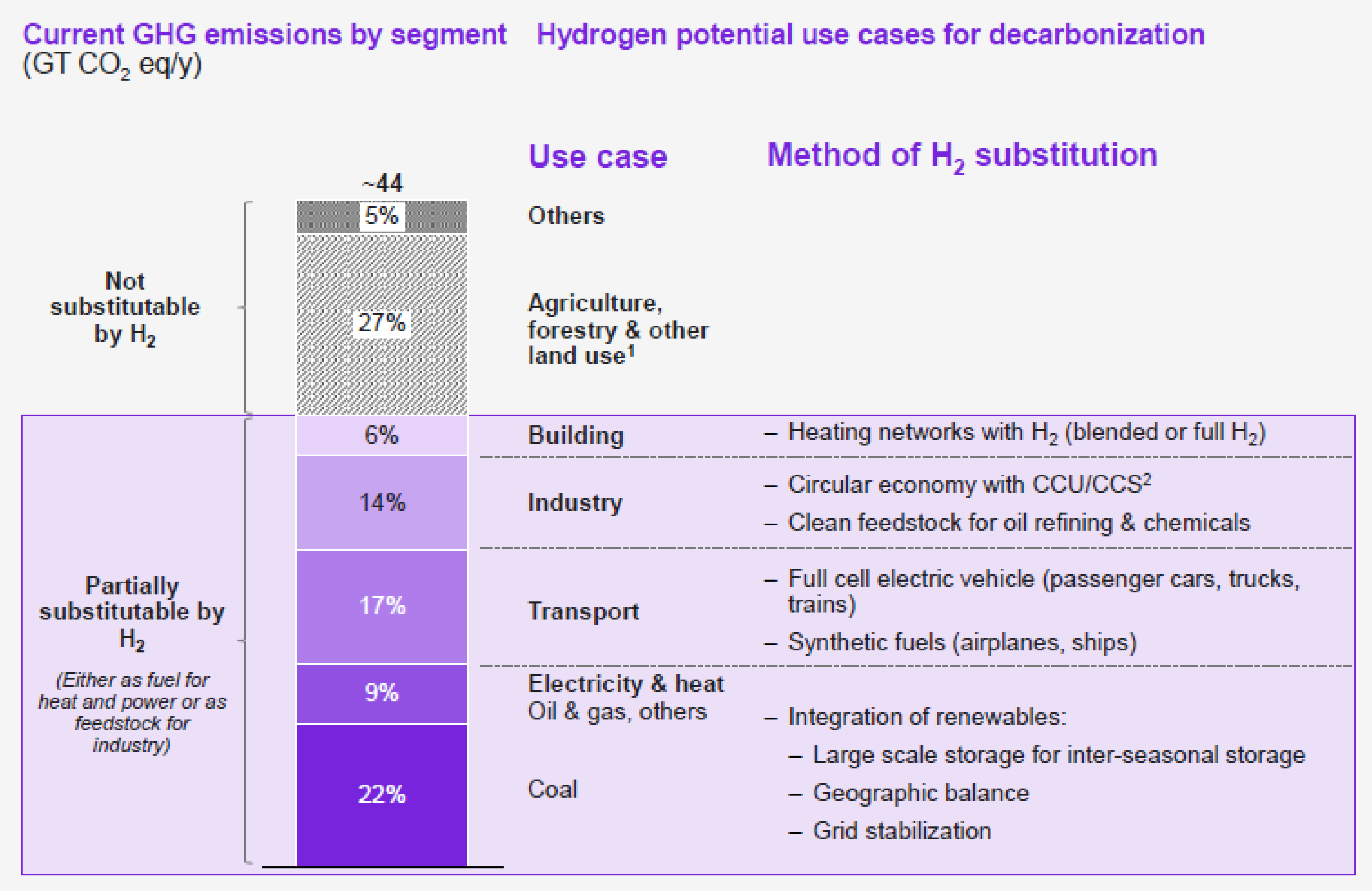
Petroleum Products, Manufactured Solid Fuels and Gases, etc.

Electricity and Heat

Hydrogen, Biofuels, etc.

To Consumption

Hydrogen's Role in Energy Transition



Current GHG emissions by segment (GT CO_2 eq/y)

Hydrogen potential use cases for decarbonization

~44

	Share	Use case	Method of H_2 substitution
Not substitutable by H_2	5%	Others	
	27%	Agriculture, forestry & other land use[1]	
Partially substitutable by H_2 *(Either as fuel for heat and power or as feedstock for industry)*	6%	Building	– Heating networks with H_2 (blended or full H_2)
	14%	Industry	– Circular economy with CCU/CCS[2] – Clean feedstock for oil refining & chemicals
	17%	Transport	– Full cell electric vehicle (passenger cars, trucks, trains) – Synthetic fuels (airplanes, ships)
	9%	Electricity & heat Oil & gas, others	– Integration of renewables: – Large scale storage for inter-seasonal storage – Geographic balance – Grid stabilization
	22%	Coal	

Hydrogen is competing with other low carbon solutions that tackle similar applications

References:
IEA, FAO, Kearney Energy Transition Institute Analysis

Benefits of H2 applied to road transport

- **Operational Benefits**
  - Long range
  - Short re-fuelling time
  - Lack of vibration
  - Smooth driving experience
- **Environmental Benefits**
  - No toxic tailpipe emissions
  - GHG emission reductions
  - Noise reduction
- **Compliance with Regulations**
  - On low-carbon mobility
  - On air quality

✚

✓Reduction of vulnerability to fossil fuel imports (Energy Security, affordable)

✓Storage solution to volatile local renewable energy that can be used as a fuel

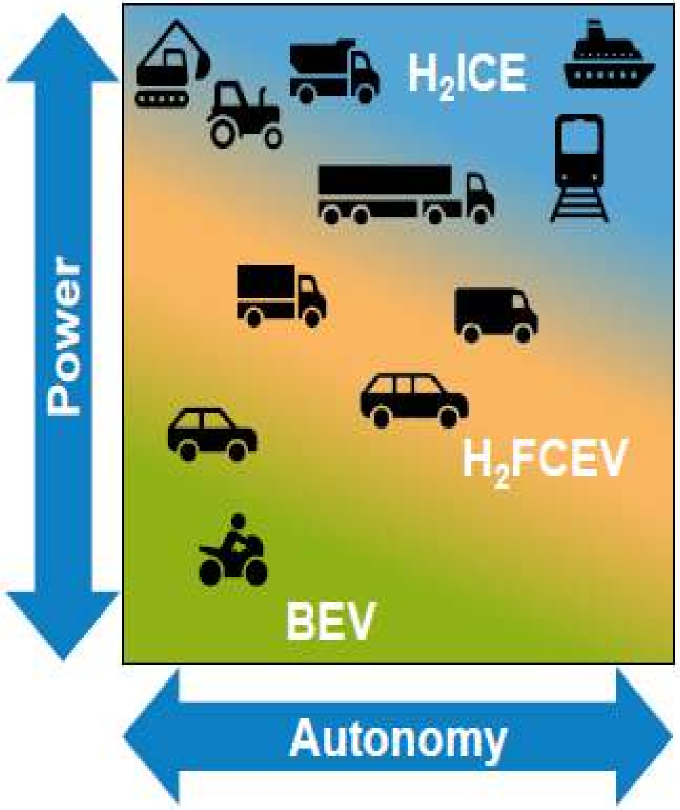
✓Production of new local jobs and improvement of economic competitiveness

✓Clean India in future will have electrification of transport and green hydrogen for industries

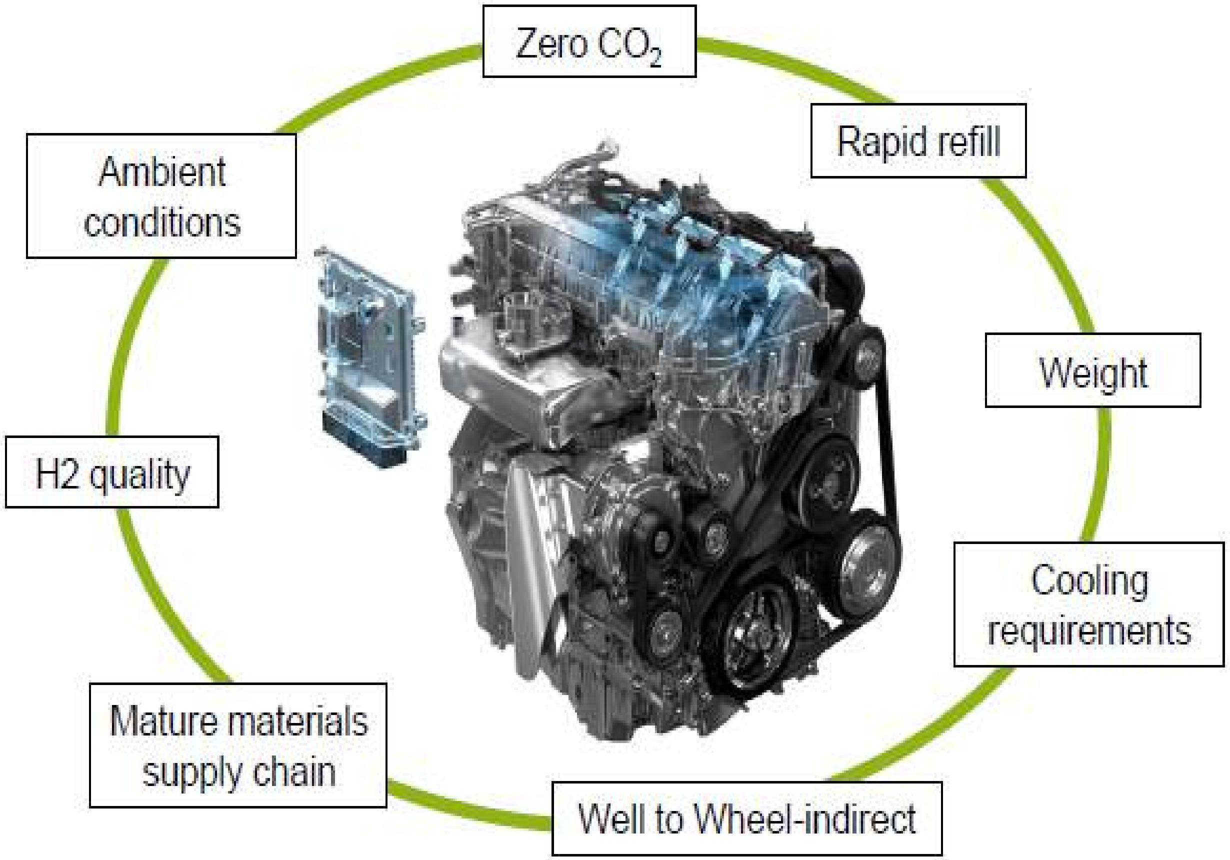
Benefits of H2 applied to road transport

Hydrogen offers several advantages over other carbon-free powertrain solutions

Application Space



Technical arguments for H_2ICE



Zero CO_2

Rapid refill

Weight

Cooling requirements

Well to Wheel-indirect

Mature materials supply chain

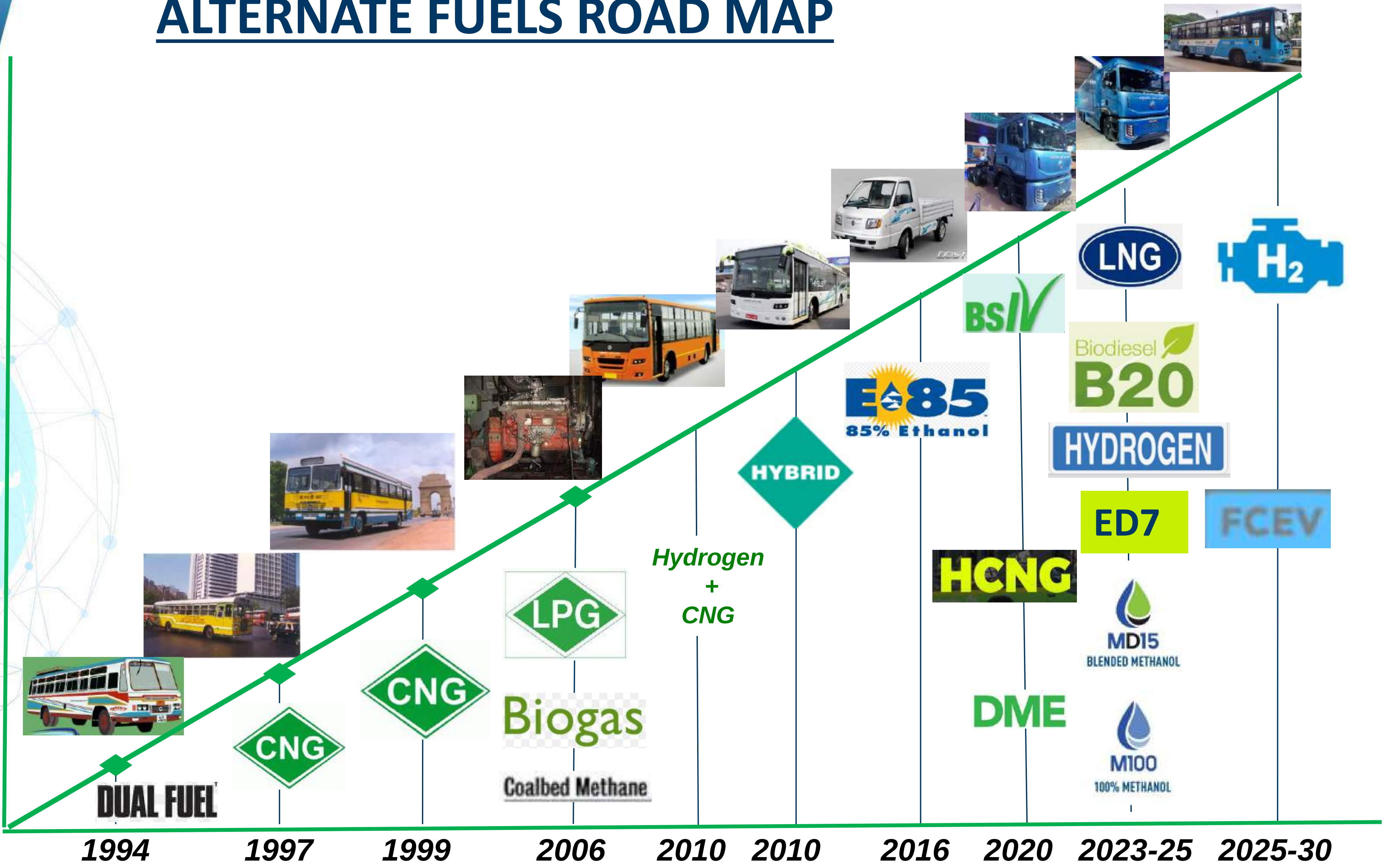
H2 quality

Ambient conditions

Contents

- AL Product Portfolio
- Setting the Context
- Future power train options
- Hydrogen as an option – production, cost, types, application
- H2 ICE vs FCEV
- H2 ICE configuration & potential
- H2 ICE development at AL & our experiences

ALTERNATE FUELS ROAD MAP



1994
- DUAL FUEL

1997
- CNG

1999
- CNG

2006
- LPG
- Biogas
- Coalbed Methane

2010
- Hydrogen + CNG

2010
- HYBRID

2016
- E85 85% Ethanol

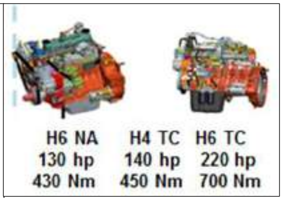
2020
- BS IV
- HCNG
- DME

2023-25
- LNG
- Biodiesel B20
- HYDROGEN
- ED7
- MD15 BLENDED METHANOL
- M100 100% METHANOL

2025-30
- H_2
- FCEV

About Ashok Leyland

P15 70/80 HP 170/190 Nm	ZD 30 140 hp 360 Nm	H4 2V (12V) 150 HP 450 Nm	H6 2V 200 HP 700 Nm	H6 4V 230 hp 800 Nm	H6 4V 250 hp 900 Nm	N4 250 hp 900 Nm	N6 360 hp 1400 Nm
Dost 1.25 T Dost 1.5 T Phoenix under testing	Partner	E Comet Boss	MBP 19T to 45.5T	MBP 35T to 45.5T	MBP 28T to 47.5T	MBP 28T to 55T	MBP 28T, 37T Tipper, 55T
	MiTR	LYNX smart, STAG SUNSHINE	MDV Bus E+2, E+3	MDV Bus E+2, E+3	ULE, JAN Bus, SLF, MDV Bus - E+2, E+3	ULE, JAN Bus, SLF, MDV Bus - E+2, E+3	Coach Bus



H6 NA	H4 TC	H6 TC
130 hp 430 Nm	140 hp 450 Nm	220 hp 700 Nm

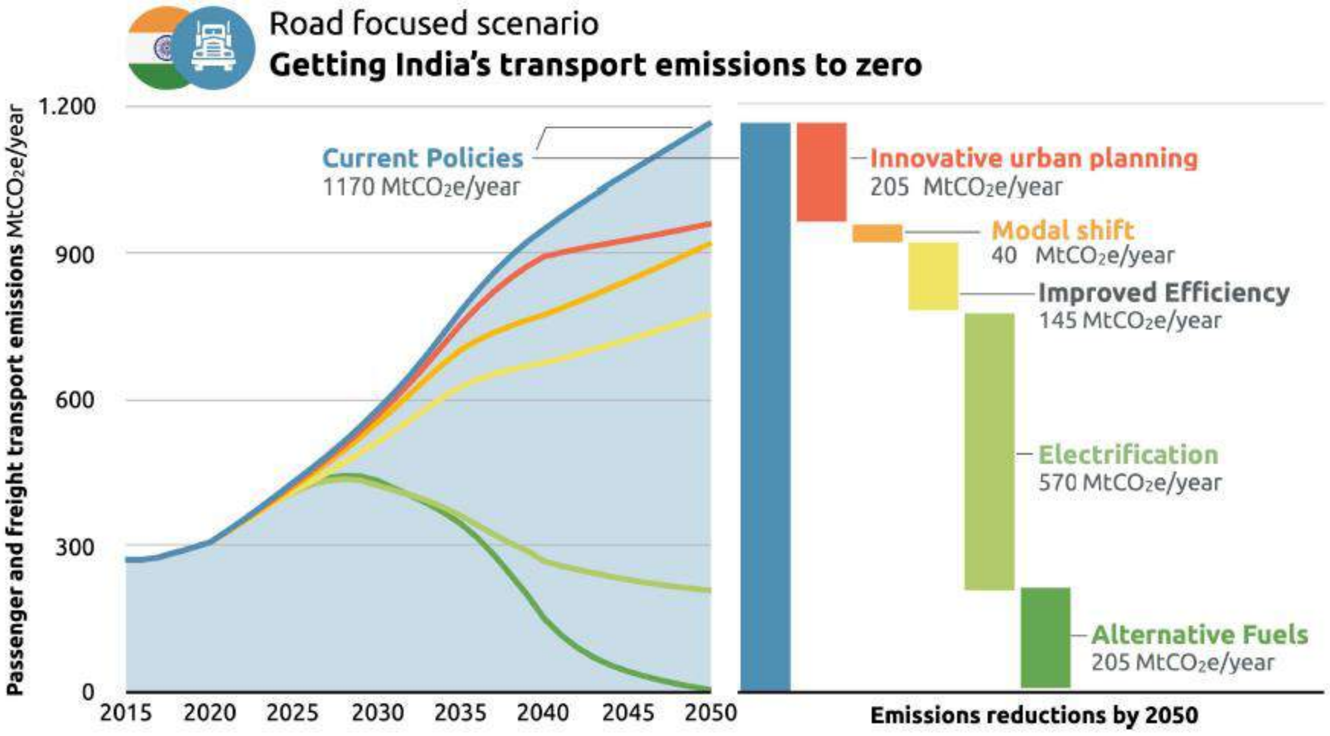
Trucks- 1T GVW (Gross Vehicle Weight) to 55T GTW (Gross Trailer Weight) & Bus- 9 seater to 80 seater

Ashok Leyland, flagship of the Hinduja group, is the 2nd largest manufacturer of commercial vehicles in India, the 4th largest manufacturer of buses in the world, and 14th largest manufacturer of trucks.

Power solution business

Defence

Contribution of Indian transport emission & shift to zero


Road focused scenario

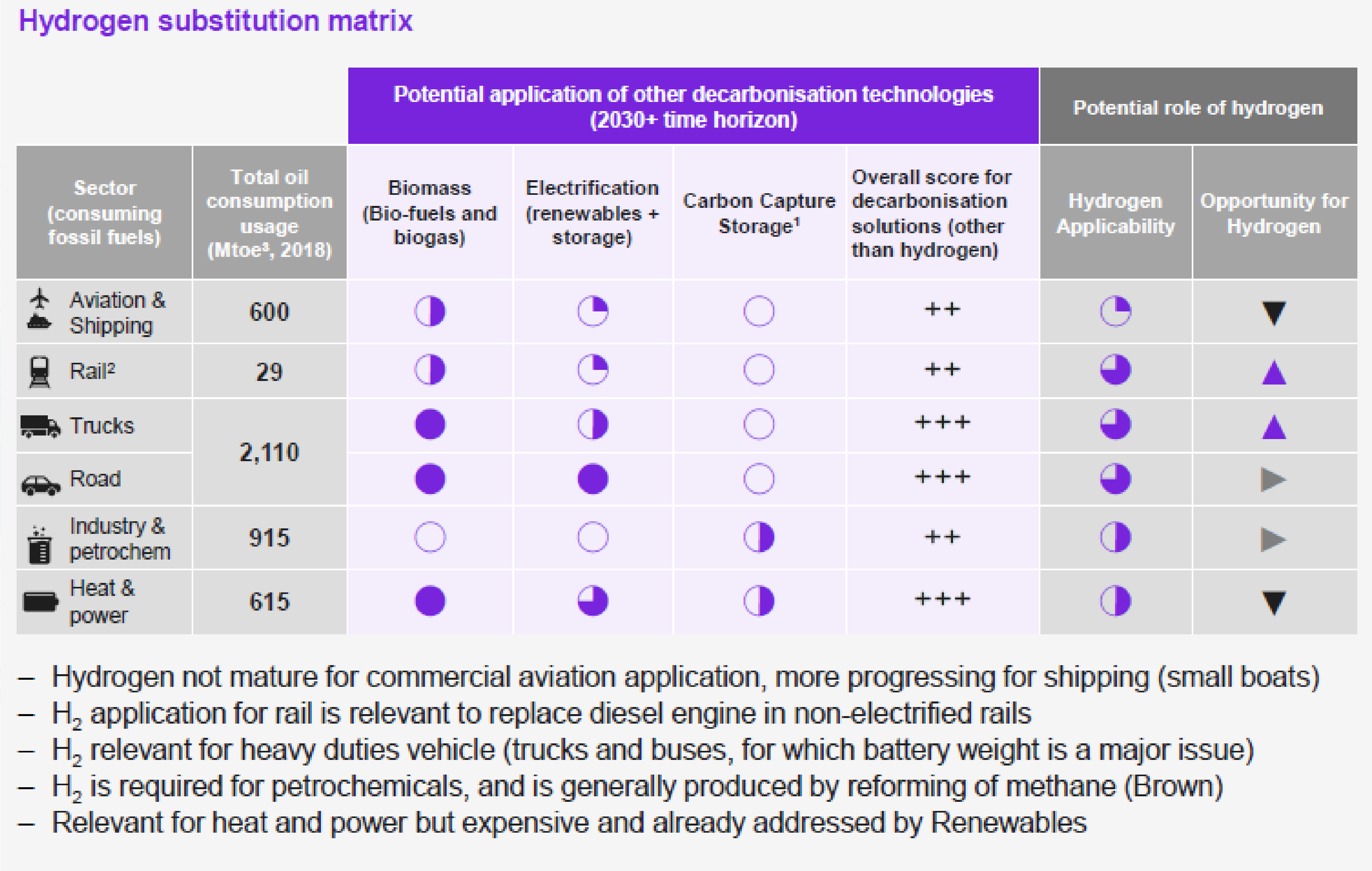
Getting India's transport emissions to zero

Emission reduction wedges compared to current policies for de-carbonization of transportation sector by 2050:

- Modes difficult to electrify like shipping/aviation can run on synthetic or bio-fuels
- Improved efficiency has potential to provide 145 $MtCO_2e$/year reduction
- Alternative Fuels has potential to provide 205 $MtCO_2e$/year reduction (Focus on H2)

References:
CAT 2020 report on Decarbonising Indian Transport Sector

Hydrogen Substitution Matrix



Hydrogen substitution matrix

		Potential application of other decarbonisation technologies (2030+ time horizon)				Potential role of hydrogen	
Sector (consuming fossil fuels)	Total oil consumption usage (Mtoe[3], 2018)	Biomass (Bio-fuels and biogas)	Electrification (renewables + storage)	Carbon Capture Storage[1]	Overall score for decarbonisation solutions (other than hydrogen)	Hydrogen Applicability	Opportunity for Hydrogen
Aviation & Shipping	600	◑	◔	○	++	◔	▼
Rail[2]	29	◑	◔	○	++	◕	▲
Trucks	2,110	●	◑	○	+++	◕	▲
Road		●	●	○	+++	◕	▶
Industry & petrochem	915	○	○	◑	++	◑	▶
Heat & power	615	●	◕	◑	+++	◑	▼

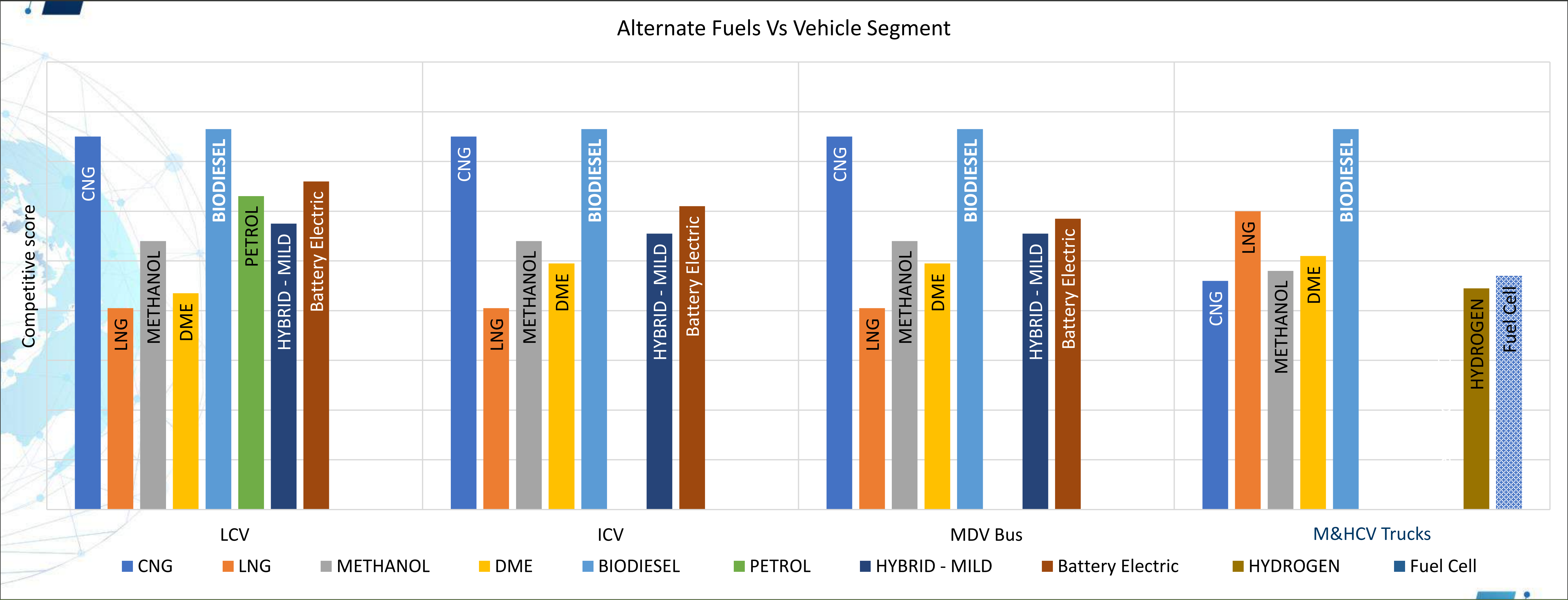
- Hydrogen not mature for commercial aviation application, more progressing for shipping (small boats)
- H_2 application for rail is relevant to replace diesel engine in non-electrified rails
- H_2 relevant for heavy duties vehicle (trucks and buses, for which battery weight is a major issue)
- H_2 is required for petrochemicals, and is generally produced by reforming of methane (Brown)
- Relevant for heat and power but expensive and already addressed by Renewables

Hydrogen could replace diesel as a Fuel in Sectors responsible for more than 65% of Global Emissions

References:
IEA, FAO, Kearney Energy Transition Institute Analysis

Alternate Fuel & Powertrain Options

Trend assessment for next 2-10 years



The above graph shows the alternate fuel assessment vehicle segment wise, based on 7 parameters

1-Economics, 2-Performance, 3-Regulation, 4-Market requirement & Govt Incentive, 5-Infrastructure, 6-Effort & Time to market (Technology Maturity), 7-IP potential

Reference: AL Internal Report

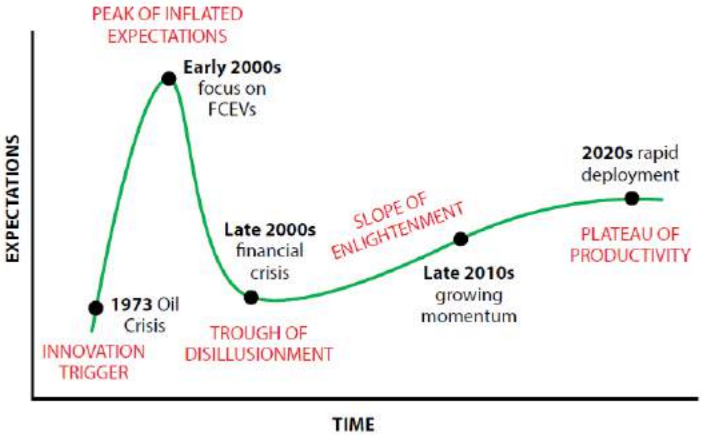
Opportunities with H2 as a fuel

Renewed interest in H_2 based IC engines has been seen due to the following reasons:

- Efforts towards de-carbonization and tightened emission standards
- Efficieny & advanced H_2 production technology => Steam reformation adds 10 kg CO2/ kg H2; SRM + CCS methods requires 3x more consumption of natural gas
- Advancement in usage (ex: high pressure DI technology)
- Advancements in storage technology => High pressure storage technology (up to 700 bar)

Renewable energy source

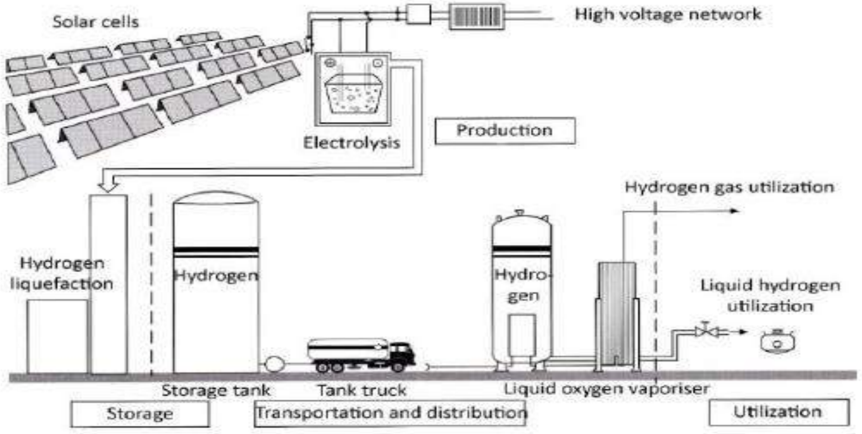
Zero CO_2



The hydrogen hype cycle (Source: TERI)

Large scale centralized hydrogen production (renewable electricity, biomass & nuclear power options are used)

Hydrogen can be transported over long distances by pipelines and trailers.

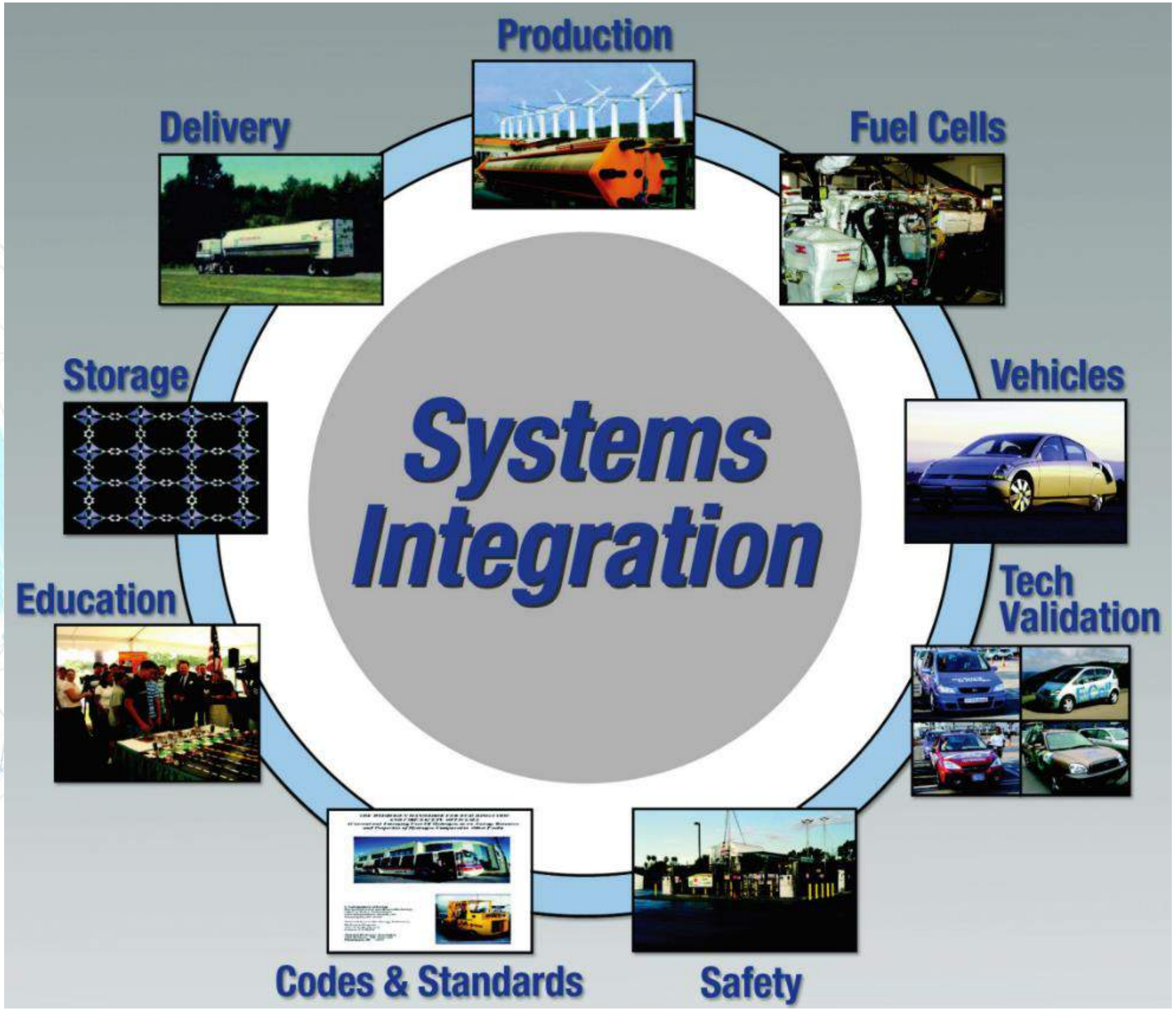


Infrastructure expected to be in place by over next few years!

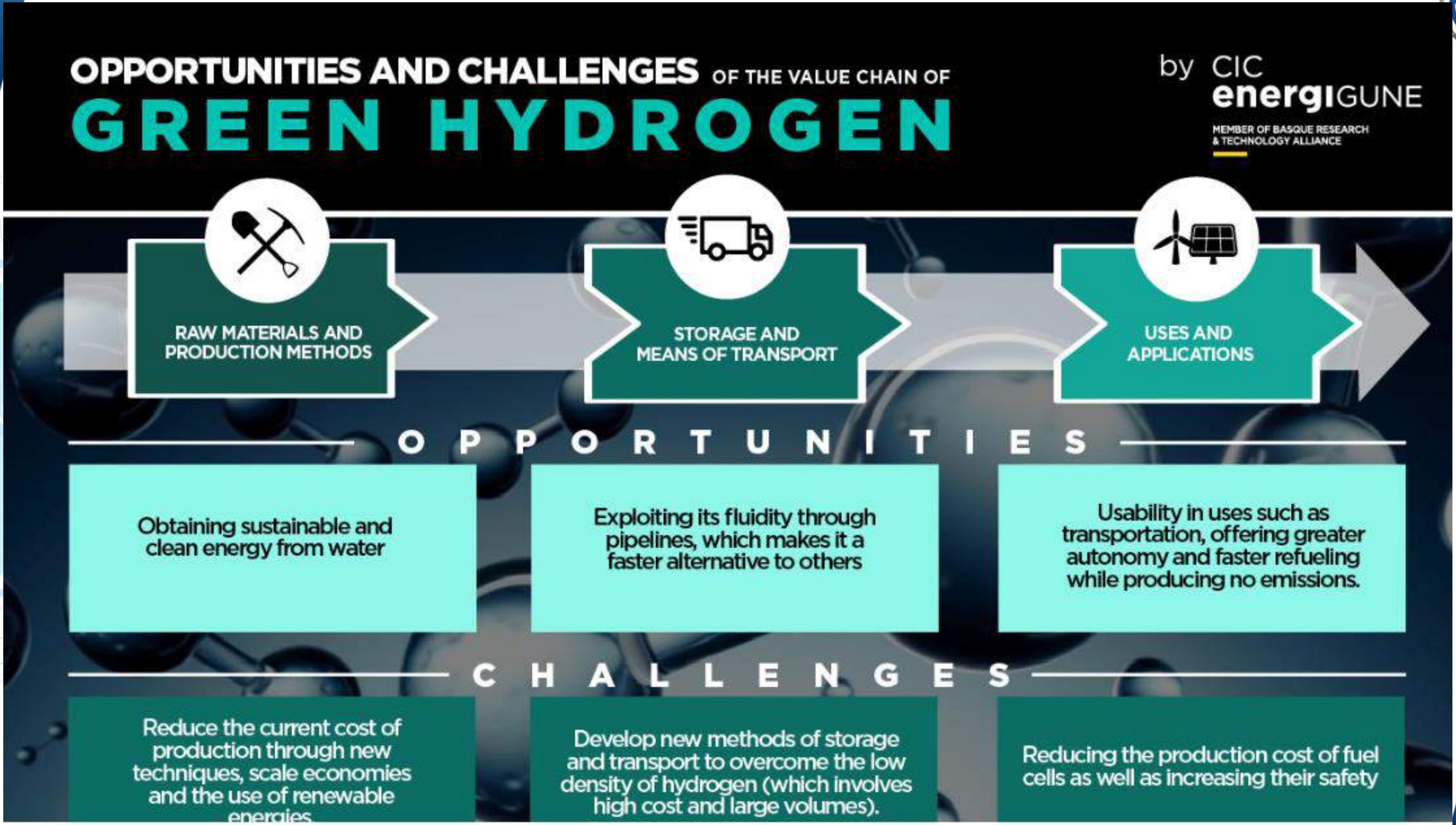
Challenges associated with Hydrogen ICE technology:

- **Cost:** Production is energy intensive. TCO competitiveness with diesel/CNG has to evolve in coming years.
- **Thermal efficiency:** Hydrogen DI offers higher thermal efficiency than PFI, but durability of DI injectors is low. Injection needs higher pressure and Injector development is a major area of thrust. Limitations are there in-terms of achieving diesel like power and torque.
- **Research Thrust:** H2 ICEs are not being researched as highly as Fuel Cells.

Hydrogen Economy - Challenges



Green Hydrogen – Opportunities and Challenges

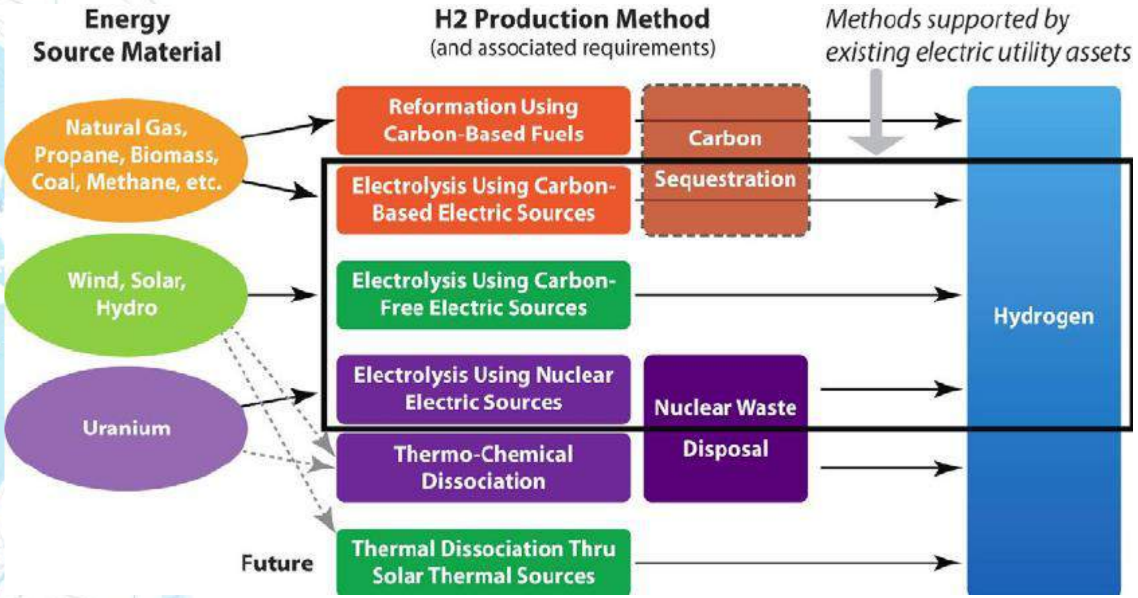


OPPORTUNITIES AND CHALLENGES OF THE VALUE CHAIN OF GREEN HYDROGEN

by CIC energiGUNE
MEMBER OF BASQUE RESEARCH & TECHNOLOGY ALLIANCE

RAW MATERIALS AND PRODUCTION METHODS	STORAGE AND MEANS OF TRANSPORT	USES AND APPLICATIONS
OPPORTUNITIES		
Obtaining sustainable and clean energy from water	Exploiting its fluidity through pipelines, which makes it a faster alternative to others	Usability in uses such as transportation, offering greater autonomy and faster refueling while producing no emissions.
CHALLENGES		
Reduce the current cost of production through new techniques, scale economies and the use of renewable energies	Develop new methods of storage and transport to overcome the low density of hydrogen (which involves high cost and large volumes).	Reducing the production cost of fuel cells as well as increasing their safety

H2 Production Methods & Types of H2



Energy Source Material

H2 Production Method (and associated requirements)

Methods supported by existing electric utility assets

Natural Gas, Propane, Biomass, Coal, Methane, etc.

Wind, Solar, Hydro

Uranium

Future

Reformation Using Carbon-Based Fuels

Electrolysis Using Carbon-Based Electric Sources

Carbon Sequestration

Electrolysis Using Carbon-Free Electric Sources

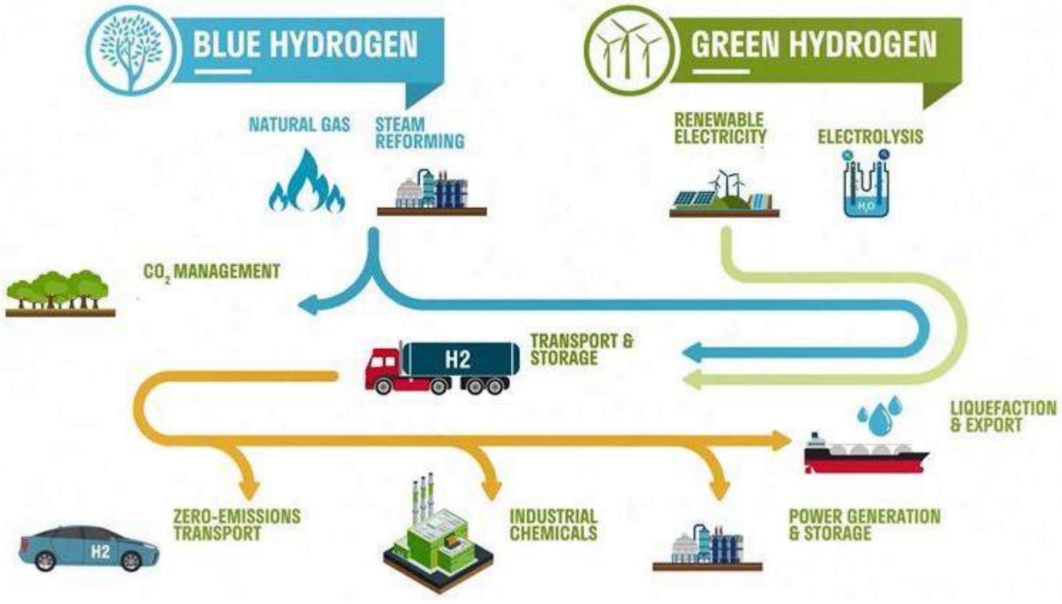
Electrolysis Using Nuclear Electric Sources

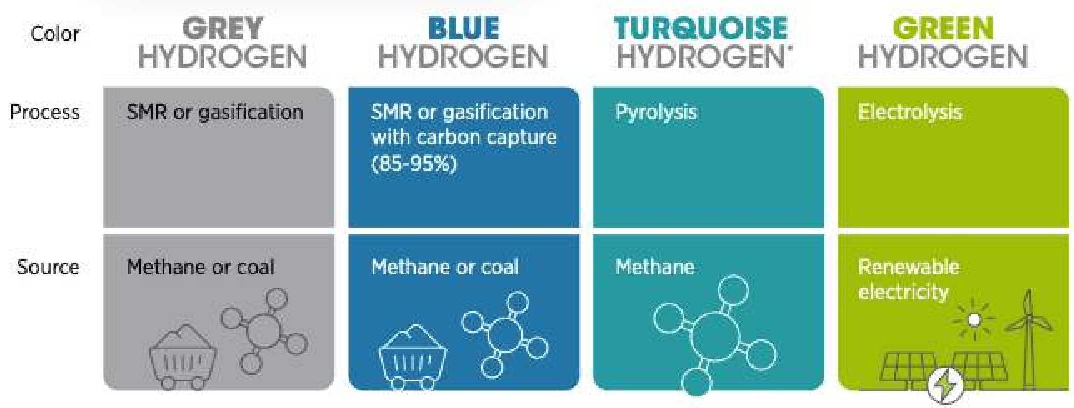
Nuclear Waste Disposal

Thermo-Chemical Dissociation

Thermal Dissociation Thru Solar Thermal Sources

Hydrogen



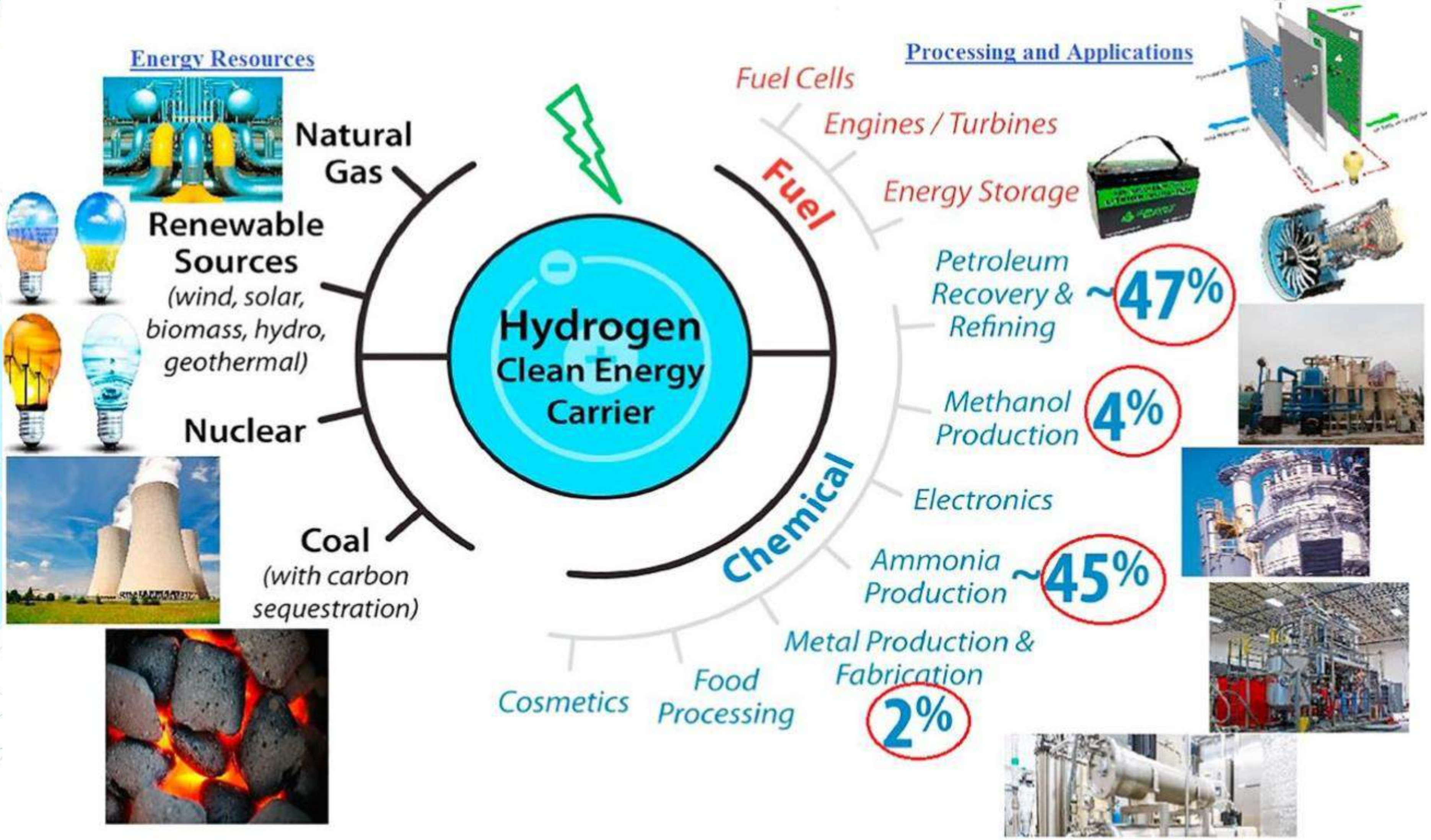


Color	GREY HYDROGEN	BLUE HYDROGEN	TURQUOISE HYDROGEN*	GREEN HYDROGEN
Process	SMR or gasification	SMR or gasification with carbon capture (85-95%)	Pyrolysis	Electrolysis
Source	Methane or coal	Methane or coal	Methane	Renewable electricity

Note: SMR = steam methane reforming.

** Turquoise hydrogen is an emerging decarbonisation option.*

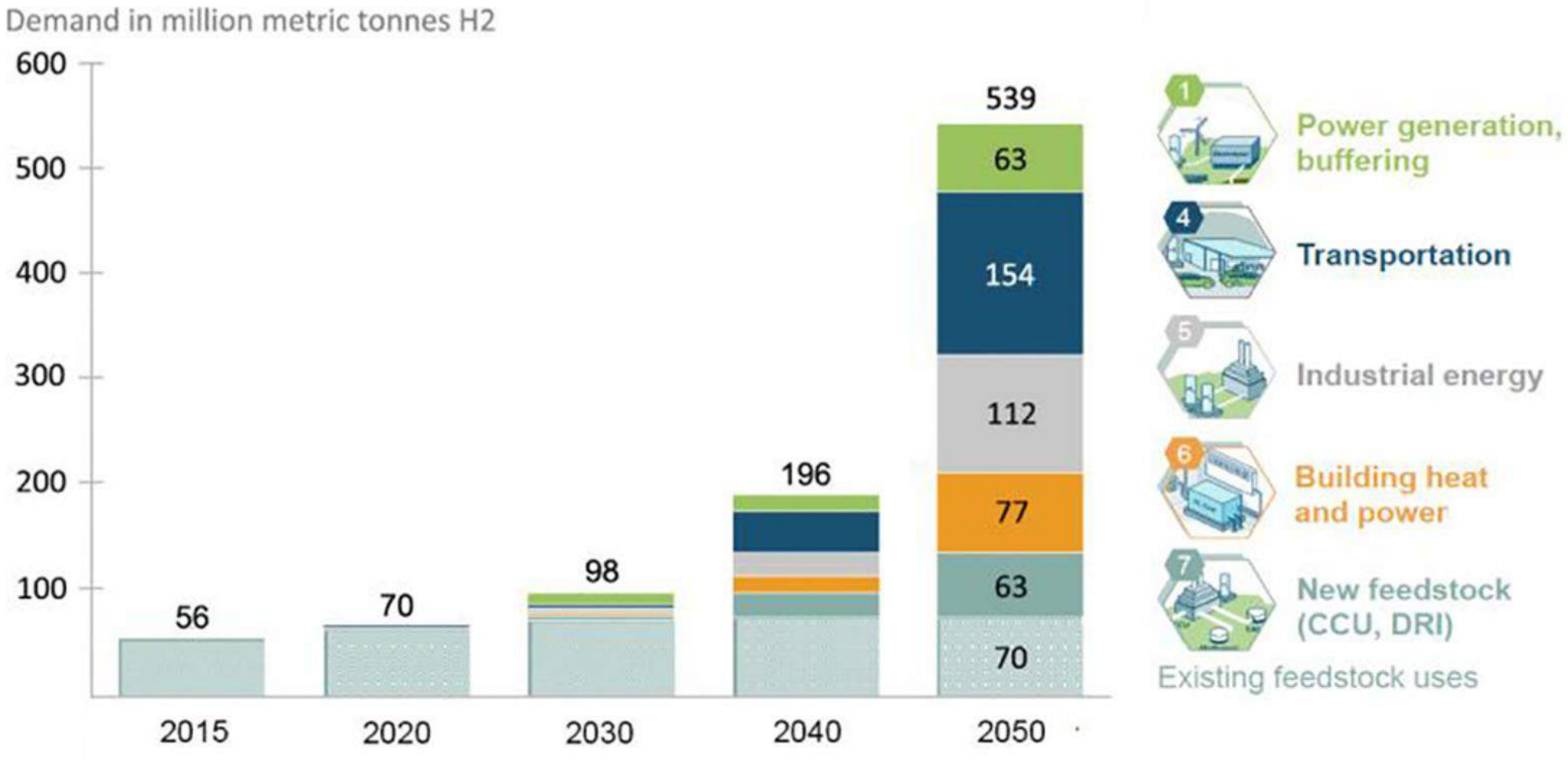
Hydrogen Production challenges



Hydrogen clean energy carrier as one of most essential clean and sustainable resource with main applications in both research and industry diverse.

Hydrogen Production Demand

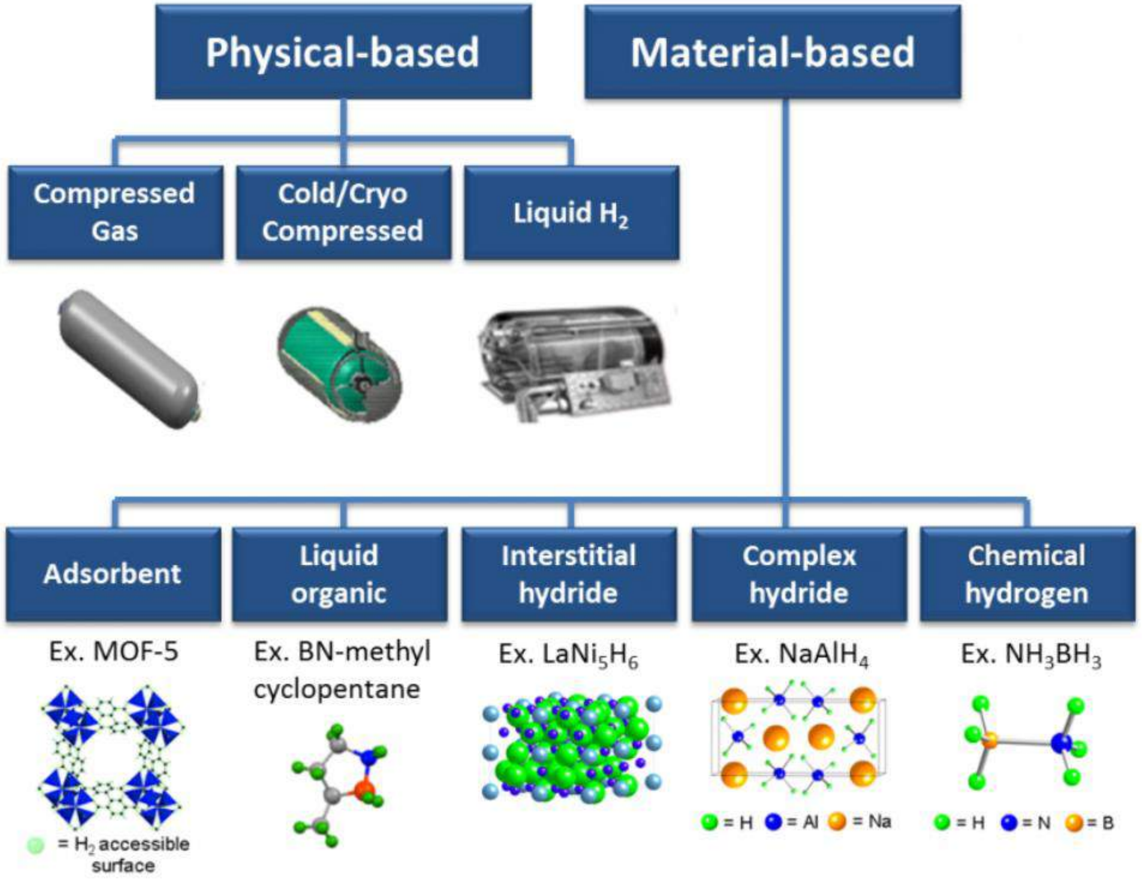
Hydrogen demand could increase 10-fold by 2050



Adapted from *Scaling Up*, Hydrogen Council, 2017. Orginal units in EJ converted to tonnes H2; 1 EJ = 7,000,000 tonnes H2.

Hydrogen Storage

How is hydrogen stored?

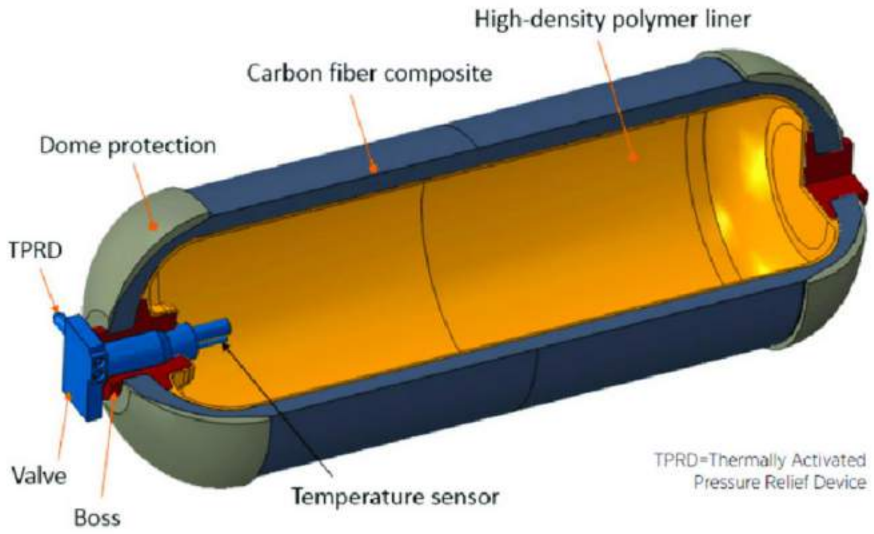


Physical-based

- Compressed Gas
- Cold/Cryo Compressed
- Liquid H_2

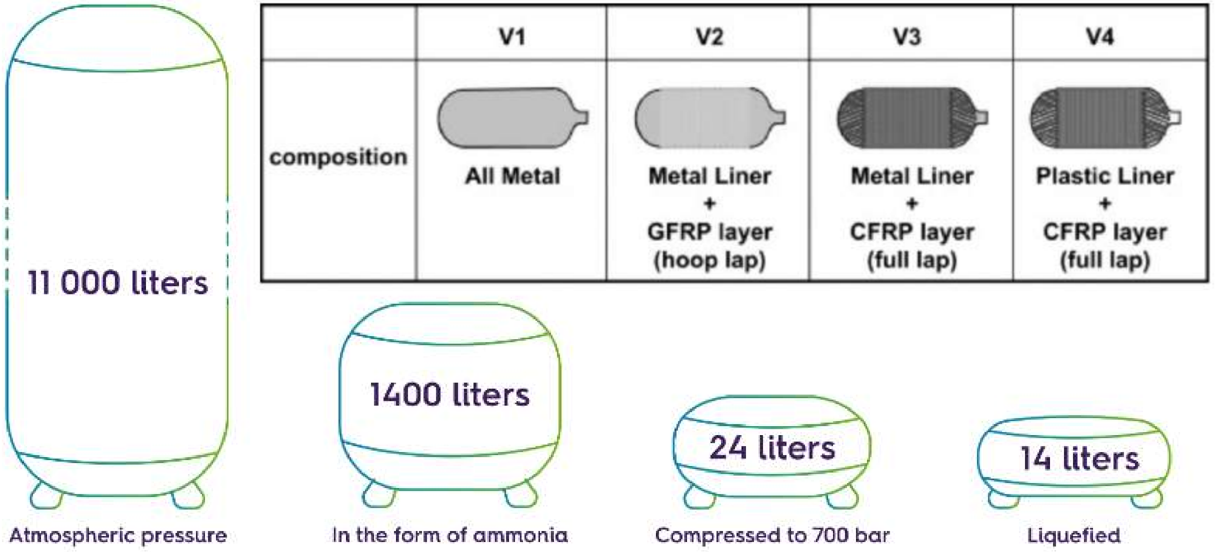
Material-based

- Adsorbent: Ex. MOF-5
- Liquid organic: Ex. BN-methyl cyclopentane
- Interstitial hydride: Ex. $LaNi_5H_6$
- Complex hydride: Ex. $NaAlH_4$
- Chemical hydrogen: Ex. NH_3BH_3



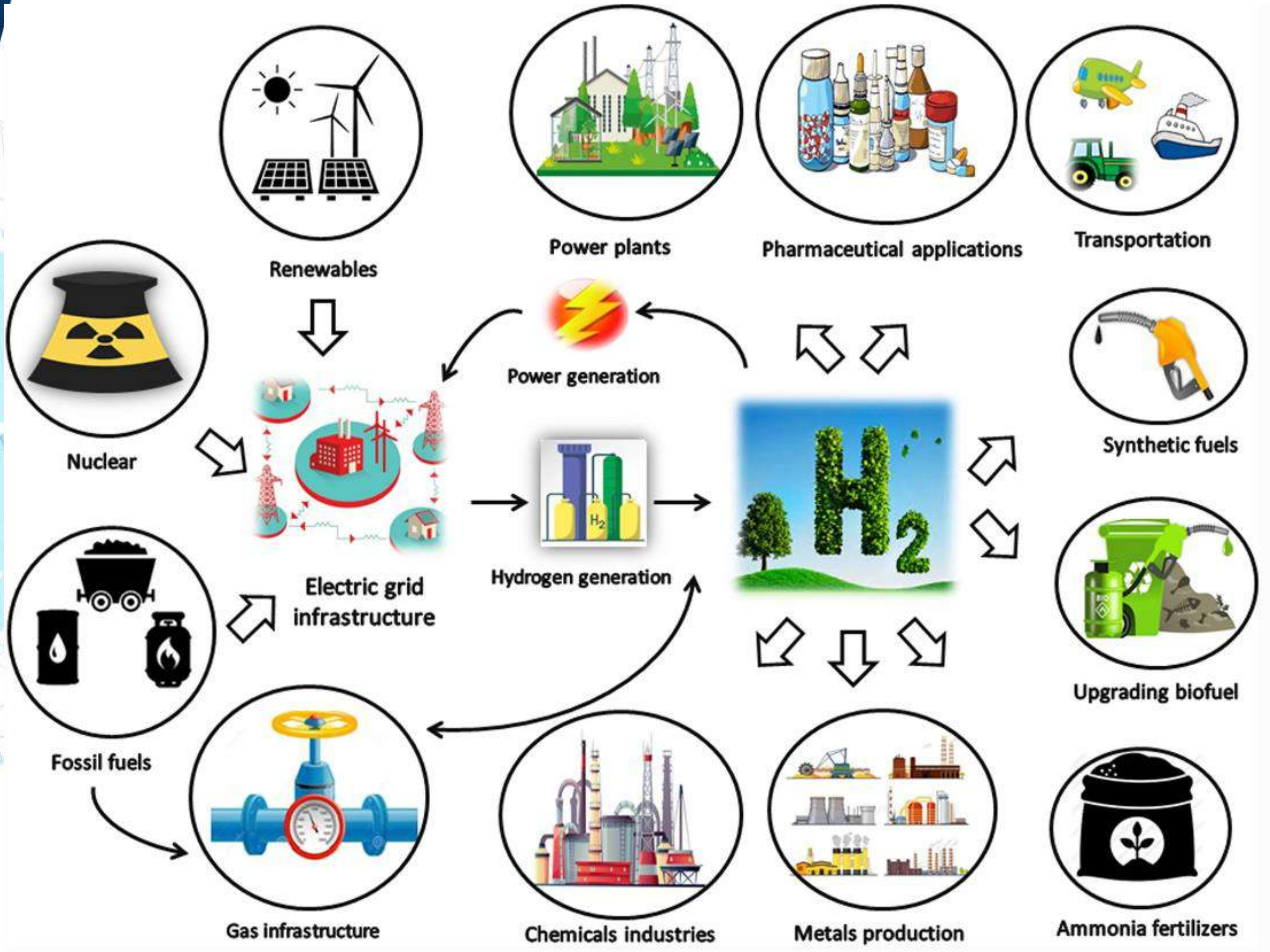
TPRD=Thermally Activated Pressure Relief Device

Storage volume for 1kg of hydrogen



	V1	V2	V3	V4
composition	All Metal	Metal Liner + GFRP layer (hoop lap)	Metal Liner + CFRP layer (full lap)	Plastic Liner + CFRP layer (full lap)

Hydrogen Economy



H2 property comparison with other fuels

Property	Hydrogen	CNG	Gasoline	Diesel	Remarks
Safety Critical					
Auto-ignition temperature (K)	858	813*	623	523	
Quenching distance (mm)	0.64	2.1*	~2	-	At 1 bar, 298 K & stoic.
Diffusion coefficient in air	$8.5x10^{-6}$	$1.9x10^{-6}$	-	-	At 1 bar, 273 K
Flammability limits in air	4-76	5.3-15	1-7.6	0.6-5.5	
Minimum ignition energy in air (mJ)	0.02	0.29	0.24	0.24	At 1 bar & stoic.
Storage Critical					
Density (kg/m^3)	0.089	0.72	730-780	830	At 1 bar, 273 K
Boiling point (K)	20	111*	298-488	453-633	At 1 bar
Combustion Behaviour					
Carbon content (mass %)	0	75*	84	86	
Lower heating value (MJ/kg)	119.7	45.8	44.8	42.5	
Volumetric energy content (MJ/m^3)	10.7	33	$33x10^3$	$35x10^3$	At 1 bar, 273 K
Molecular weight	2.016	16.043*	~110	~170	
Stoichiometric air/fuel mass ratio	34.5	17.2*	14.7	14.5	
Stoichiometric volume fraction in air (%)	29.53	9.48	~2$^{\#}$		
Research Octane Number (RON)	62-64	110-130	90-100	15-25	
Laminar flame speed in air (m/s)	1.85	0.38	0.37-0.43	0.37-0.43^{+}	At 1 bar, 298 K & stoic.
Adiabatic flame temperature (K)	2480	2214	2580	~2300	At 1 bar, 298 K & stoic.

* CNG properties specified for Methane; # - Vapor, + - n-heptane

H2 has got unique properties as compared to other fuels as shown in highlighted cells.

What it means to us , these properties ?

- Flame speed is higher , high fuel velocity , so complete combustion is possible. Complete combustion and more air flow , makes exhaust temperature is low , but coolant heat rejection relatively more.
- Flame travels fast to liner wall , lub oil will be deteriorated , need to focus on oil development.
- It displaces the fresh air with hydrogen (15 to 20%) , which reduces torque but we are compensating it by increasing airflow with VGT or two stage , also high calorific value of fuel helps us
- Higher coolant temperature , greater than 85 deg , it tend to knock . So need to select thermostat , radiator and cooling system properly, need to arrive by experimentation. Combustion temperature is relatively high . Heat rej. To coolant also will be relatively high. (Shorter quenching)
- SFC is the function of Calorific value . Almost sfc will be around one third of diesel
- Air – fuel mixture in port injection is better than DI , literature says , however we also feel the same , for homogeneous SI engine combustion , port injection may be better , we can standardize engine inline with CNG and all other fuels can be tried. In DI , because of low density , it wont penetrate. Mixture formation may be difficult in DI.
- Timing we used to advance around 17deg bef TDC for CNG but in H2 we are retarding (around 12)
- If diesel requires 600 kg/hr air , H2 ICE requires 900 Kg/hr air , also low end we require 2 lamda , hence VGT or two stage TC is a must.
- As enthalphy available for turbine is less we require smaller turbine (rpm limit to 1.8 lacs)

H2 Fuel – Pros and Cons

		Pros	Cons
1	Combustion phasing control/Ignition energy	Hydrogen has lowest ignition energy which enables prompt ignition of lean mixtures.	Due to low ignition energy, it can cause ignition by hotspots or residues in combustion chamber. This can lead to pre-ignition of fuel. Results in loss of combustion phasing control, knocking and possible mechanical engine failure.
2	Emissions	Since it is zero carbon fuel, no CO, CO2 or soot emissions exist.	NOx emission from Hydrogen engine is an issue as the combustion temperature is very high as compared to Gasoline or Diesel. (NOx can be reduced by operating lean and inducing EGR).
3	Auto-ignition	Nil	Auto-ignition temperature of hydrogen is higher than diesel and hence auto-ignition is not possible even at higher compression ratio.
4	Flammability	Combustible over a wide range of air-fuel ratios due to 4-75% flammability range	Nil
5	Quenching distance	Nil	It has lowest quenching distance which means more tendency of backfire.
6	Flame speed	Hydrogen has highest flame speed which means they can easily approach ideal cycle efficiencies.	Nil
7	Density	Nil	Hydrogen has the lowest density. Due to this it requires more storage space and gives lesser power output.
6	Storage	Nil	Has to be stored as a compressed gas due to low boiling point. Increases the storage space. Or, it has to be stored in cryogenic state if it has to kept as a liquid.

The cons of H_2 as a fuel exceed the pros which need careful engine design and storage system. Solution is available for each Cons

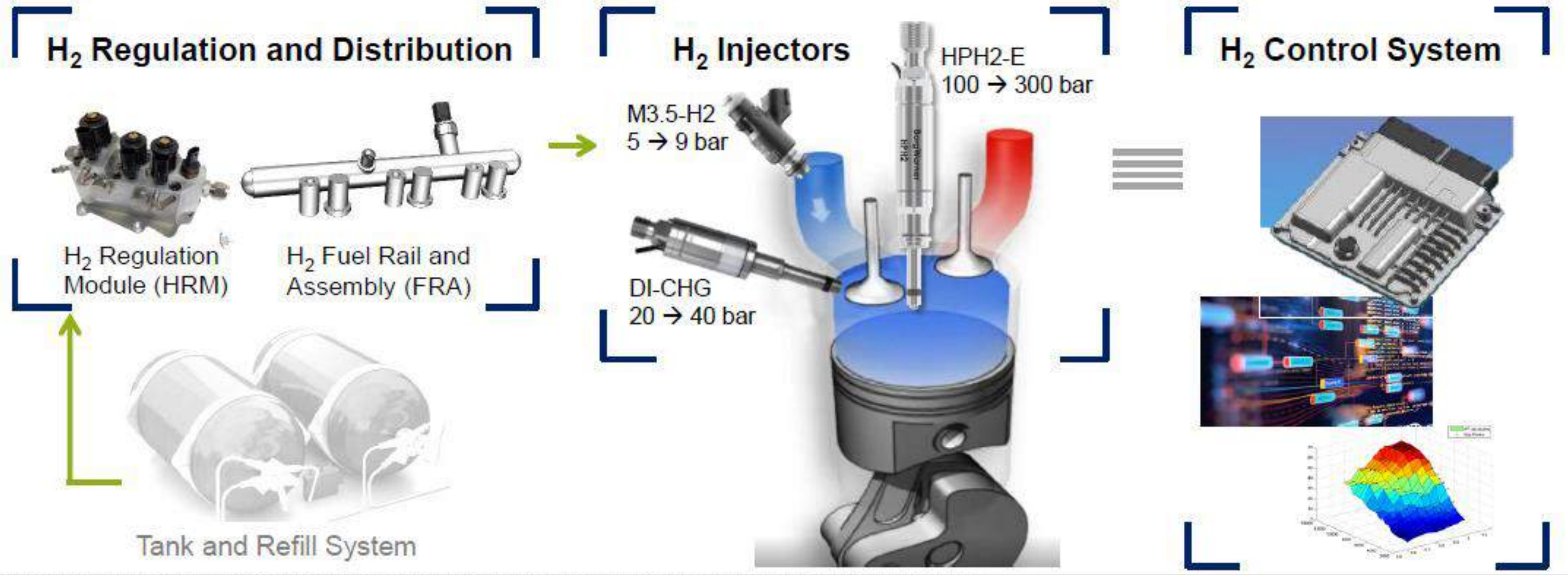
H2 ICE vs FCEV

Sl. No	Parameter	Hydrogen ICE	Hydrogen Fuel Cells
1	Efficiency	Thermal efficiency: 40-47% Tank to wheel efficiency: ~20% (Efficient at high specific loads) Well to wheel efficiency: 14-17% 🟡	Thermal efficiency: >95% Tank to wheel efficiency: ~45% (Efficient at low loads) Well to wheel efficiency: 27% 🟢
2	Emissions	No CO, CO_2 and Soot is present. Only NO_x is present. 🟡	Water 🟢
3	Tolerance to fuel impurities	Higher 🟢	Lower 🟡
4	Flexibility to switch between fuels	Yes 🟢	No 🟡
5	Reduction of rare metal usage	Yes 🟢	No 🟡
6	Transition from conventional engines & Development stage. Retro-fitment possibility.	Easy. Existing manufacturing facilities can be used. Retro-fitment is possible. 🟢	Difficult. Existing manufacturing facilities cannot be used. Development is moving slow paced. Retro-fitment not possible. 🟡
7	Storage technology	Requires special measures in design of vehicle and fuel delivery system. Hydrogen embrittlement is a common failure due to high pressure hydrogen usage. Also there is a risk of hydrogen leakage as it's diffusivity is high. 🟡	Same as Hydrogen ICE, but requires smaller fuel tanks. 🟢

🟢 Advantage 🟡 Dis-advantage 🔵 Neutral

H2 ICE shows better advantages as compared to fuel cells at-least for a transition phase till fuel cell maturity is reached.

Typical H2 ICE Fuel Injection System



H_2 Regulation and Distribution

H_2 Regulation Module (HRM)

H_2 Fuel Rail and Assembly (FRA)

Tank and Refill System

H_2 Injectors

M3.5-H2
5 → 9 bar

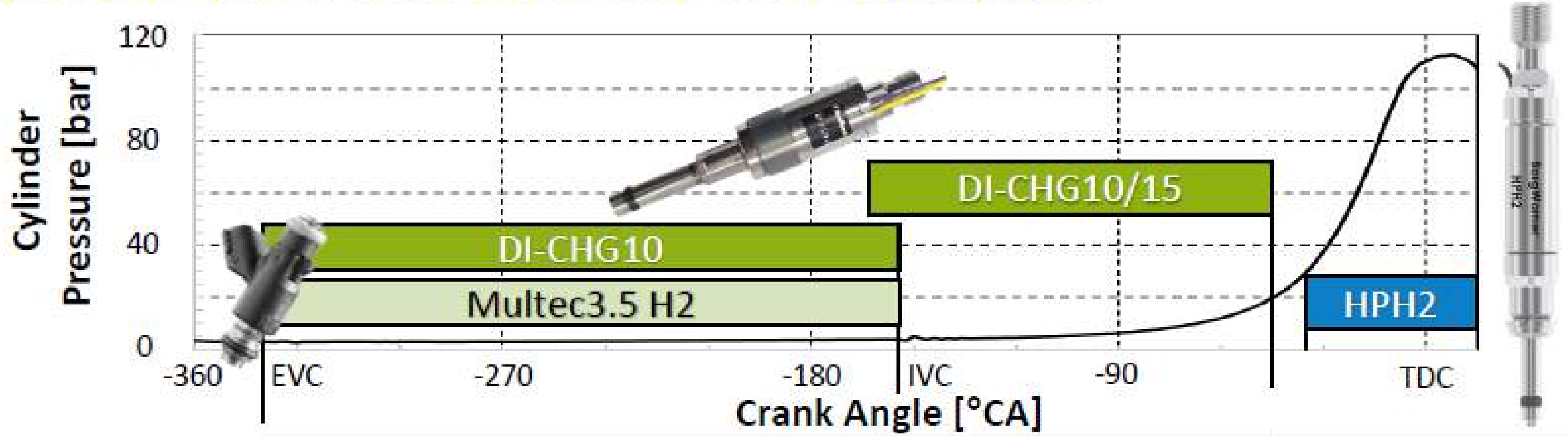
HPH2-E
100 → 300 bar

DI-CHG
20 → 40 bar

H_2 Control System

Typical H2 ICE Fuel Injection System Varieties

Full spectrum of Hydrogen system architectures are under development



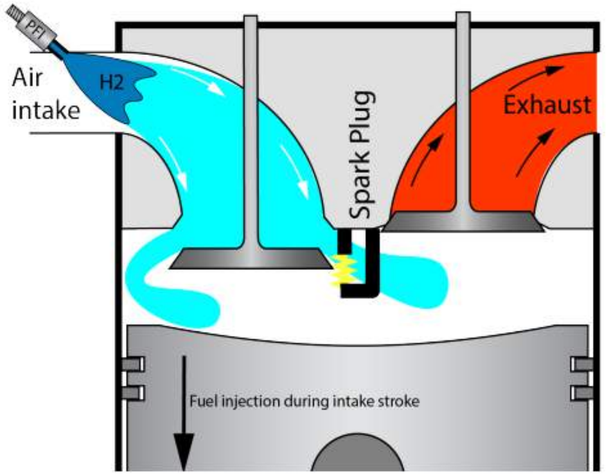
	Port Injection	Medium Pressure Direct Injection	High Pressure Direct Injection
Efficiency	🟧	🟧	🟨
NOx Emissions	🟩	🟩	🟧
Volumetric Efficiency & Power	🟧	🟩	🟩
Abnormal Combustion Risk	🟥	🟨	🟩
Complexity including System	🟩	🟧	🟥

H2 ICE Fuel Induction Technology

Various methods of fuel induction

Port-injection spark-ignition

3-10 bar injection pressure



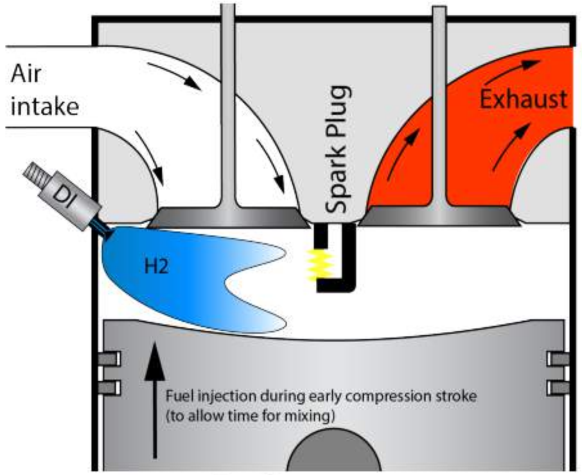
Key challenges: power density, abnormal combustion, efficiency

"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



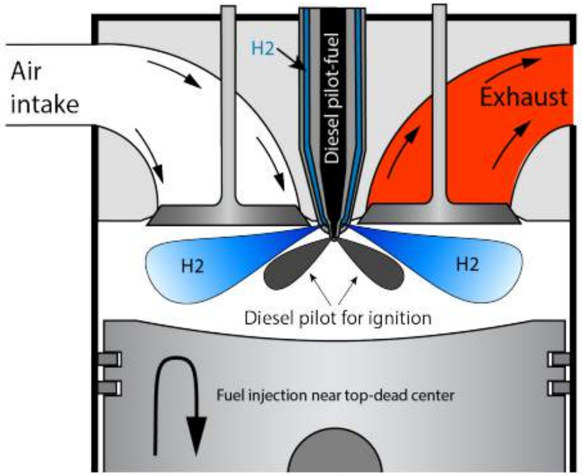
Key challenges: injection technology, abnormal combustion

"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

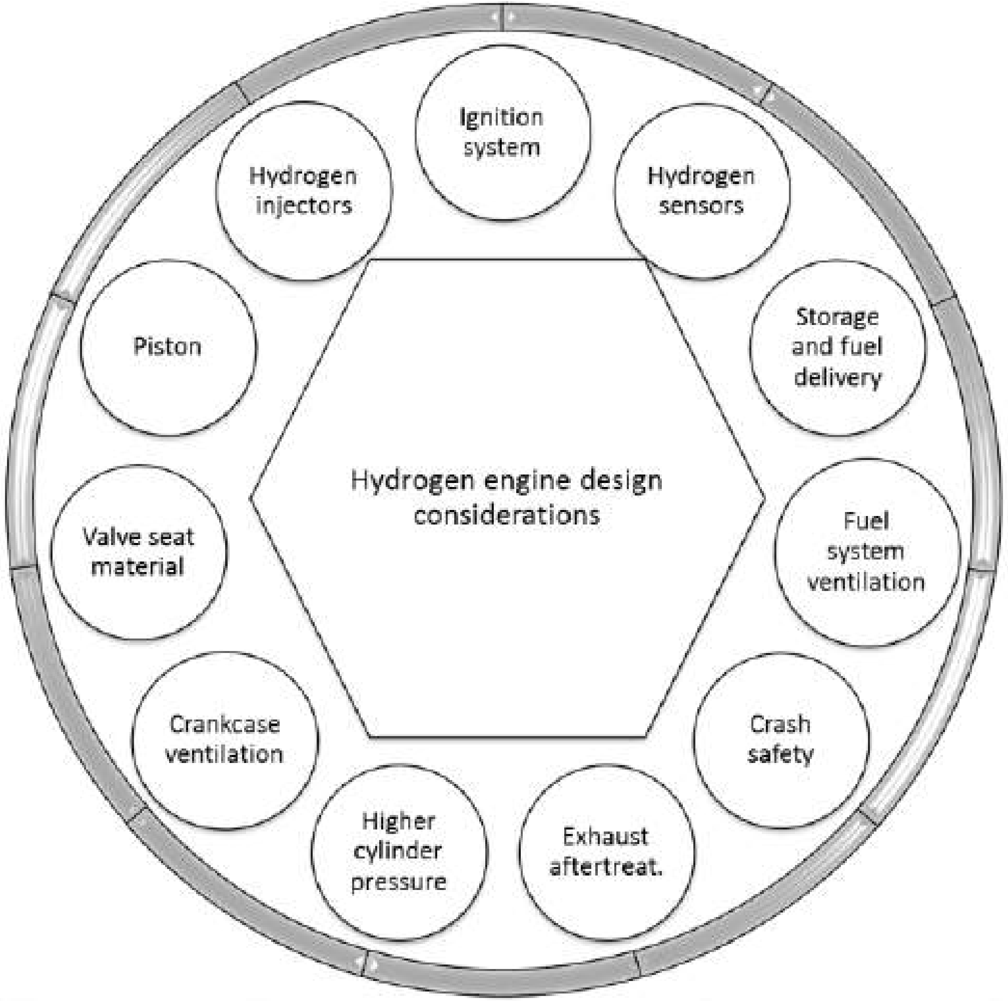
Trends of H2 Usage in SI combustion

		Single point fuel injection	Multi-point fuel injection	Direct injection
1	**Injection strategy**	Injection into the central point continuously 🟡	Injection into each port after beginning of intake stroke 🟡	Injection directly into the cylinder to form air-fuel mixture towards end of compression stroke 🟢
2	**Injection pressures**	Low injection pressure required 🟢	Higher than carburetion method 🟢	Higher than port fuel injection method 🟡
3	**Mixture formation**	Not suitable as volume occupied by fuel is 1.7%. 🟡	More suitable than carburetion 🟢	Non-homogeneous mixture formation. 🟡
4	**Power generation**	>20% power drop as compared to diesel 🟡	10-20% power drop as compared to diesel 🔵	5% drop in power as compared to diesel 🟢
5	**Combustion stability**	Uncontrolled combustion due to unscheduled combustion in various points of cycle. Pre-ignition and backfire tendency is there. 🟡	Pre-ignition tendency is there but it is less severe than carburetion method 🟡	Stable combustion and no pre-ignition or backfire possibility in manifold. Some possibility of pre-ignition in combustion chamber may happen. 🔵
6	**Ease of conversion of standard IC engine to H_2 based engine**	Easy 🟢	Moderate 🔵	Complex than carburetion and PFI methods but it is the most efficient 🟡

🟢 Advantage 🟡 Dis-advantage 🔵 Neutral

MPFI methodology of H2 injection would be most feasible option to start with as it is less complex and would not require highpressure injection.

Trends – Engine Design Considerations



Sasa Milojevic, University of Kragujevac, Republic of Serbia, 2016

Additional considerations:
1) Engine controls
2) Oil consumption reduction

Some of these design considerations are taken care for CNG engines and few additional ones are specific to Hydrogen engine. Engine controls is a major area in case of hydrogen engine development. Reduction of oil consumption is another focus of development to avoid residual HC, CO and PM.

Trends – Engine Design Considerations

The following engine design considerations are required to be made for a hydrogen engine:

a) *Combustion chamber:* The bath tub or cylindrical shape helps produce low radial and tangential velocity components and does not amplify inlet swirl during compression. This can help to reduce pre-ignition and knock.

b) *Cooling system:* The cooling system must be designed to avoid hot spots , hence uniform flow and reach to be ensured at needed cooling location . (especially spark plug area cooling , provision or jet given in cylinder head)

c) *Bore-stroke ratio:* Since unburned hydrocarbons are not a concern in hydrogen engines, a large bore-to-stroke ratio can be used with this engine. ((Not to bother about crevice volume etc)

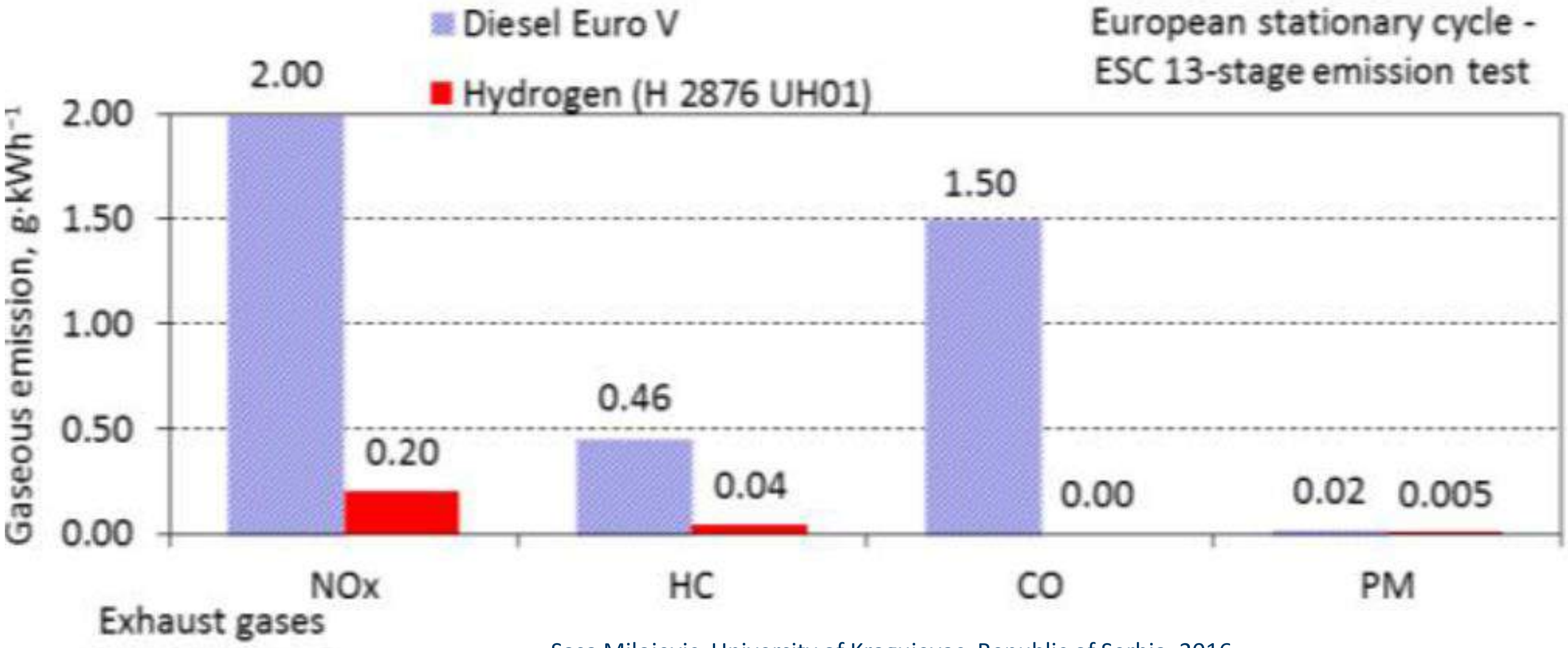
d) *Cylinder head design:* Additional measures to decrease the probability of pre-ignition are the use of two small exhaust valves as opposed to a single large one, and the development of an effective scavenging system. (keep chamber cool) (Theory only)

e) *Spark plug:* Ignition systems that use a waste spark system should not be used for hydrogen engines. (Flat earth electrode)

f) *Crankcase ventilation:* Crankcase ventilation is even more important for hydrogen engines than for gasoline engines. Hydrogen should be prevented from accumulating through ventilation. When hydrogen ignites within the crankcase, a sudden pressure rise occurs. To relieve this pressure, a pressure relief valve must be installed on the valve cover. (Rings design to be reviewed to reduce blow-by)

H2 ICE Emission Potential

H2 ICE is a promising transition technology that would provide zero CO_2 capability and also a competitive TCO along with reliability.



Sasa Milojevic, University of Kragujevac, Republic of Serbia, 2016

All emissions are very low with H2 ICE. NOx can be managed by suitable after-treatment strategy & EGR. HC, CO and PM are very minimal – source being the engine lubricant burning within the combustion chamber.

H2 ICE Vehicle Architecture

Engine

H2 Engine

Electrical

Wiring Harness change to suit H2 system.

Fuel system

Complete Fuel piping change – H2

Cooling System

Cooling system piping to suit H2 Engine

ECU

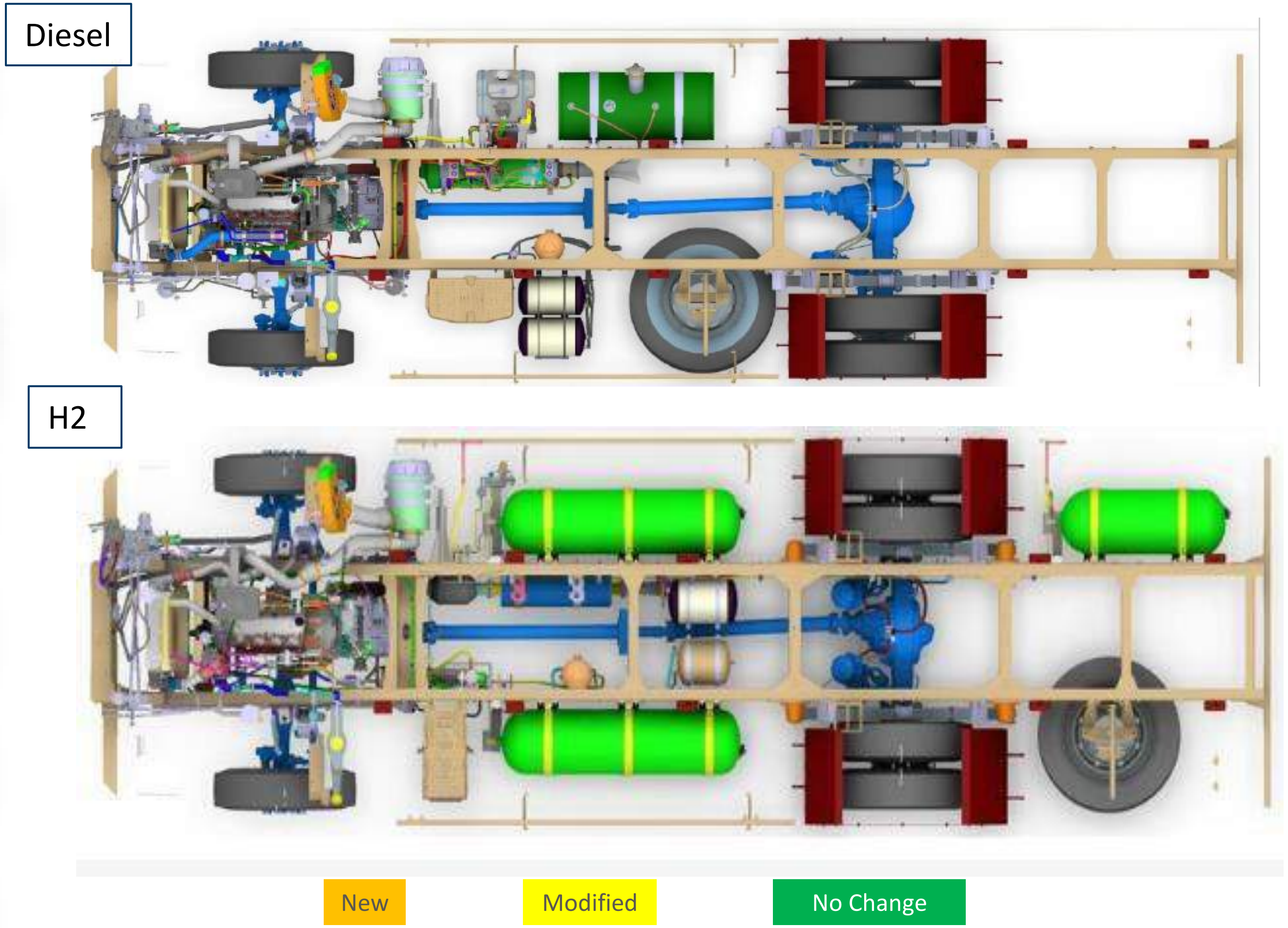
ECU dataset to suit H2 system

Frame

Modification to drill new holes for H2 mtg

Exhaust system

Less complex than diesel



Subsystem on chassis with no Changes	
Air intake System	Gear box
Propeller shaft	Pedals
FES/Bus body	Fr and Rr suspension
Engine Mount	Chassis Equipment's
Wheel & Tyre	Air Piping
Rear Axle	Brakes
Frame assy	Clutch
Steering System	

H2 ICE Configuration

Combustion system, Fuel & Ignition System

Turbocharging

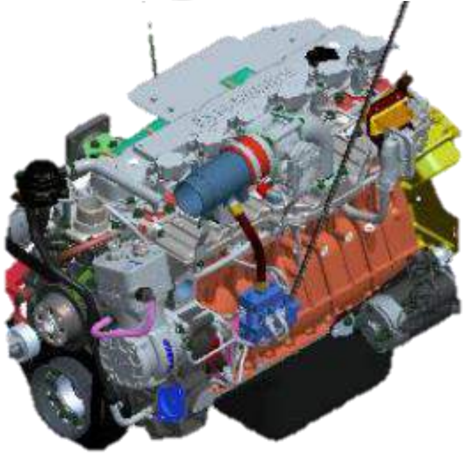
Diesel

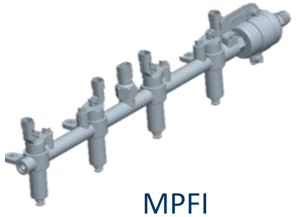
Common rail high pressure pump

Injector

Waste Gated Fixed Geometry TC

H2





MPFI

Throttle body

Piston

Injector

Spark plug

Coil on Plug

VGT or
2-stage TC

CCV for
H2 conc.
dilution

Combustion system, Fuel & Ignition system, Charging system for H2 ICE

Typical Hydrogen engine specification

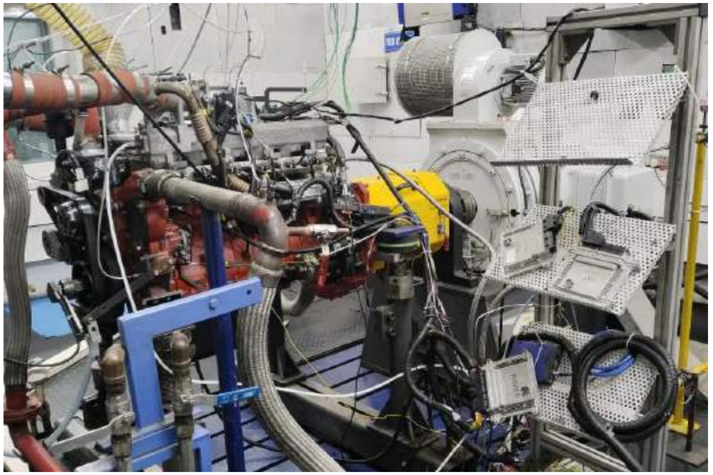
Engine Specification	
Fuel injection system	MPFI strategy (DI strategy may be chosen based on injector availability) Rail pressure: 8-10 bar for MPFI ECU: H2 transient capable for lean burn strategy Regulator: Mechanical or Electronic (based on calibration reqmt.)
Ignition system	Passive or Active ignition coils without ghost ignition
Crankcase ventilation	CCV with crankcase H2 concentration dilution
Turbocharging	VGT for providing excess air ratio and meeting transient demands
Compression Ratio	Same as CNG in the range of 10 to 14
Exhaust after-treatment system	SCR strategy for lean burn combustion
Hydrogen embrittlement	Based on durability assessment

Ashok Leyland's **H2 ICE** Vehicle Display in Auto Expo'23

GVW	40500 kg
Engine type	H Series 6 cylinder, Hydrogen IC engine
Max power	186 kW @ 2400 rpm
Max torque	900 Nm @ 1200 - 2000 rpm
Clutch	380 mm diameter - with air assisted hydraulic booster
Gearbox	6-speed synchromesh
Front axle	Forged I section - Reverse Elliot type
Rear axle	Full floating single reduction hypoid axle
Front suspension	Parabolic suspension
Rear suspension	Non- reactive suspension
Chassis frame	Bolted construction with constant width over chassis
Brakes	Full air dual line brakes with ABS
Tyres	Low resistance tubeless tyres - 295/ 80 R 22.5
Cabin	N - Premium cabin
Max speed	80 kmph
Overall length	11960 mm
Wheelbase	6600 mm
Turning circle diameter	22700 mm
Fuel tank	3 x 350L tank (T4)

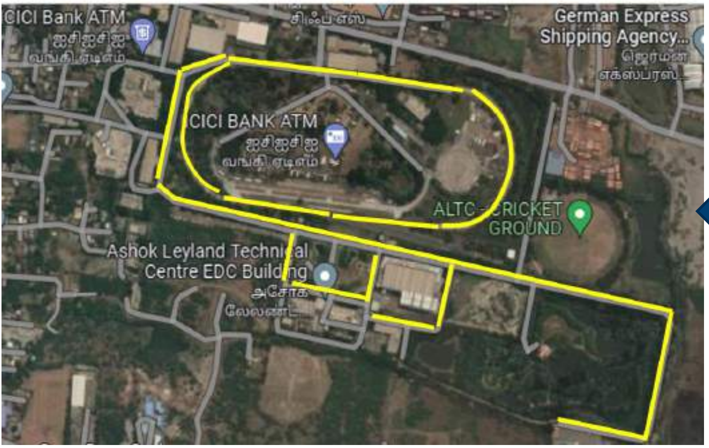
Experience: Hours and Miles accumulated with Hydrogen

2975 kgs of H2 consumed (since Jan’22)



2605 hours of engine dyno run (since Nov’21)

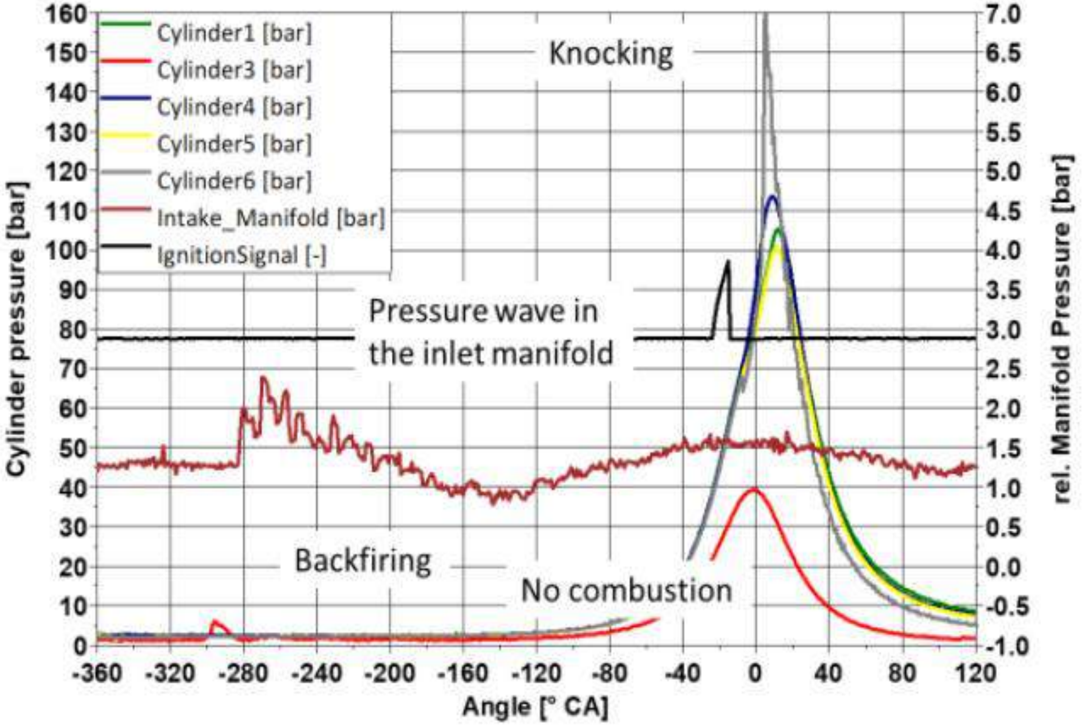
250 kms of vehicle run Since Feb’23



Vehicle tonnage : 41T
Condition of Vehicle : Unladen (Container weight ~ 3 tons)
Max. vehicle speed achieved : 30 kmph
Max. torque : 200 Nm
Max. engine speed : 1800 rpm
Gear of operation : 4th gear
Driver feedback : Silent and smooth operation with backfiring at 3rd gear idle
Total mileage accumulation : 250 kms

H2 Combustion Anomalies – Backfire and Knocking

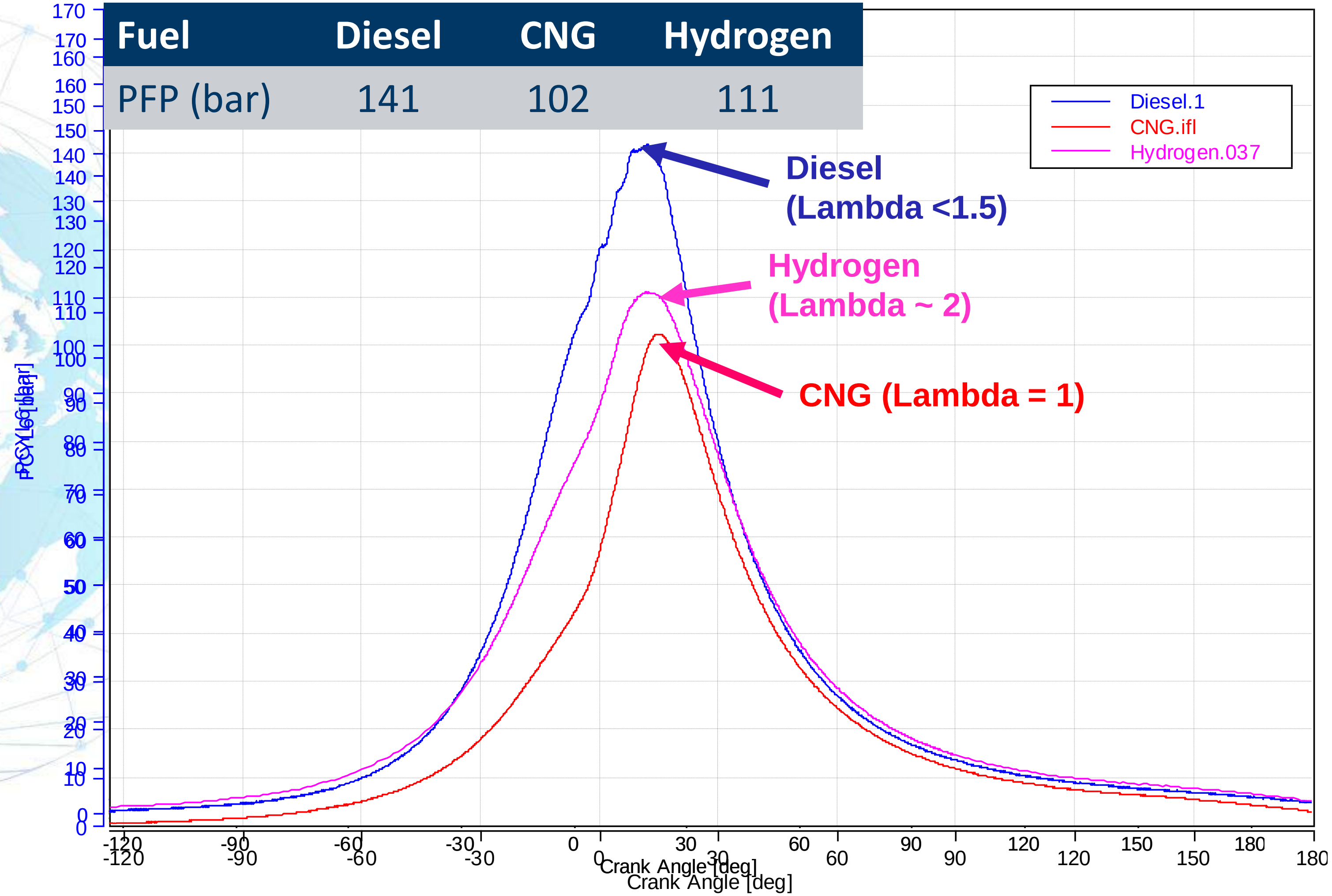
- Backfiring is a combustion anomaly in PFI engines that requires design and calibration measures to resolve. Interestingly, this also leads to knocking.
- A backfire event at medium engine load in cylinder 3 is demonstrated in the graph.
- A pressure wave in the combustion chamber is seen at approximately 300 °CA BTDC.
- Mixture has completely ignited before the inlet valves close and combustion can no longer take place at the actual time within the cylinder.
- The pressure wave created by the backfire moves through the intake manifold at the speed of sound and interferes with the electronic load detection of the engine's own pressure sensors and the MAF.
- The pressure wave simulates a higher pressure which estimates an higher air volume than is actual present in the combustion chambers.
- This results in a temporarily higher amount of fuel injection into the following cylinder 6 (firing order: 1-5-3-6-2-4), which leads to knocking combustion.



H2 ICE Development – Performance Comparison

Combustion Data Analysis- Diesel, CNG and H2

Fuel	Diesel	CNG	Hydrogen
PFP (bar)	141	102	111



Diesel (Lambda <1.5)

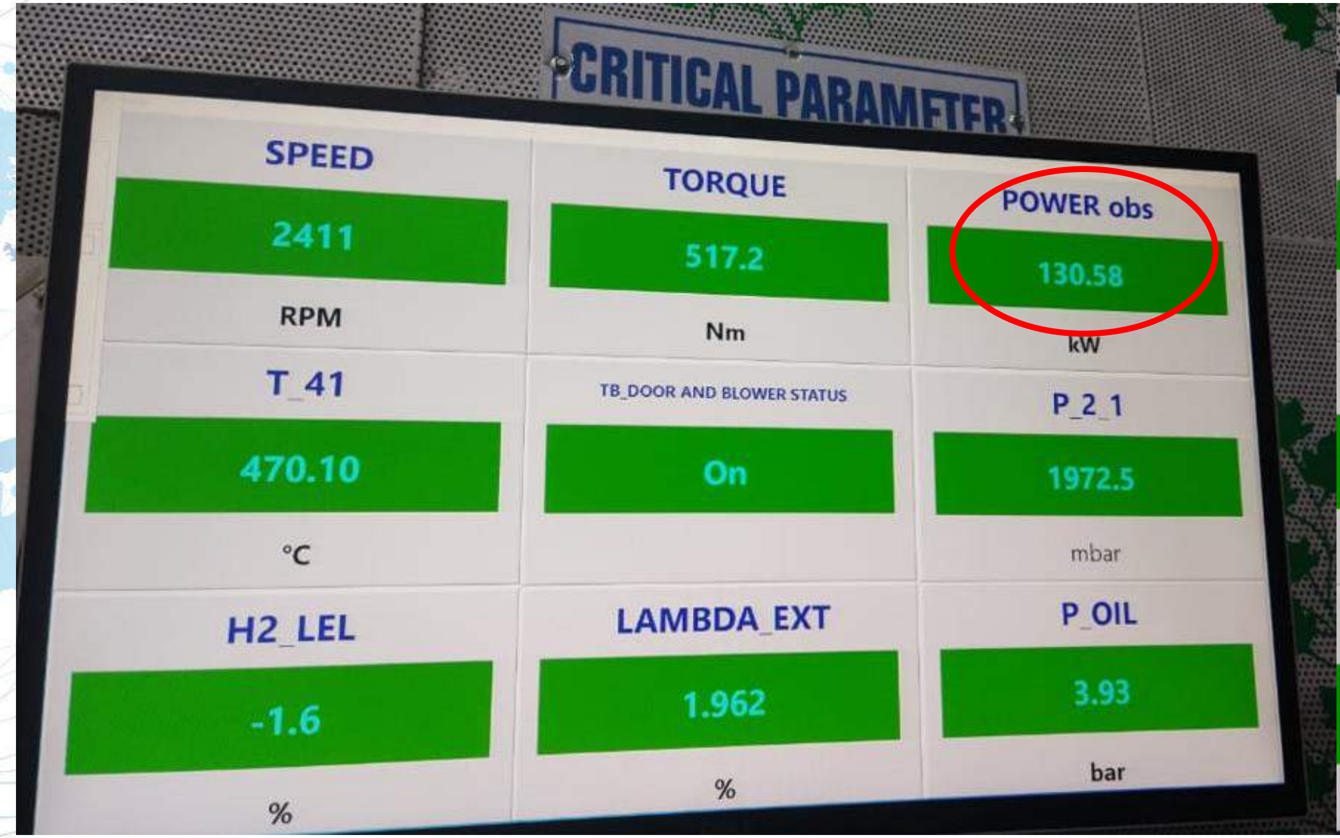
Hydrogen (Lambda ~ 2)

CNG (Lambda = 1)

1. Diesel combustion pressure is higher due to premixed combustion peak and higher compression ratio.
2. Hydrogen higher flame speed is controlled by higher lambda + lower compression ratio → Hence combustion pressure is lower .
3. CNG combustion pressure is limited by lower CR / Stoichiometric.
4. Heat release varies based on BMEP variation.

H2 ICE Development – Performance results

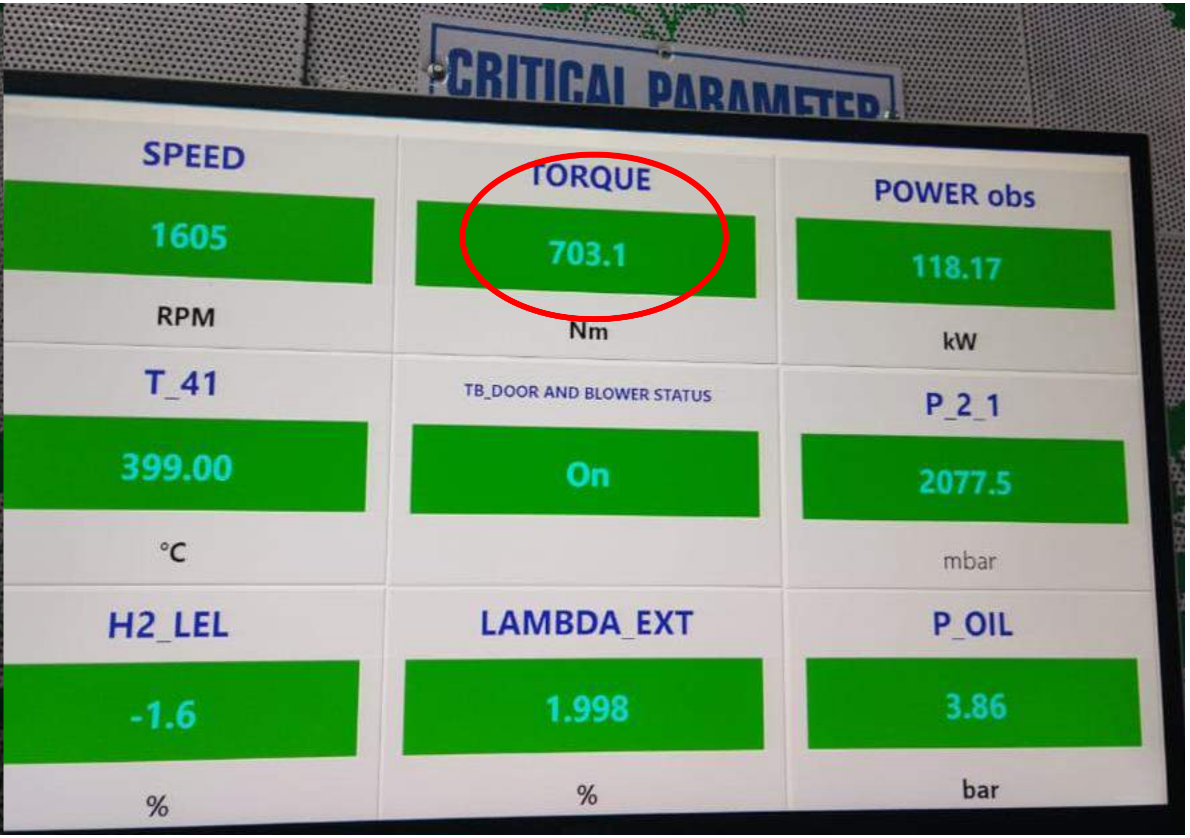
Power



CRITICAL PARAMETER

SPEED: 2411 RPM
TORQUE: 517.2 Nm
POWER obs: 130.58 kW
T_41: 470.10 °C
TB_DOOR AND BLOWER STATUS: On
P_2_1: 1972.5 mbar
H2_LEL: -1.6 %
LAMBDA_EXT: 1.962 %
P_OIL: 3.93 bar

Torque

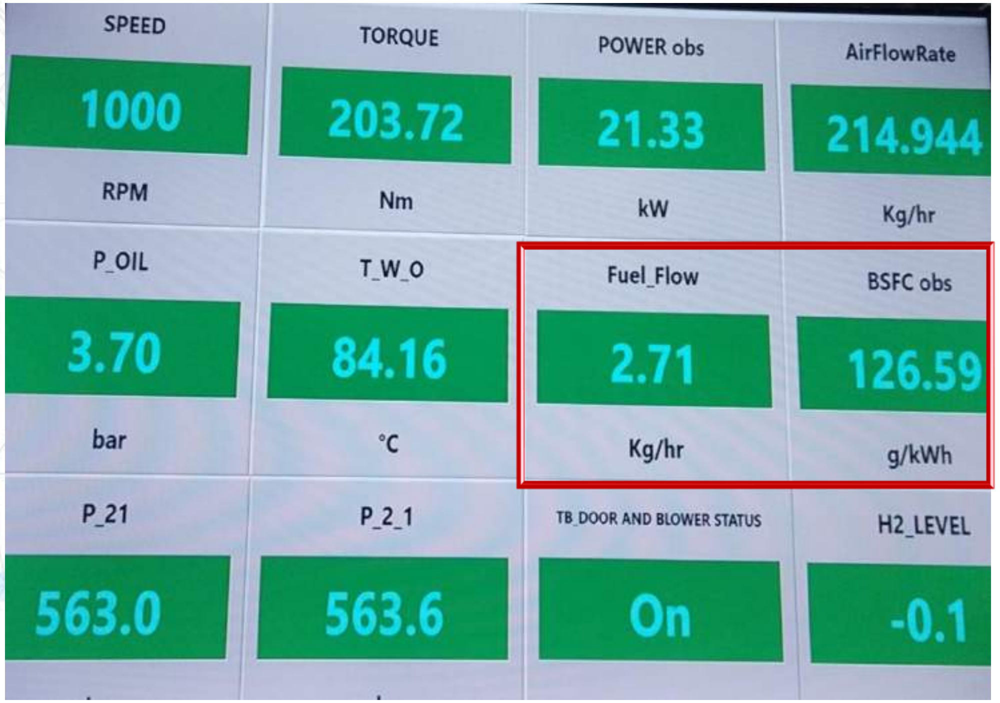


CRITICAL PARAMETER

SPEED: 1605 RPM
TORQUE: 703.1 Nm
POWER obs: 118.17 kW
T_41: 399.00 °C
TB_DOOR AND BLOWER STATUS: On
P_2_1: 2077.5 mbar
H2_LEL: -1.6 %
LAMBDA_EXT: 1.998 %
P_OIL: 3.86 bar

H2 ICE Development – Performance Comparison

H2 ICE



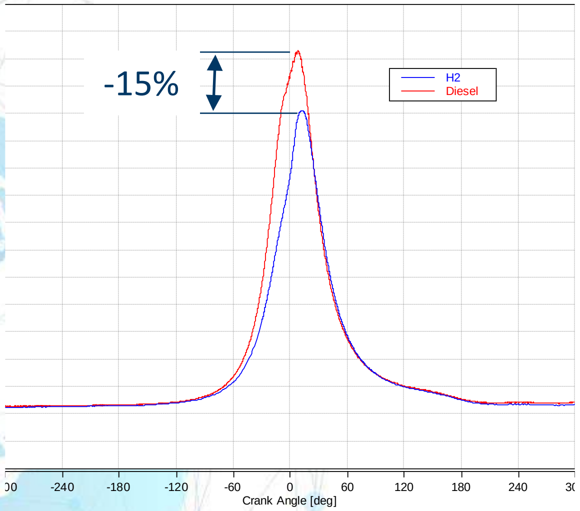
SPEED	TORQUE	POWER obs	AirFlowRate
1000	203.72	21.33	214.944
RPM	Nm	kW	Kg/hr
P_OIL	T_W_O	Fuel_Flow	BSFC obs
3.70	84.16	2.71	126.59
bar	°C	Kg/hr	g/kWh
P_21	P_2_1	TB DOOR AND BLOWER STATUS	H2_LEVEL
563.0	563.6	On	-0.1

DIESEL ENGINE

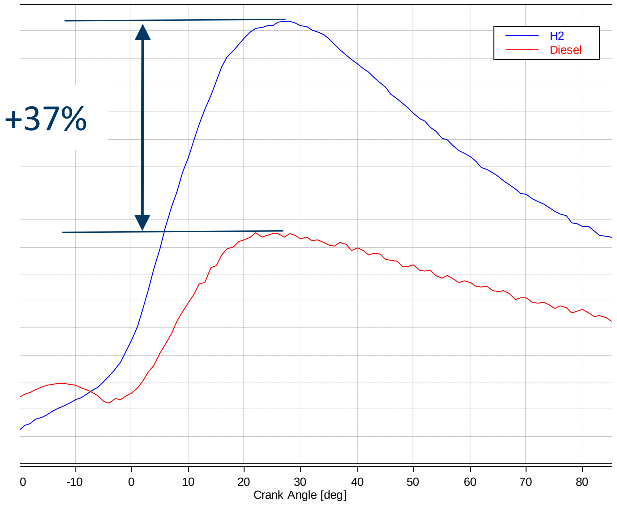
Speed	Torque	Power	Airflow Rate
1000	205.68	21.5	219.61
RPM	Nm	kW	Kg/hr
P_OIL	T_W_O	Fuel_Flow	BSFC obs
3.65	82.5	4.901	228
bar	deg	kg/hr	g/kWh
P_21	P_2_1		
250	230.78		
mbar	mbar		

45 % better on BSFC - better on H2 ICE Engine

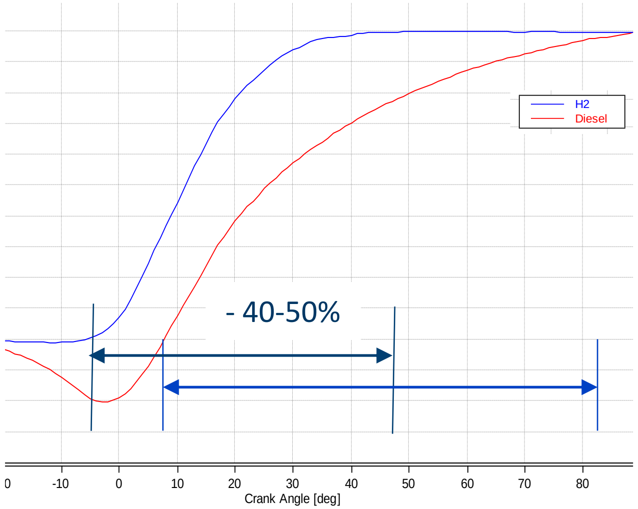
H2 ICE combustion behavior



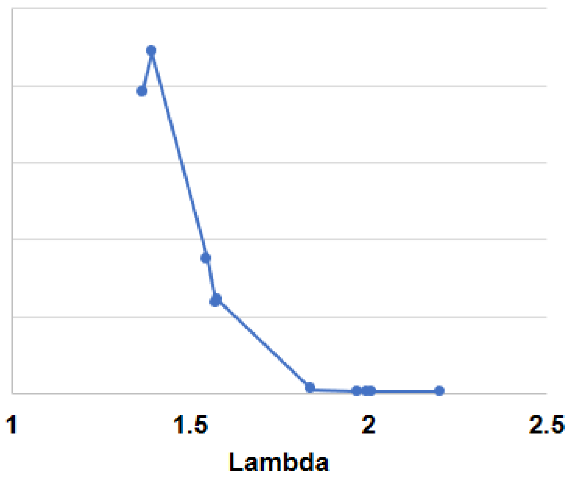
In-cylinder pressure



In-cylinder temperature



Cumulative heat release



NO_x vs Lamda sensitivity

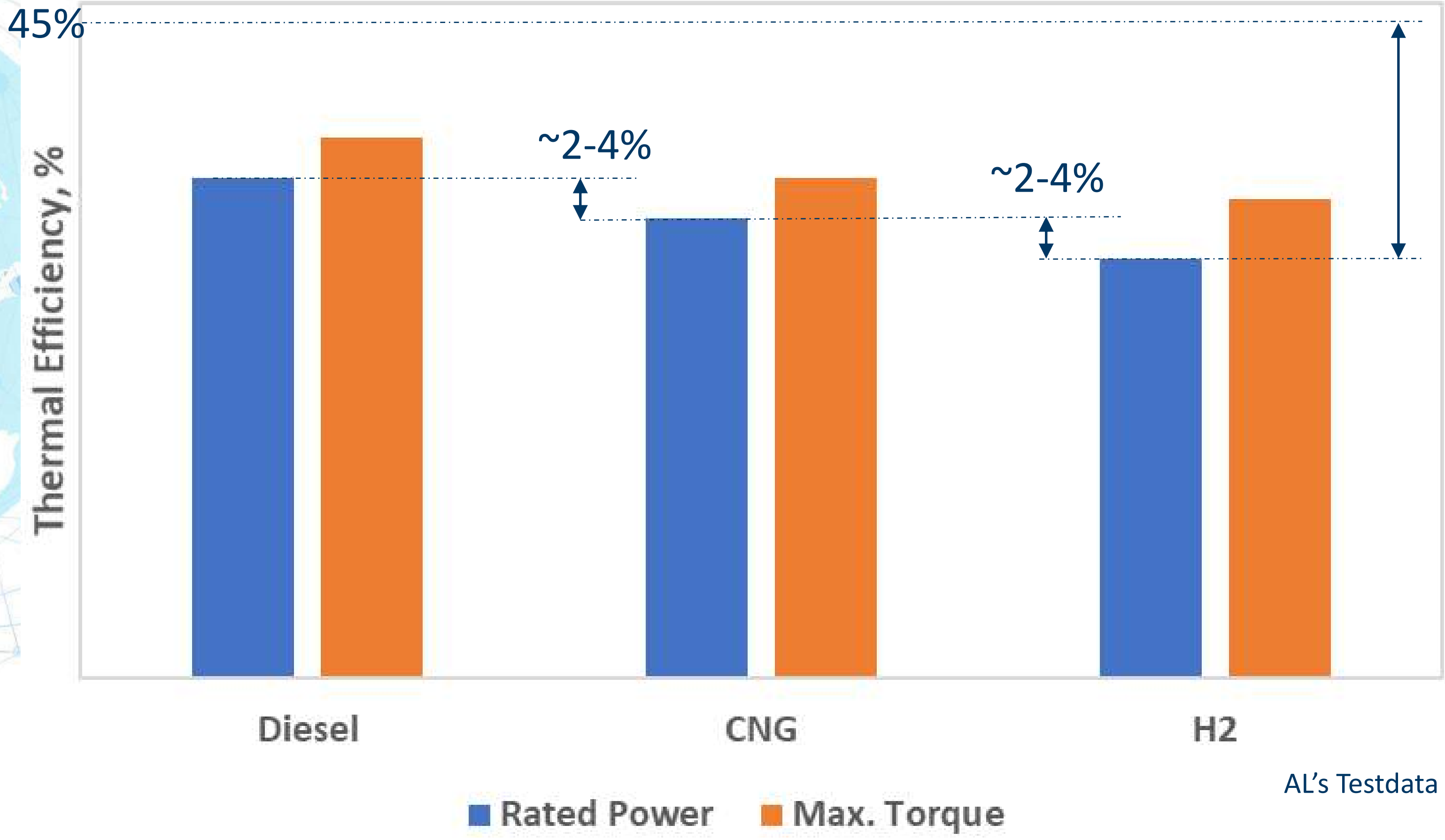
A like to like comparison at similar operating speed and load for lean operated H2 vs Diesel ICE shows that:

- In-cylinder peak pressures is 15% lower in H2 ICE but has 37% higher peak cylinder temperatures
- Combustion duration for H2 ICE is very fast and is only 50-60% that of Diesel ICE
- NO_x is highly sensitive to lamda and is almost non-existant beyond lamda 1.8 to 2.

Reference: AL Internal Report

H2 ICE Thermal Efficiency

The focus of H2 ICE technology would be to improve the efficiency to about 45% in the long term to make it competitive in-terms of TCO.



AL's Testdata

Following methods to be assessed for achieving the efficiency of 45%:

1) VGT or 2-Stage turbocharging
2) Skip firing
3) Variable valve actuation
4) Cylinder de-activation
5) Low pressure/High pressure DI

H2 ICE Modelling using GT Power at AL

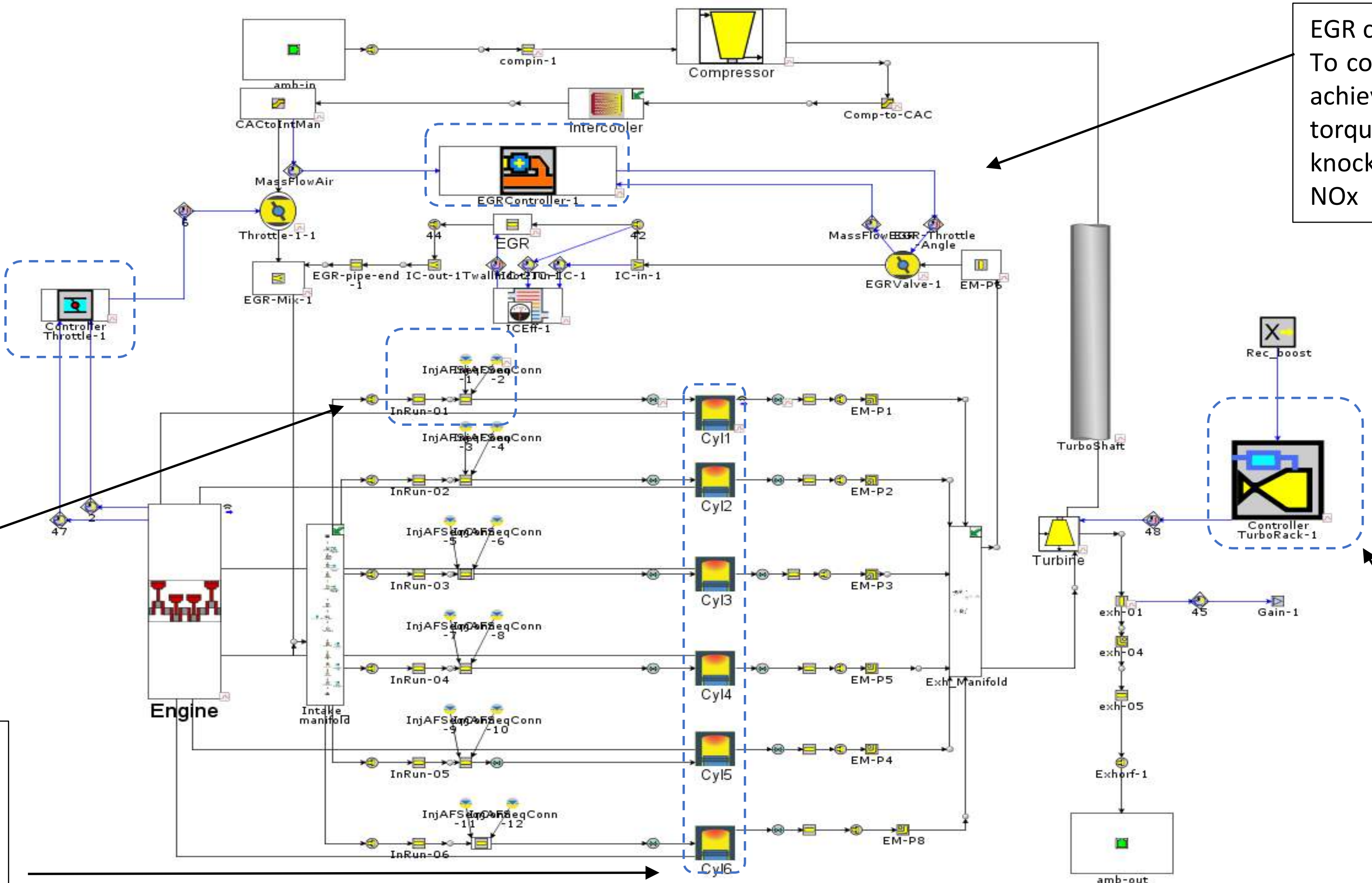
Throttle control:
To control airflow to achieve targeted brake torque

EGR control:
To control EGR flow to achieve targeted brake torque without knocking and lower NOx

Fuel injection control:
To control lambda upon the airflow from throttle valve

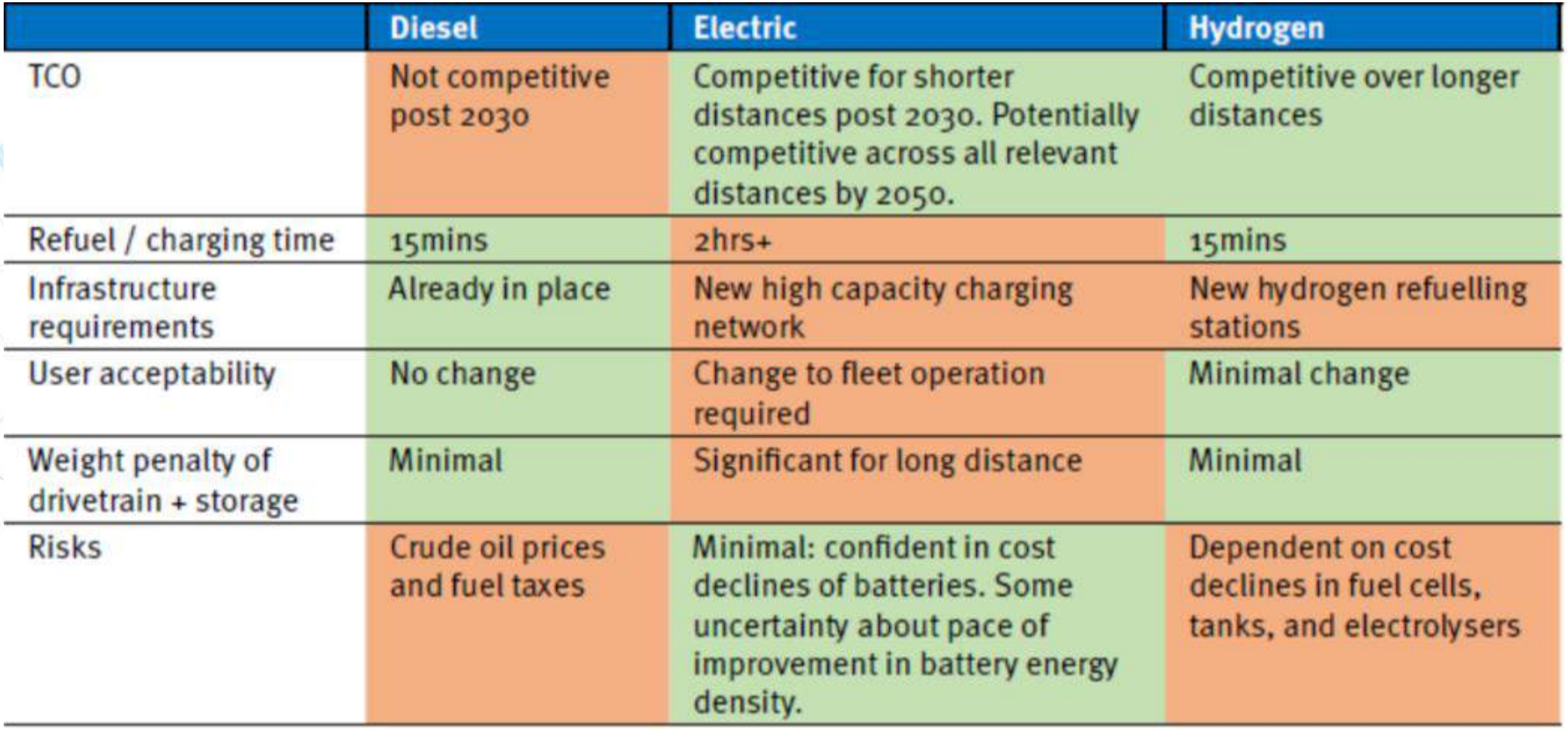
VGT control:
To control boost pressure to achieve targeted brake torque

Combustion model:
Laminar flame speed and knock models were prepared in co-simulation platform and imported in GT Power



Schematic diagram of 1-D Thermodynamic simulation model in GT Power

Multi-criteria assessment for HD trucks and Inter-city buses



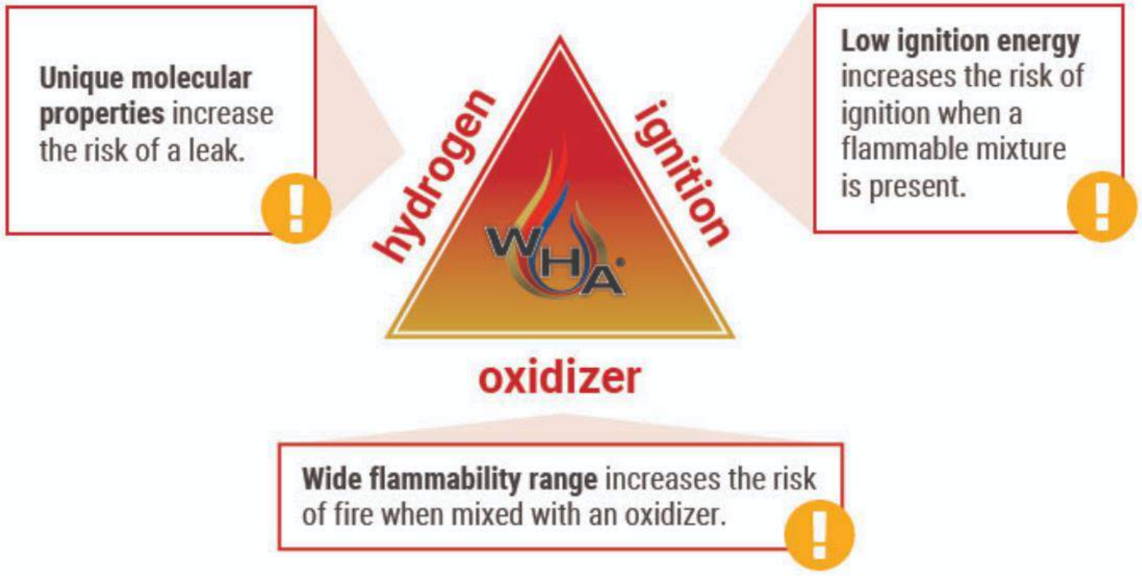
	Diesel	Electric	Hydrogen
TCO	Not competitive post 2030	Competitive for shorter distances post 2030. Potentially competitive across all relevant distances by 2050.	Competitive over longer distances
Refuel / charging time	15mins	2hrs+	15mins
Infrastructure requirements	Already in place	New high capacity charging network	New hydrogen refuelling stations
User acceptability	No change	Change to fleet operation required	Minimal change
Weight penalty of drivetrain + storage	Minimal	Significant for long distance	Minimal
Risks	Crude oil prices and fuel taxes	Minimal: confident in cost declines of batteries. Some uncertainty about pace of improvement in battery energy density.	Dependent on cost declines in fuel cells, tanks, and electrolysers

Reference: TERI report – The potential role of hydrogen in India, 2020

Challenges Faced and Resolution Action

Sl. No.	Challenges	Resolution	Current Status
1	Severe Backfiring	Resolution by H2 ICE specific ignition coil, EGR & calibration	Closed
2	High intensity knocking	Resolution by lean calibration (lamda >1.7 to 2)	Closed
3	Not able to achieve diesel like power and torque	Increased boost pressure using VGT and double injector usage per cylinder	Closed
4	H2 Leakage from engine during testbed operation & risk of fire	Testbed safety installations like H2 concentration sensing, fuel cut off, blower and door control, fire safety	Closed
5	Hydrogen embrittlement	Material upgrade for high risk components	In progress

Hydrogen Risk Management



Unique molecular properties increase the risk of a leak.

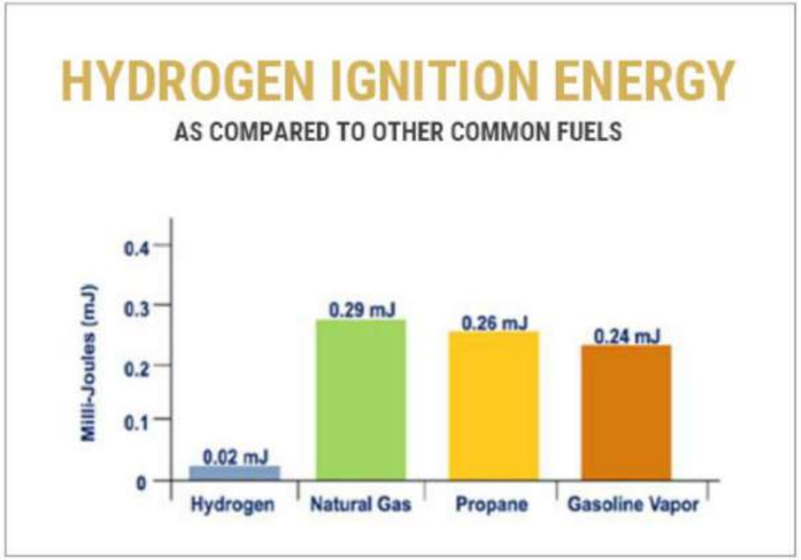
Low ignition energy increases the risk of ignition when a flammable mixture is present.

Wide flammability range increases the risk of fire when mixed with an oxidizer.

Avoid unintentional mixing: Use only hydrogen compatible materials and consider design and safety factors to prevent leaks.

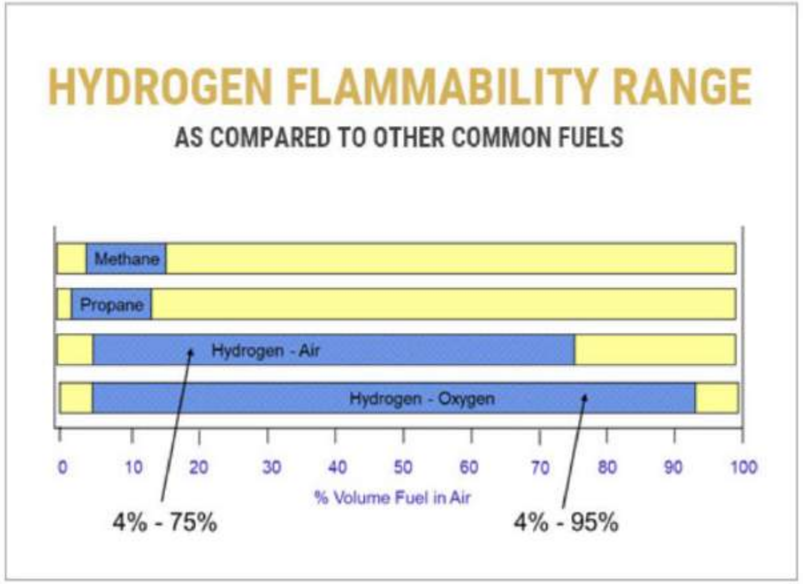
Anticipate ignition mechanisms: Control mechanisms that can ignite hydrogen-oxidizer mixtures.

Adopt best practices: Implement safe practices with inspection, assembly, operation, maintenance, and safety systems.



HYDROGEN IGNITION ENERGY

AS COMPARED TO OTHER COMMON FUELS



HYDROGEN FLAMMABILITY RANGE

AS COMPARED TO OTHER COMMON FUELS

Learnings from H2 ICE Development

Combustion Characteristics
Faster flame speed
Shorter combustion duration
Lower exhaust temperatures

Combustion Strategy
Lean combustion (lambda $\geq$ 2)

Engine-out Emissions
Zero CO_2 & Soot
Negligible NO_x
Steam(H_20)

rake Thermal Efficiency
At Rated speed: 35%
At Max Torque: 38%

Performance
No starting difficulty
Smooth steady-state operation
Full throttle performance same as diesel engine

We will add more learnings as we move on!

H2 ICE Development – Knowledge Gaps – Impact on Performance and Cost

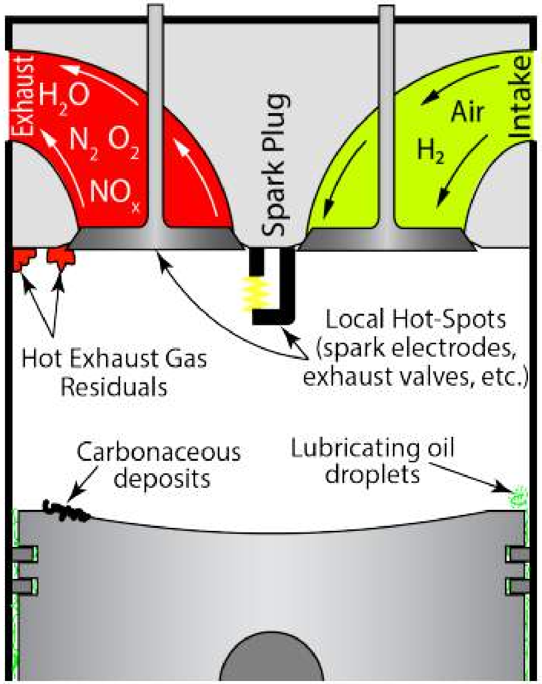
Current OEM perspective:

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

Collective Impetus to Create Hydrogen Economy

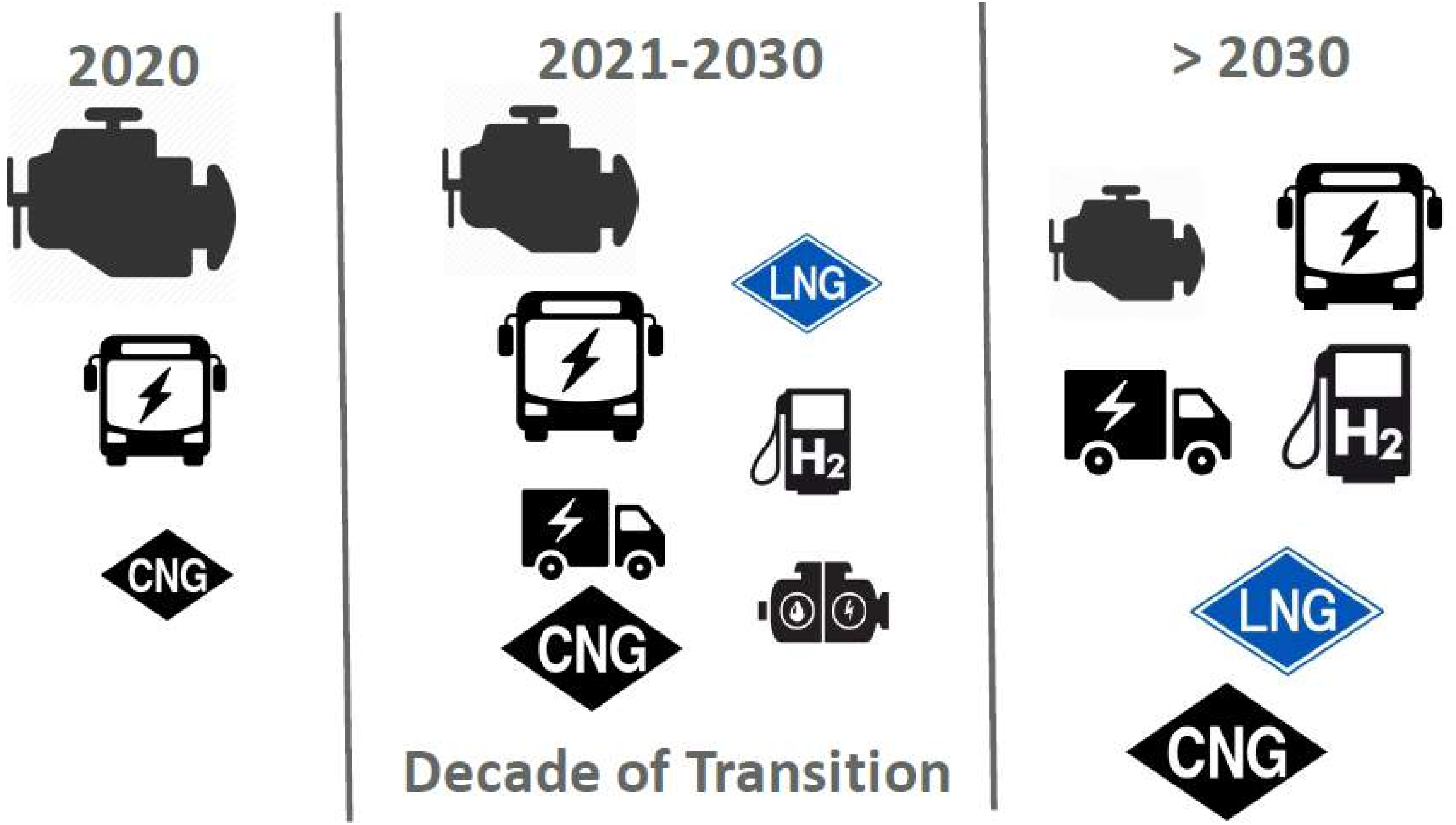
- Hydrogen tank technology localization
- Injector, ECU and regulator localization
- Turbocharging technology for H2 ICE
- Ignition coil technology for H2 ICE
- Embrittlement related study, labs & collaboration

Towards Atmanirbhar!

Engine Specification

Description	3.8 L H4	5.7 L H6-2V	6.0 L H6-2V	6.3 L H6-2V	8.0 L A6
Bore x Stroke (mm)	104 x 113	104 x 113	104 x 118	106 x 118	112 x 135
Power (hp)	150 hp	180-BSIV / 200-BSVI	220 hp	250 hp	300 hp
Rated Speed (RPM)	2400	2400	2400	2400	2200
Idle Speed (RPM)	750	750	750	750	750
Torque (Nm)	450	700	800	850	1000
Max Torque Range (RPM)	1200 – 2000	1300-1900	1300-1900	1400-1800	1400-1800
Aspiration	TCIC	TCIC	TCIC	TCIC	TCIC
Fuel System	MPFI & DI	MPFI	MPFI & DI	MPFI	MPFI
CR	11.5:1	11.5 : 1	11.5 : 1	11.5 : 1	11.5 : 1
Combustion	Lean $\lambda > 2$	Lean $\lambda > 2$	Lean $\lambda > 2$	Lean $\lambda > 2$	Lean $\lambda > 2$
After Treatment	TBD	TBD	TBD	TBD	TBD
EGR	Yes	Yes (cooled EGR)	Yes (cooled EGR)	Yes (cooled EGR)	Yes (cooled EGR)

Decade of Energy Transition



2020

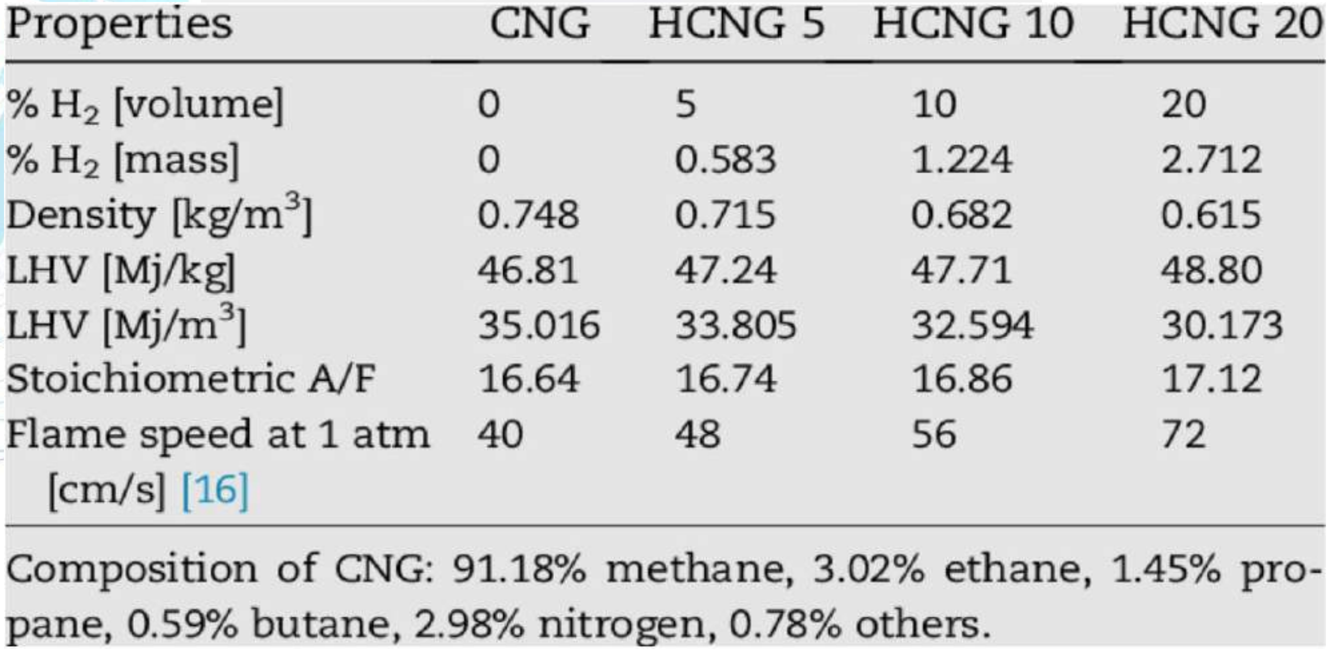
2021-2030

> 2030

Decade of Transition

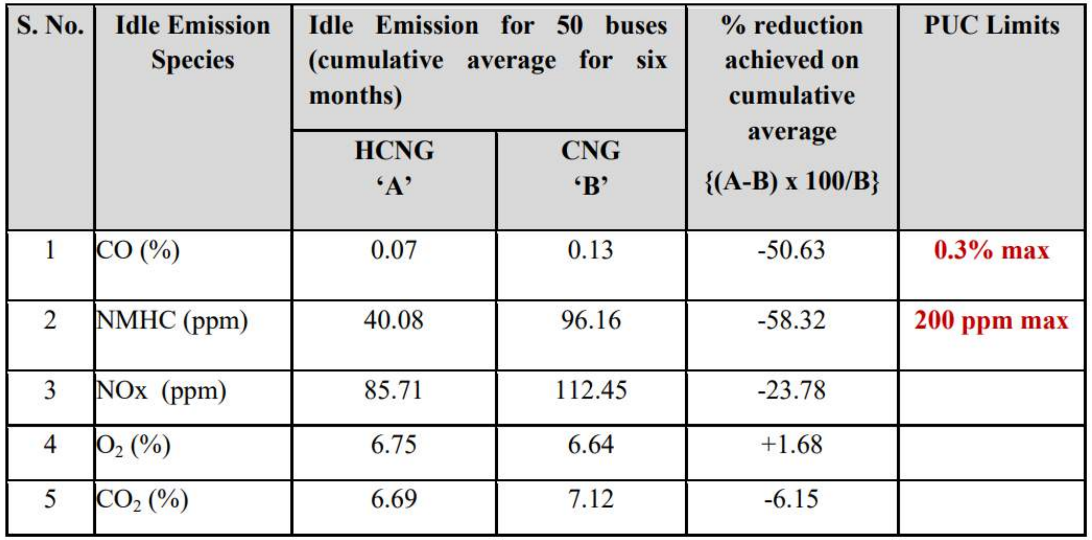
H2+CNG Engines

- **AL – IOCL jointly runs 50nos of HCNG buses in Delhi.**
- **Hydrogen blending improves flame speed.**
- **Complete, faster combustion helps CO, HC emissions.**



Properties	CNG	HCNG 5	HCNG 10	HCNG 20
% H_2 [volume]	0	5	10	20
% H_2 [mass]	0	0.583	1.224	2.712
Density [kg/m^3]	0.748	0.715	0.682	0.615
LHV [Mj/kg]	46.81	47.24	47.71	48.80
LHV [Mj/m^3]	35.016	33.805	32.594	30.173
Stoichiometric A/F	16.64	16.74	16.86	17.12
Flame speed at 1 atm [cm/s] [16]	40	48	56	72

Composition of CNG: 91.18% methane, 3.02% ethane, 1.45% propane, 0.59% butane, 2.98% nitrogen, 0.78% others.



S. No.	Idle Emission Species	Idle Emission for 50 buses (cumulative average for six months)		% reduction achieved on cumulative average {(A-B) x 100/B}	PUC Limits
		HCNG 'A'	CNG 'B'		
1	CO (%)	0.07	0.13	-50.63	0.3% max
2	NMHC (ppm)	40.08	96.16	-58.32	200 ppm max
3	NOx (ppm)	85.71	112.45	-23.78	
4	O_2 (%)	6.75	6.64	+1.68	
5	CO_2 (%)	6.69	7.12	-6.15	

H2 ICE Development – Summary of Learnings

1. No starting difficulty with H2 and engine runs quieter than CNG/Diesel.
2. BSFC is 1/3rd of diesel engines primarily due to 3x more calorific value of H2.
3. Max. exhaust temperature before turbine (T3) is lower than diesel.
4. Max. peak firing pressure is lower than diesel. Higher than CNG.
5. Max. air flow required is higher than diesel. For the same BMEP, the in-cylinder pressure ~20% lower with H2 compared to diesel. Turbo charger selection is very critical to meet the low end air flow. VGT TC is able to deliver the required air flow.
6. 7 to 10% EGR is required at higher speeds and loads to manage backfiring.
7. Steam formation in exhaust characteristic of H2 combustion. Lowest CO2 & zero soot

H2 ICE Development – Summary of Learnings

7. NOx emission is very sensitive to lambda , maintain always more than 2.0. Negligible NOx emissions then.

8. Spark plug gap to be 0.2-0.3 levels – latest learning from Tenneco is that we have to move to ring type electrode than from currently used conventional J type.

9. Spark timing is very sensitive and leading to knocking if advance the timing.

10. Combustion rate (fuel burning rate) is much higher than conventional fuels.

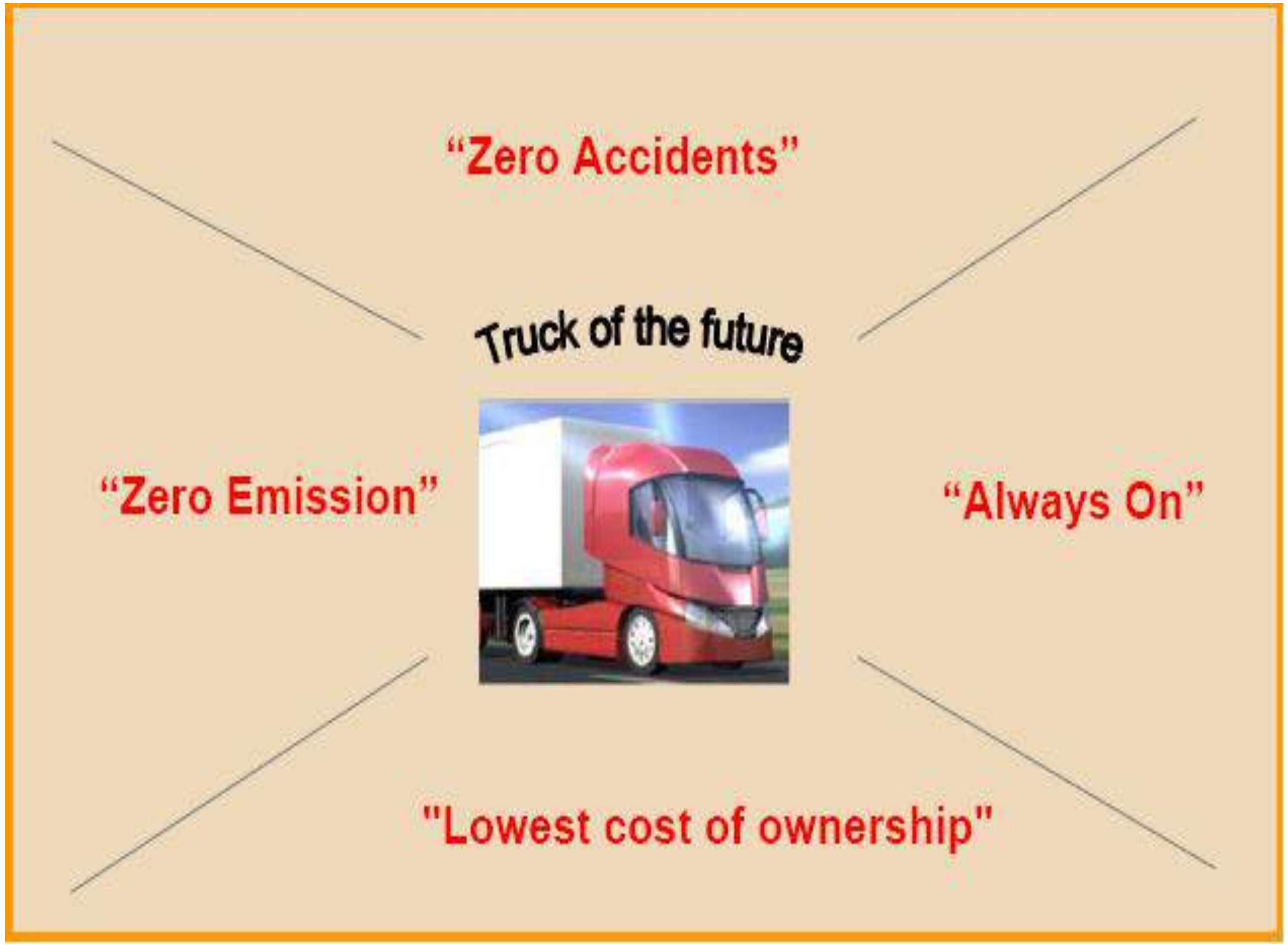
11. M50% & M90% are ~50% lower with H2 compared to diesel fuel.

12. Fuel injection duration <120CA helps no backfire (in case of CNG it is more than 300CA). However, with improved ignition coils, the above could be extended

Summary

- H2 ICE is attractive for reducing global warming in comparison with gasoline and diesel engines as it is a zero CO_2 solution.
- Hydrogen can be used in spark ignition engines with minimal modifications in the existing systems.
- Backfiring in hydrogen engines is a challenge and is limited to external mixture formation (PFI) and can be avoided by specific design & calibration efforts.
- Thermal efficiency of the hydrogen operated engine is lower than CNG and diesel operated engines due to lower calorific value on volumetric basis. This can be enhanced by various means.
- The TCO study between diesel and H2 ICE shows that H2 ICE is beneficial as H2 fuel price is expected to drop in near future.
- H2 ICE can be an intermediate step between Diesel ICE and Fuel cells. The recommended route for this would be a MPFI based technology considering cost, complexity and performance parameters.

Future Vehicle



“Zero Accidents”

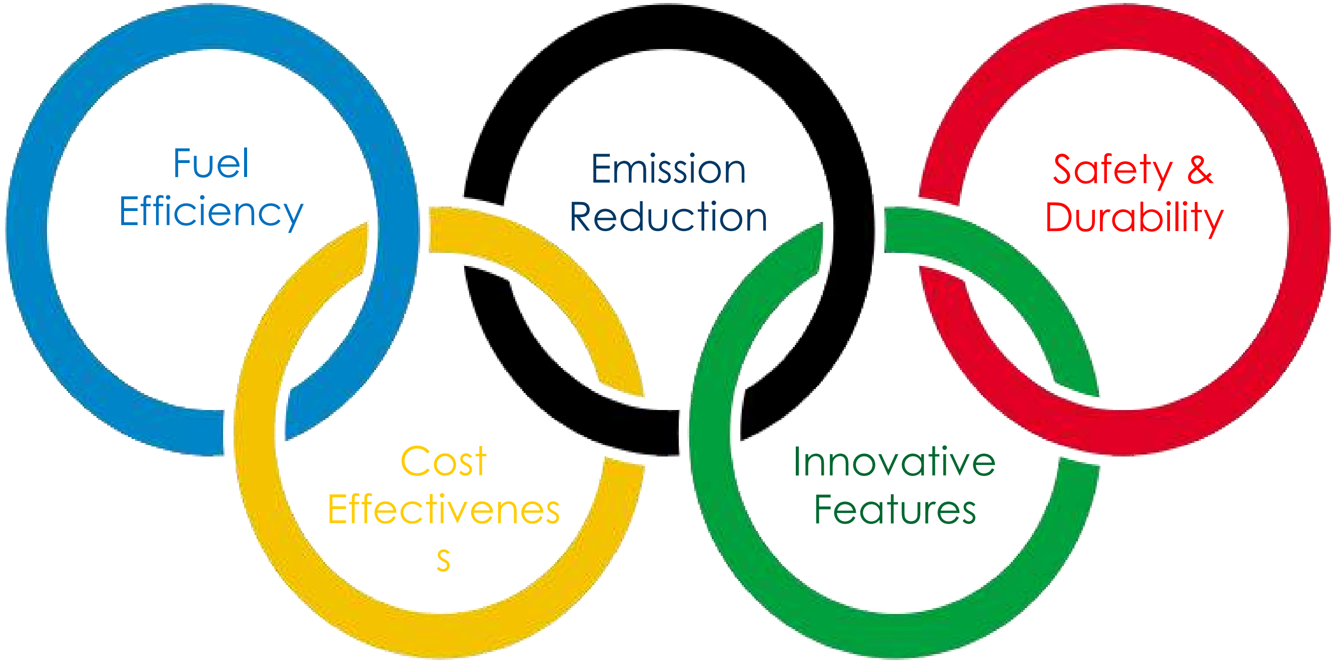
Truck of the future

“Zero Emission”

“Always On”

"Lowest cost of ownership"

Facets of future technological competitiveness



Fuel Efficiency

Emission Reduction

Safety & Durability

Cost Effectiveness

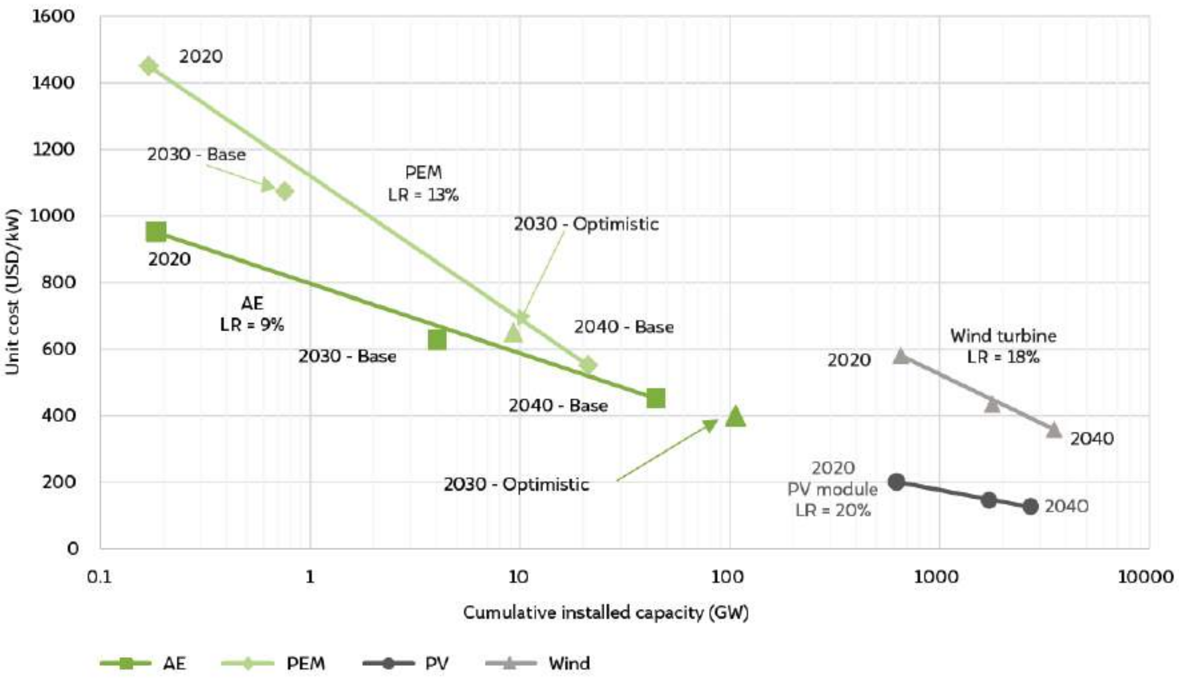
Innovative Features

An interwoven web of often conflicting requirements

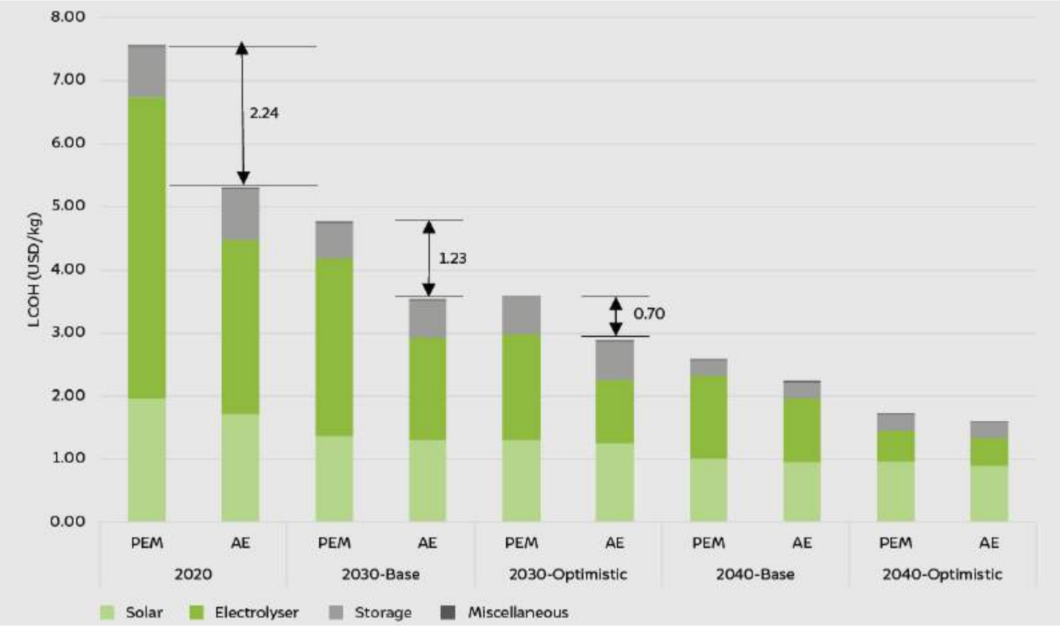
ASHOK LEYLAND

No Dream Too Far

Economics & Cost of H2 production



Learning rates for electrolyzers, solar modules and wind turbines

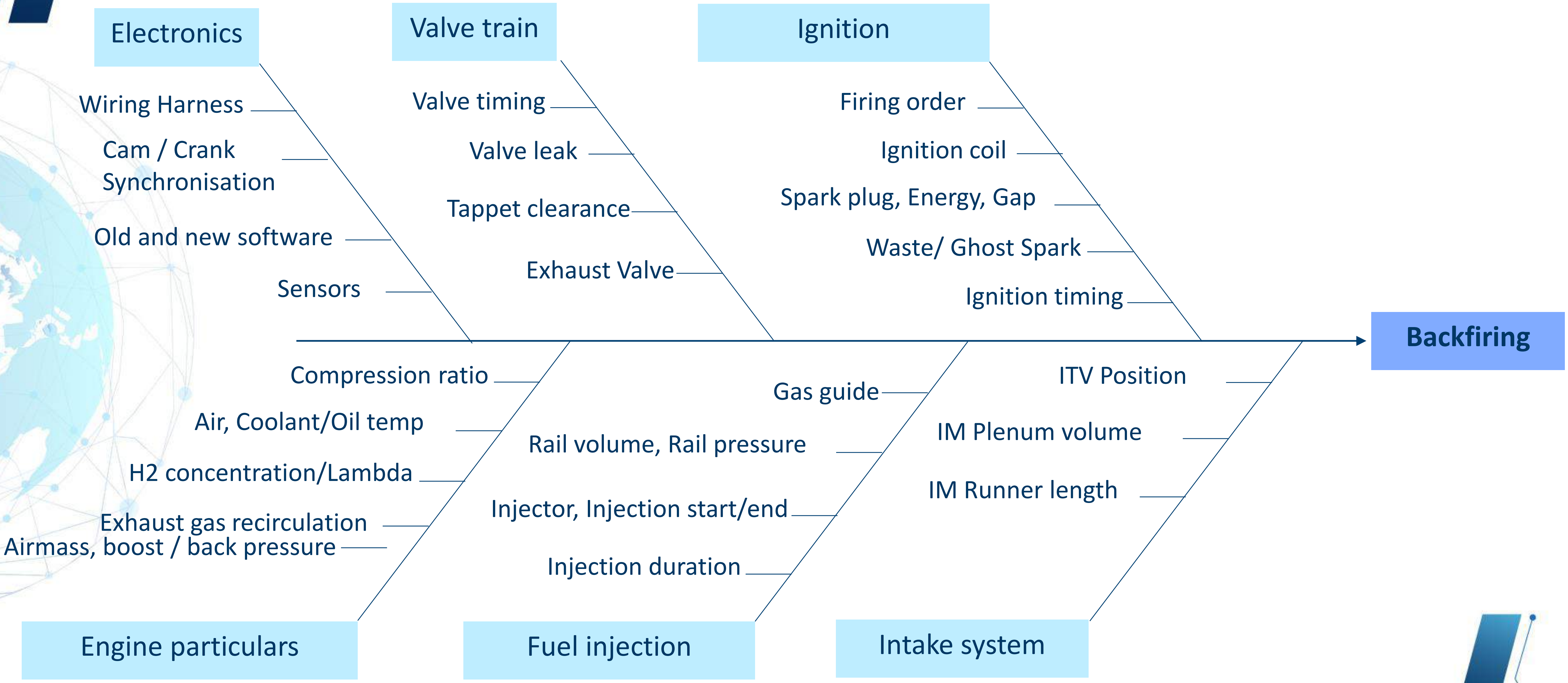


Hydrogen obtained from PEM electrolyzer is expensive than alkaline electrolyser, but difference is expected to decrease in future. (LCOH: Levelized cost of H2)

Reducing the electrolyzer costs would be possible only if the annual global production capacity of 50 GW is achieved by 2040. A strong international commitment towards scaling up hydrogen economy is needed.

Source: H2 economy for India, Sakthi Foundation report)

H2 ICE Development – Ishikawa diagram for backfiring



Electronics
- Wiring Harness
- Cam / Crank Synchronisation
- Old and new software
- Sensors

Valve train
- Valve timing
- Valve leak
- Tappet clearance
- Exhaust Valve

Ignition
- Firing order
- Ignition coil
- Spark plug, Energy, Gap
- Waste/ Ghost Spark
- Ignition timing

Backfiring

Engine particulars
- Compression ratio
- Air, Coolant/Oil temp
- H2 concentration/Lambda
- Exhaust gas recirculation
- Airmass, boost / back pressure

Fuel injection
- Gas guide
- Rail volume, Rail pressure
- Injector, Injection start/end
- Injection duration

Intake system
- ITV Position
- IM Plenum volume
- IM Runner length

H2 ICE Development – Analysis for backfiring

What is backfire: The combustion event takes place outside the engine's combustion cylinders

Reason for Backfire:

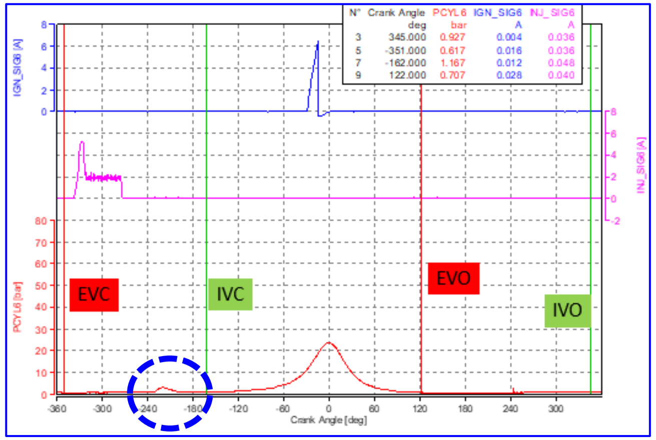
1. Higher Flame Velocity
2. Low Ignition Energy
3. Smaller Quenching Distance

How to identify Backfire:

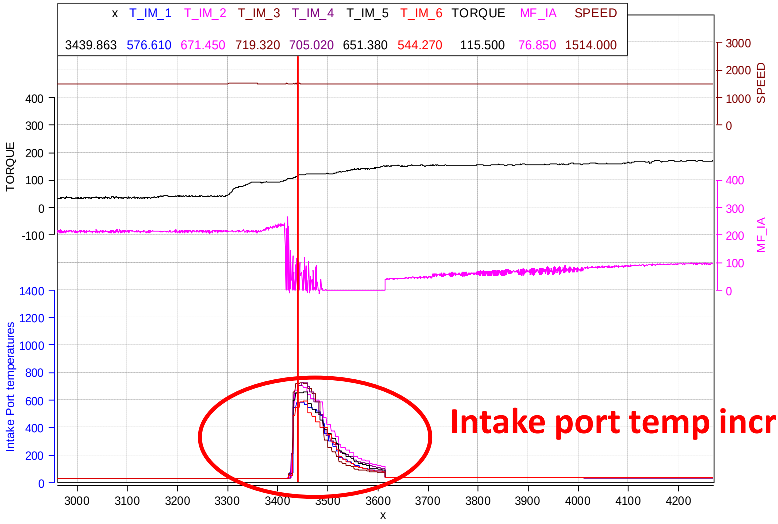
1. Audible sound
2. In cylinder pressure
3. Intake port temperatures

What needs to be optimized:

1. Valve timing
2. Fuel Injection Timing
3. Ignition timing
4. Ignition System
5. EGR
6. AFR



N°	Crank Angle deg	PCYL6 bar	IGN_SIG6 A	INJ_SIG6 A
3	345.000	0.927	0.004	0.036
5	-351.000	0.617	0.016	0.036
7	-162.000	1.167	0.012	0.048
9	122.000	0.707	0.028	0.040



x	T_IM_1	T_IM_2	T_IM_3	T_IM_4	T_IM_5	T_IM_6	TORQUE	MF_IA	SPEED
3439.863	576.610	671.450	719.320	705.020	651.380	544.270	115.500	76.850	1514.000

Intake port temp increase

H2 ICE Development – EGR effect on Knock

- As the EGR rate increases, the susceptibility to knocking decreases and the position of the combustion centre of gravity can be shifted in the early direction
- The adjustment of ignition timing can be seen in the figure on the right of Figure 13. When considering the ignition timing at Lambda = 2.2, a shift from 12.5°CA b. TDC to approximately 21.5°CA b. TDC at full EGR rate is discernible.
- The displacement of ignition timing is greater than that of the combustion centre of gravity due to two influences that must be included.
    - Firstly, the ignition delay increases with increasing EGR rate and
    - secondly, the combustion speed decreases with increasing EGR rate.

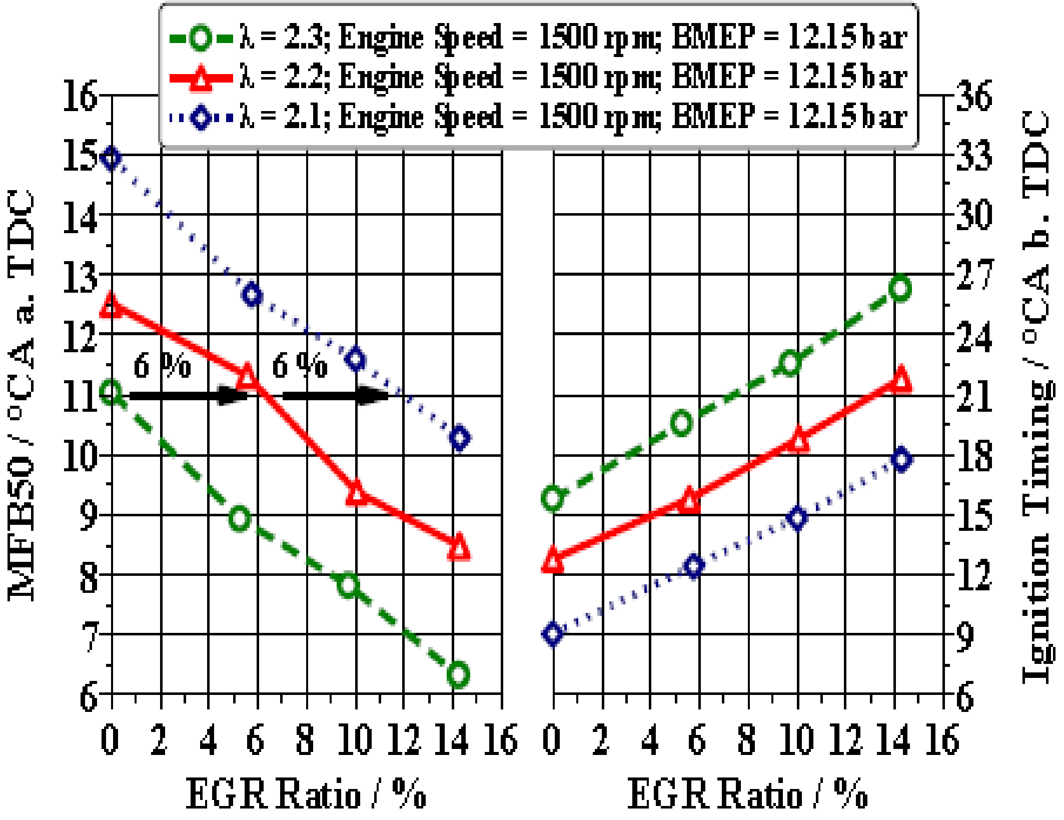
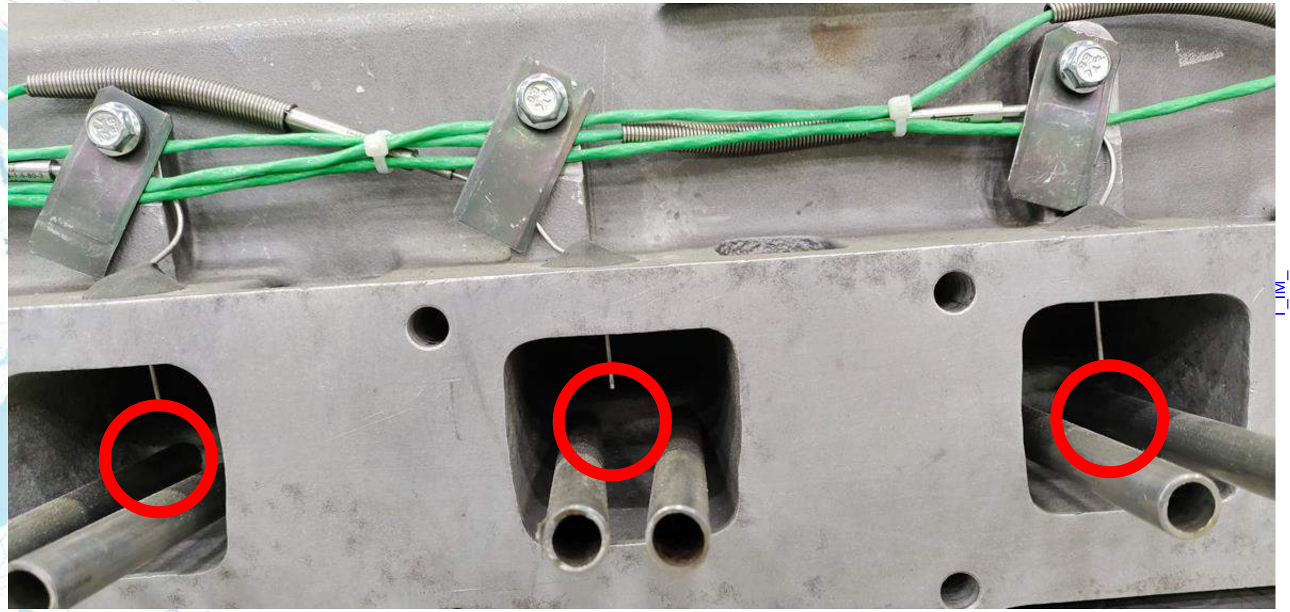


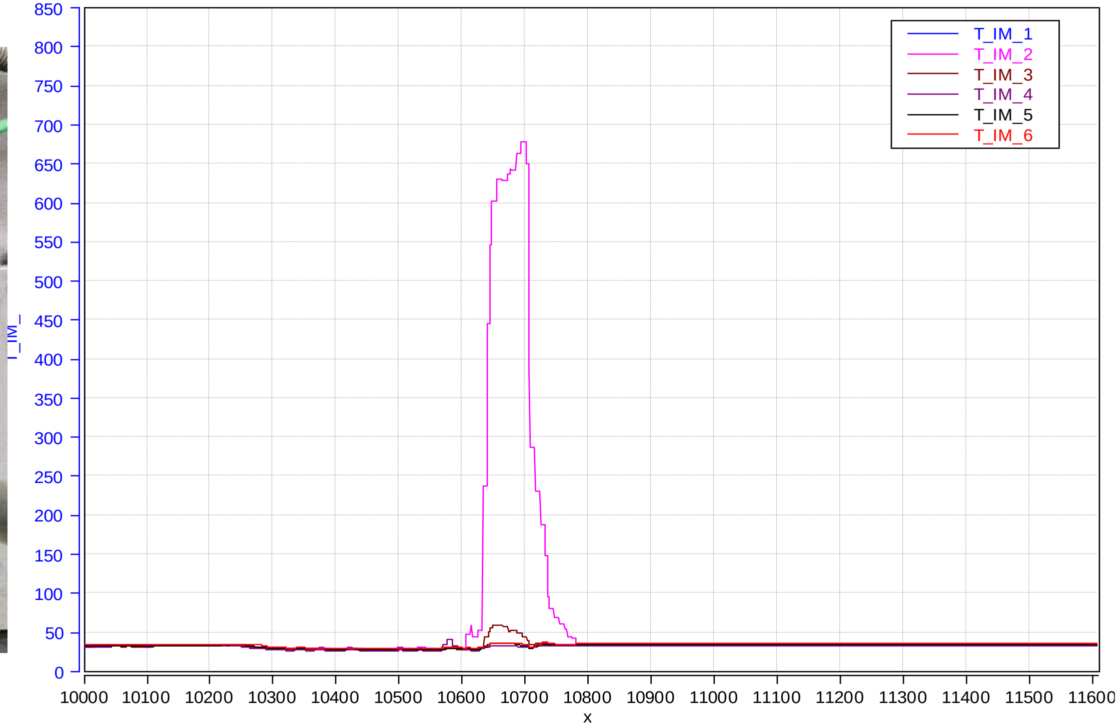
Figure 13: Influence of EGR-Ratio regarding the centre of combustion & Ignition timing

HYDROGEN ENGINE DEVELOPMENT EXPERIENCE

H2 ICE Development – Engine Instrumentation

Intake manifold should be instrumented with individual intake port temperature sensors→ to identify the backfire

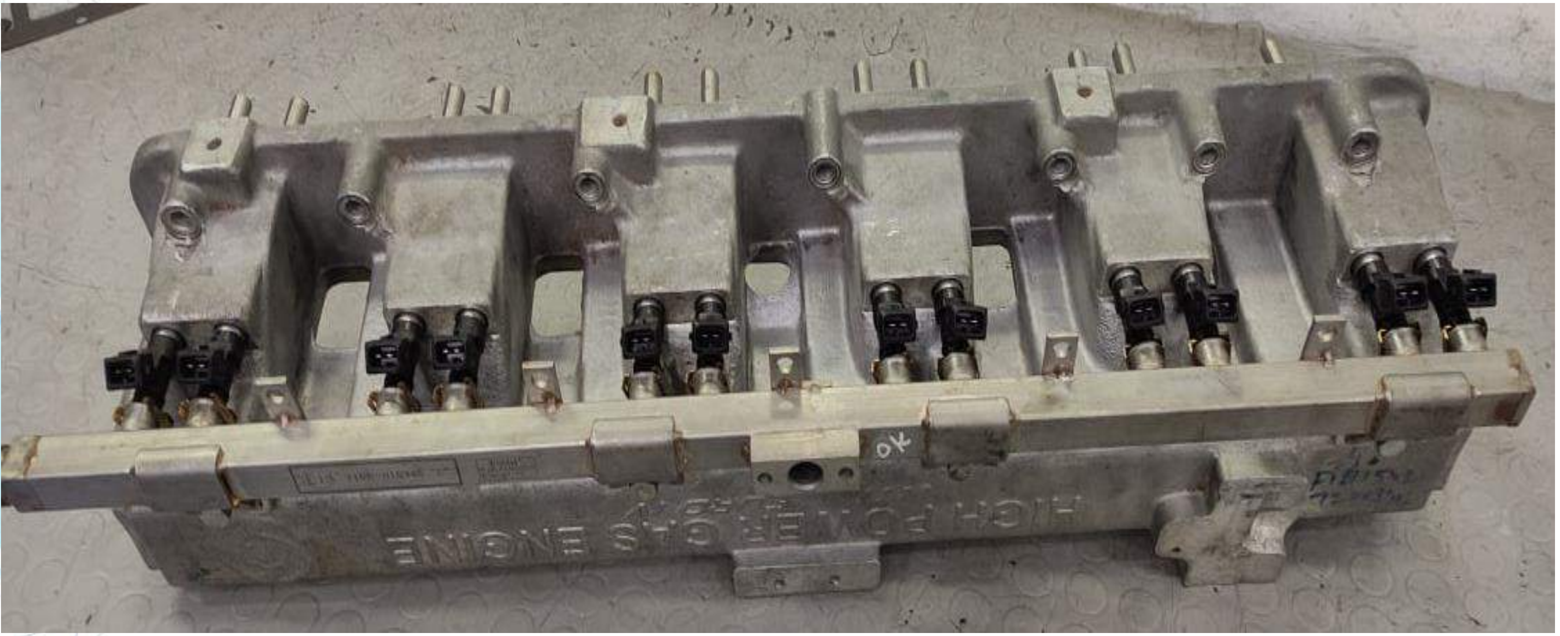




Intake Port temperature increased during the backfire to 650degC momentarily. We can able to identify which cylinder is backfired

H2 ICE Development – Engine Instrumentation

Gas port injection should be very close to the intake valve→ to avoid the backfire

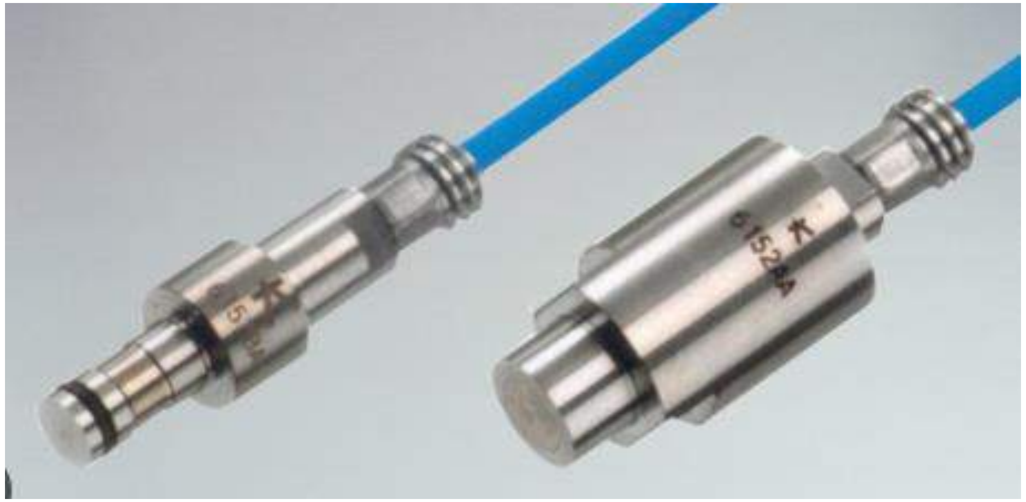


Gas guides are provided to inject the fuel very close to the intake port so that NO hydrogen is stored in the intake port.

H2 ICE Development – Engine Instrumentation

In cylinder pressure measurement→ instrumented spark plug is not recommended

✗

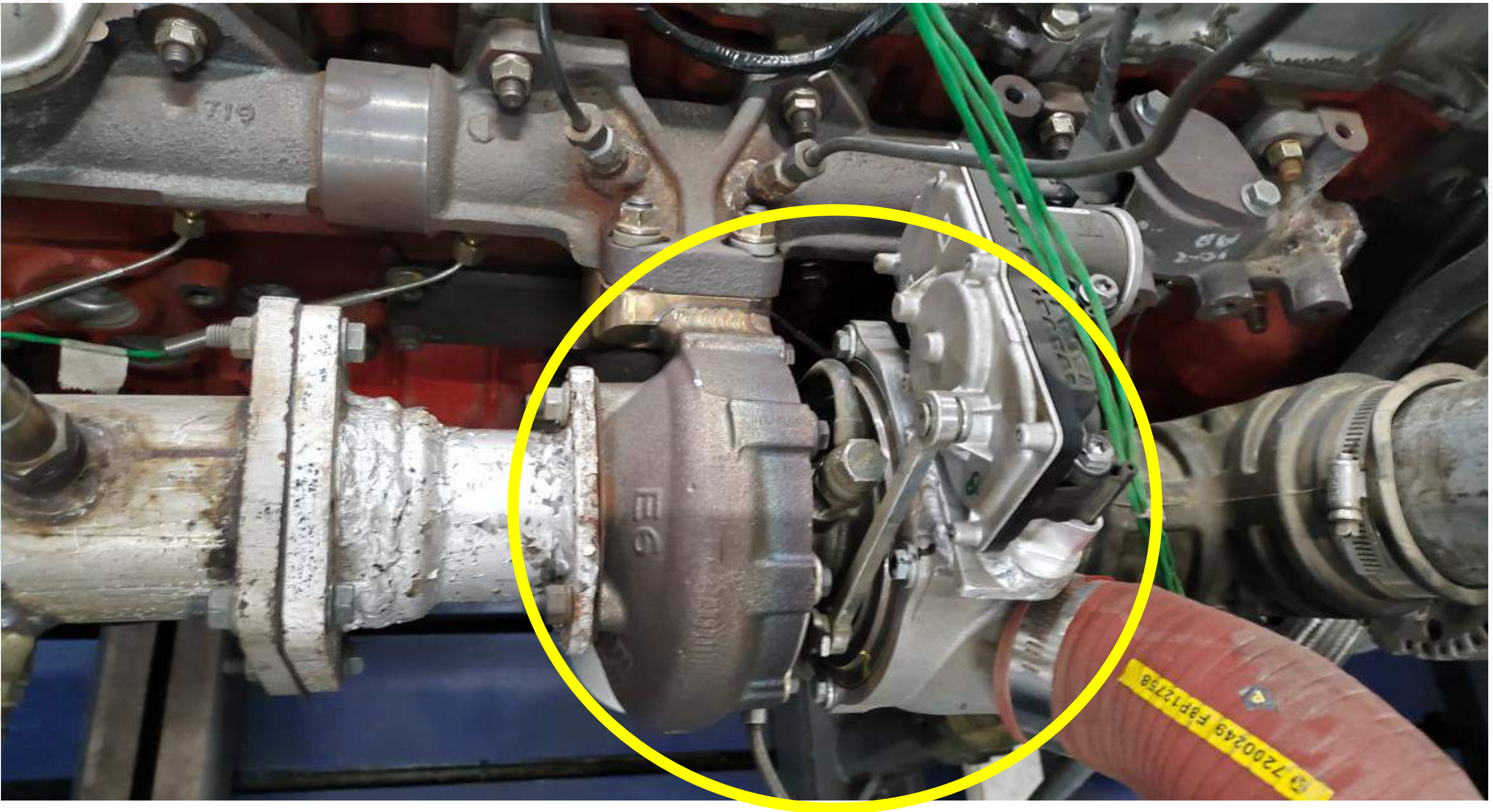


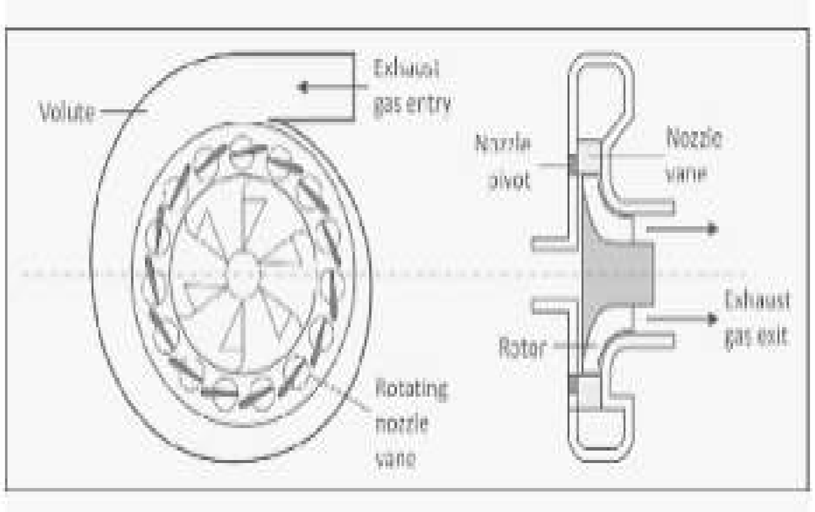
✓

We have noticed that instrumented spark plugs are frequently getting damaged. Hence, pressure transducer should be used.

H2 ICE Development – Hardware Selection

Variable Geometry Turbocharger (VGT) is required to meet the air flow demand→ to reduce the NOx and backfire

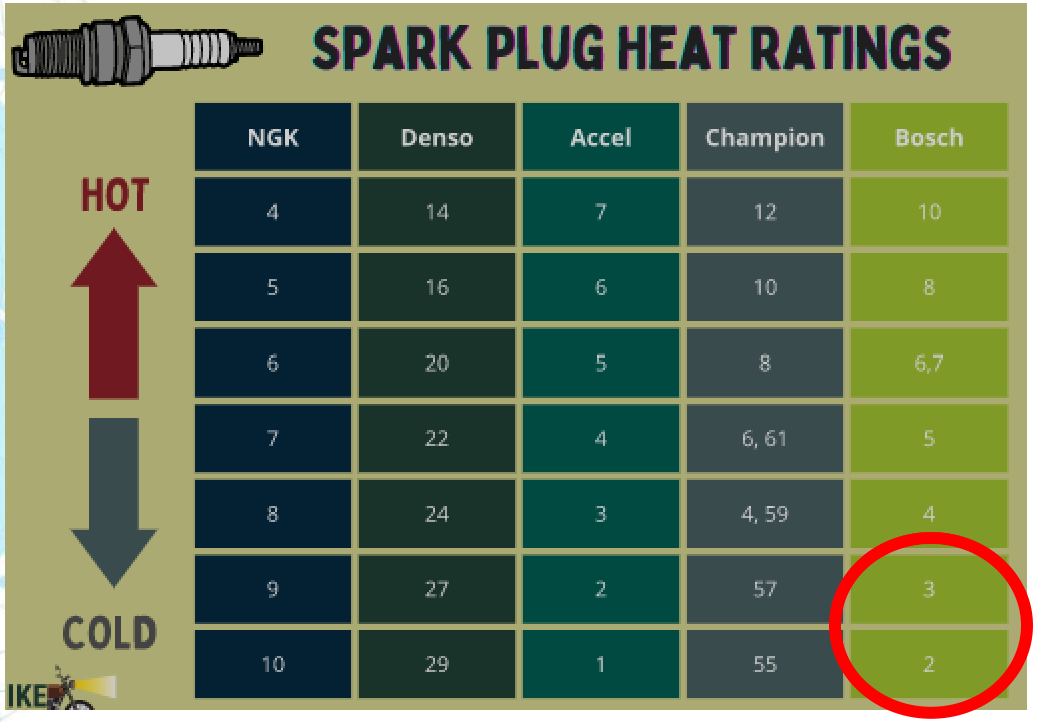




VGT is required to deliver higher air flow at lower engine speeds (lambda>2)

H2 ICE Development – Hardware Selection

Cold rated spark is required→ to avoid backfire



SPARK PLUG HEAT RATINGS

NGK	Denso	Accel	Champion	Bosch
4	14	7	12	10
5	16	6	10	8
6	20	5	8	6,7
7	22	4	6, 61	5
8	24	3	4, 59	4
9	27	2	57	3
10	29	1	55	2

FR3KII spark plug is suitable for hydrogen combustion, durability is to be verified.

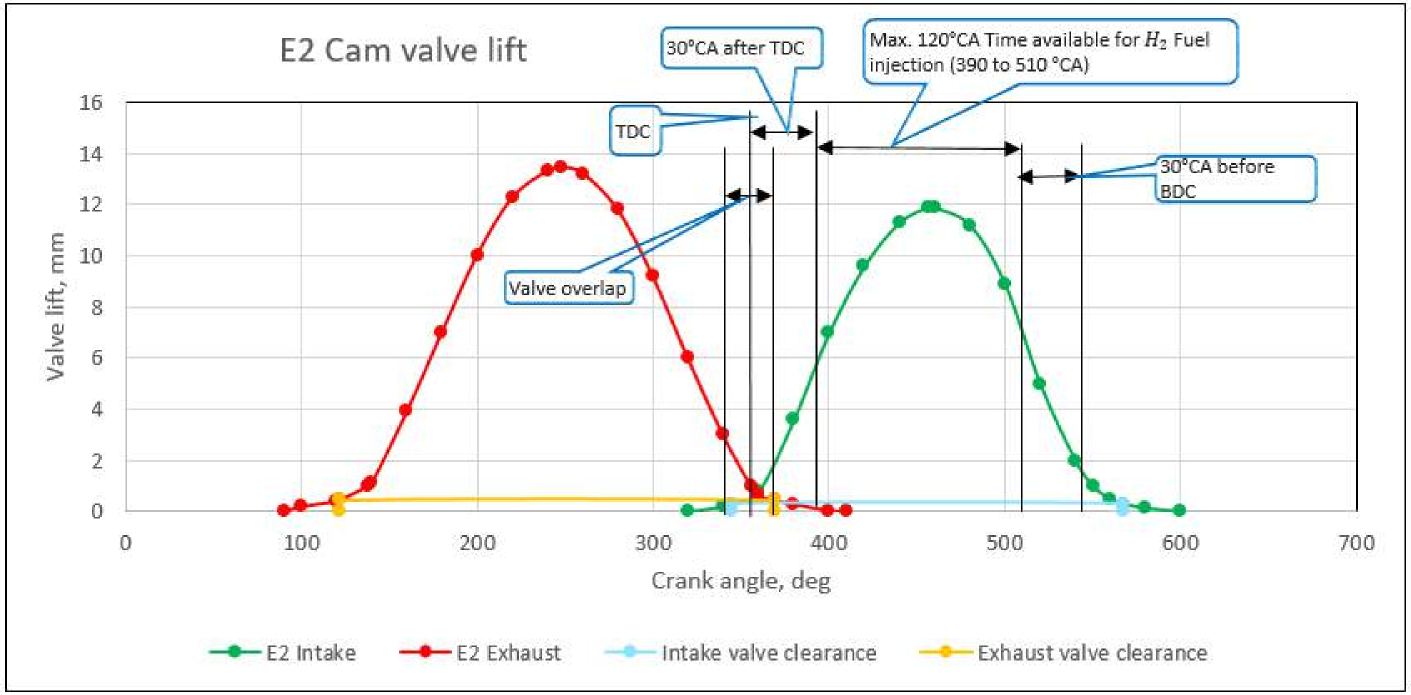
H2 ICE Development – Hardware Selection

Spark plug gap should be smaller (<0.3mm)→ to avoid backfire and to have stable combustion

Multiple experiments were carried out to identify the correct spark plug for hydrogen fuel and observed that combustion is stable with smaller gap (0.3mm).

H2 ICE Development – Hardware Selection

Fuel injector through flow should be high enough to ensure lesser injection duration→ to avoid backfire. With better ignition coils, however, we can allow higher injection durations



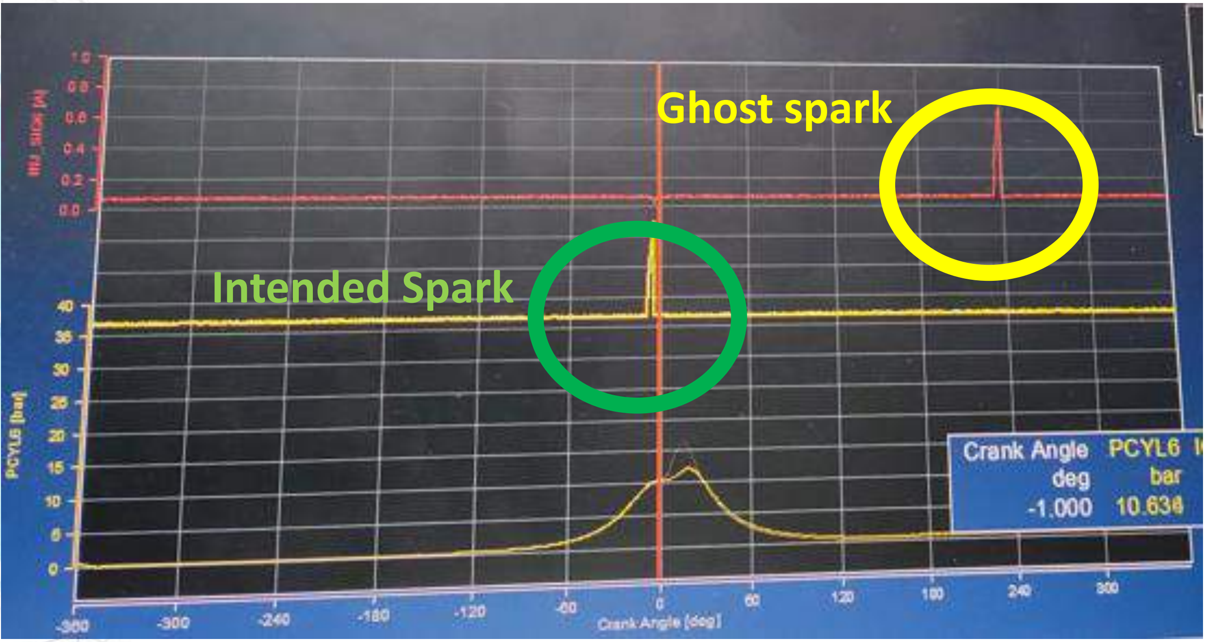
valve timing at valve clearance intake/exhaust : 0.3/0.45 mm	
EVO	**122**
EVC	**369**
IVO	**345**
IVC	**568**

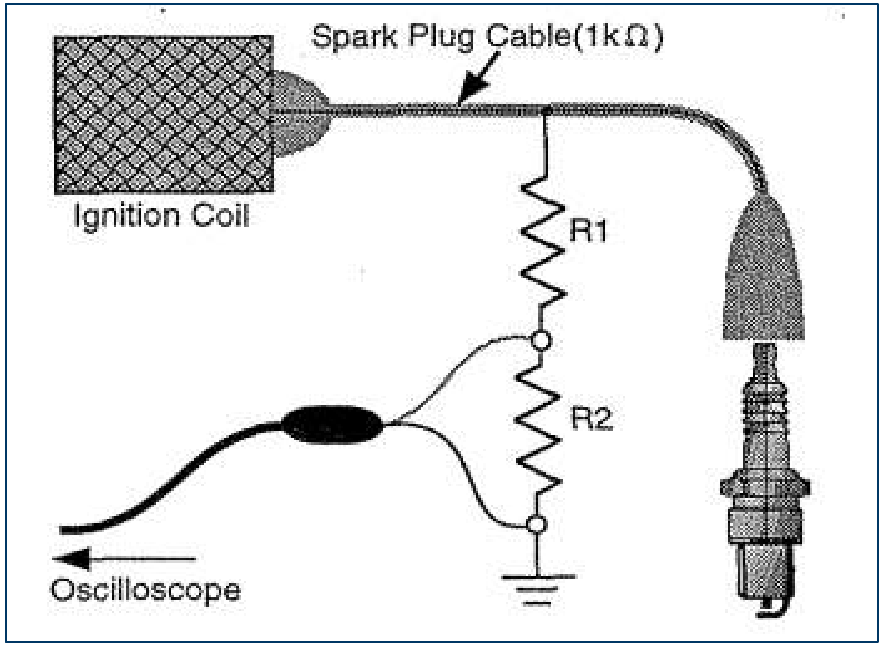
EVO (deg. CRA BBDC)	58
EVC (deg. CRA ATDC)	9
IVO (deg. CRA BTDC)	15
IVC (deg. CRA ABDC)	28

Consider only the duration of suction stroke when piston moves from TDC to BDC. Hence, time available for H_2 fuel injection = 180°CA- (30°CA+30°CA) = 120°CA (max.).

H2 ICE Development – Hardware Selection

Ignition coil should have very less ignition energy (<10mJ)→ to avoid ghost spark.

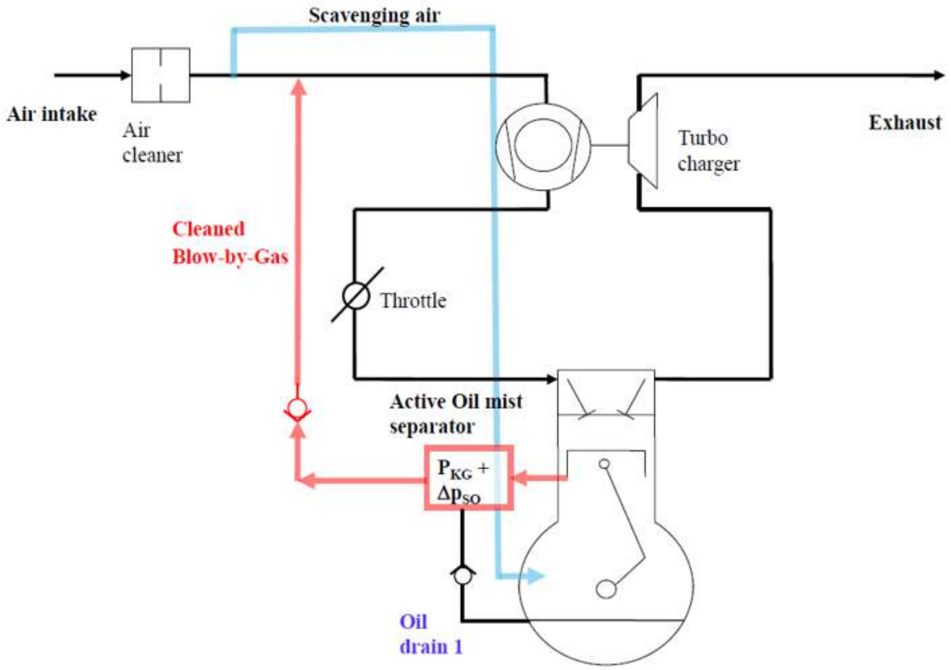




- Residual energy in spark plug
- Modified cable for quick release of residual energy

H2 ICE Development – Hardware Selection

Crank case ventilation is to be modified→ to reduce the H2 concentration in the blow by

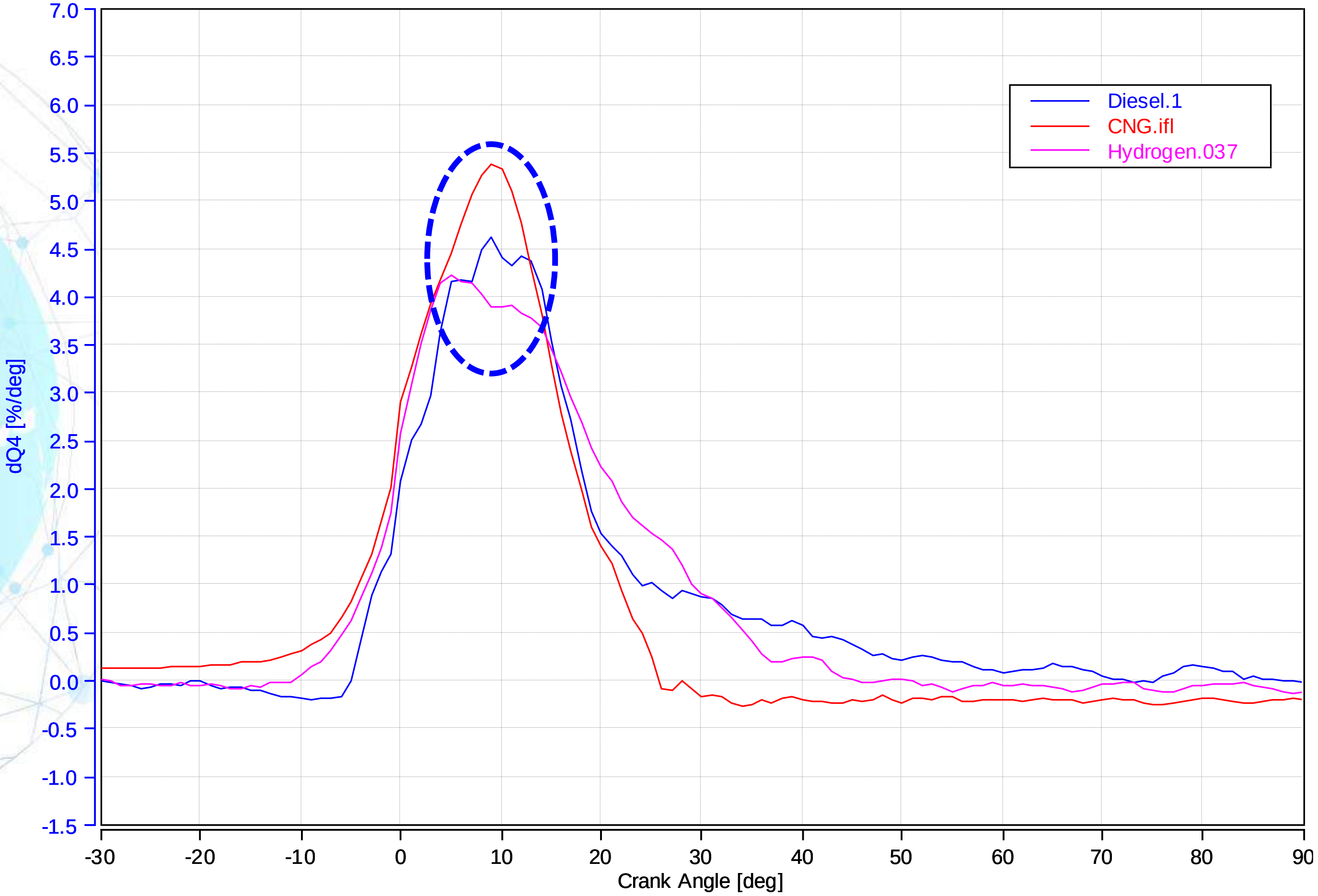


Active system to be designed for diluting H2 concentration in crankcase.

HYDROGEN COMBUSTION DEVELOPMENT EXPERIENCE

H2 ICE Development – Performance Comparison

Combustion Data Analysis- Diesel, CNG and H2

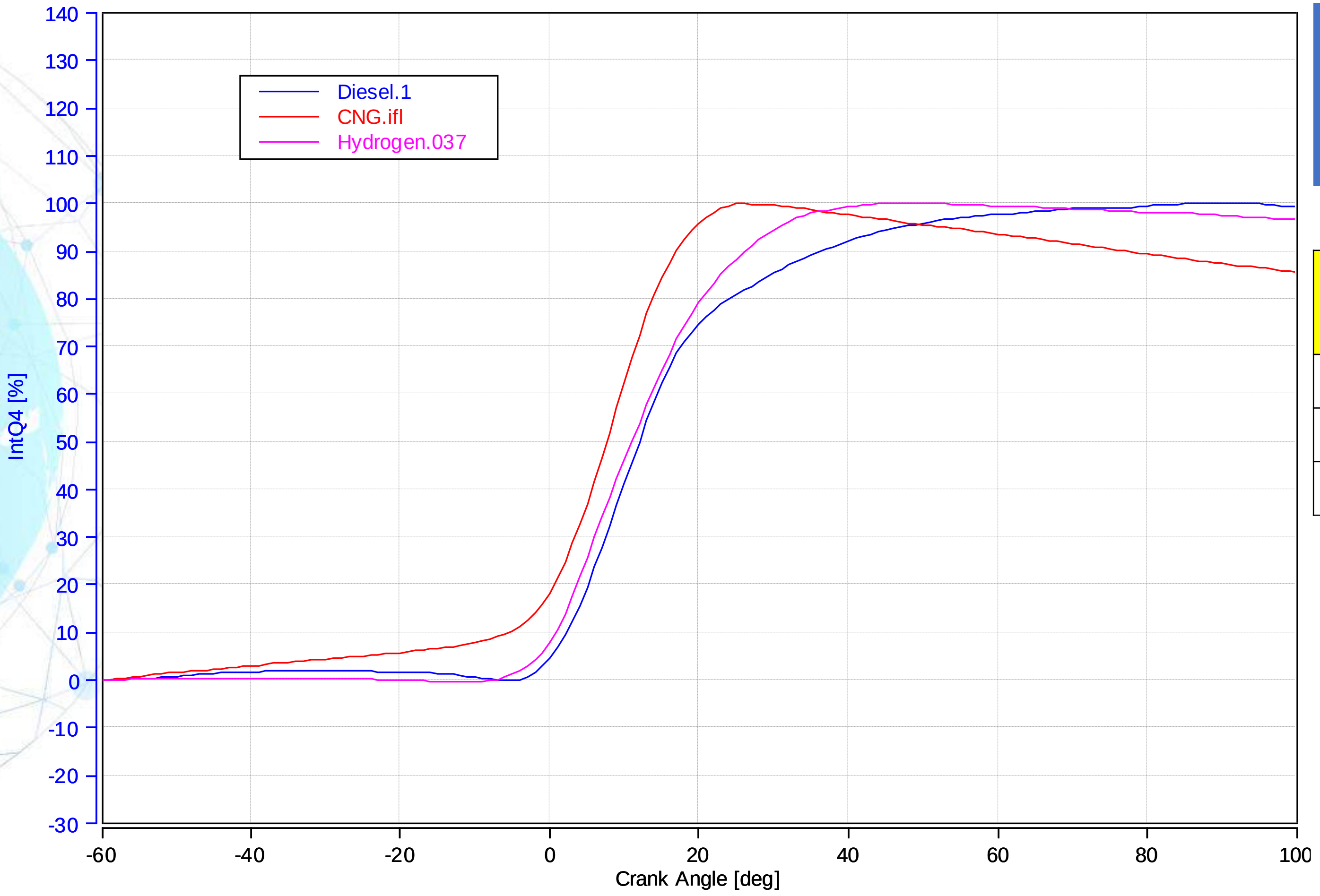


- Instantaneous peak HRR is higher with CNG compared to diesel and H2.
- Higher Lambda is reducing HRR in H2
- Lower HRR helps to reduce knocking

Water from exhaust and no soot (Our first experience of Zero CO2 exhaust!)

H2 ICE Development – Performance Comparison

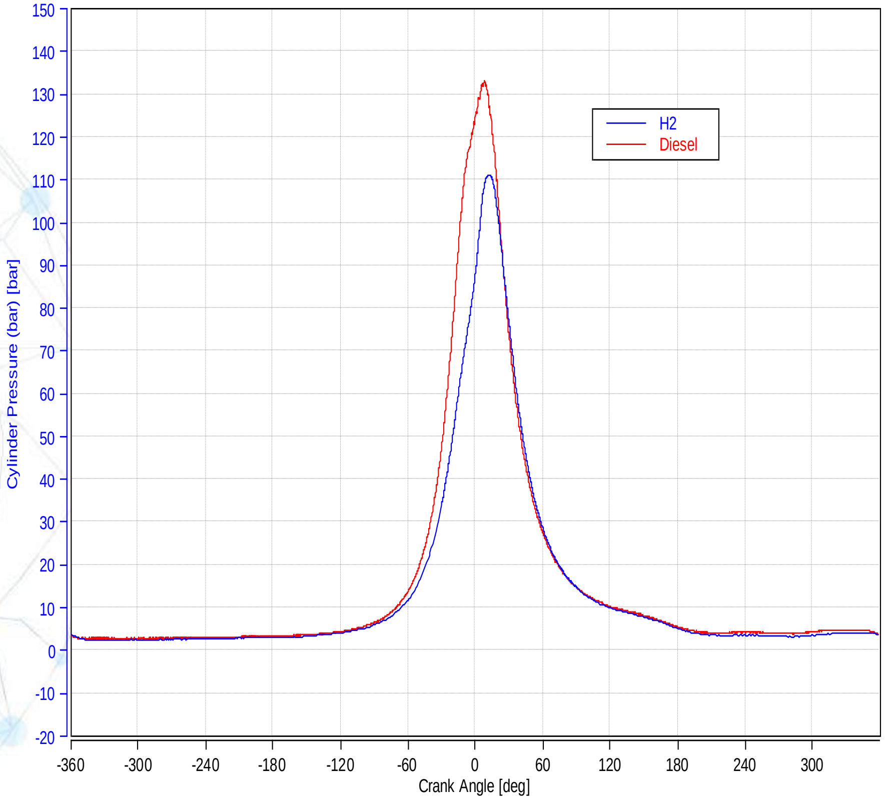
Combustion Data Analysis- Diesel, CNG and H2

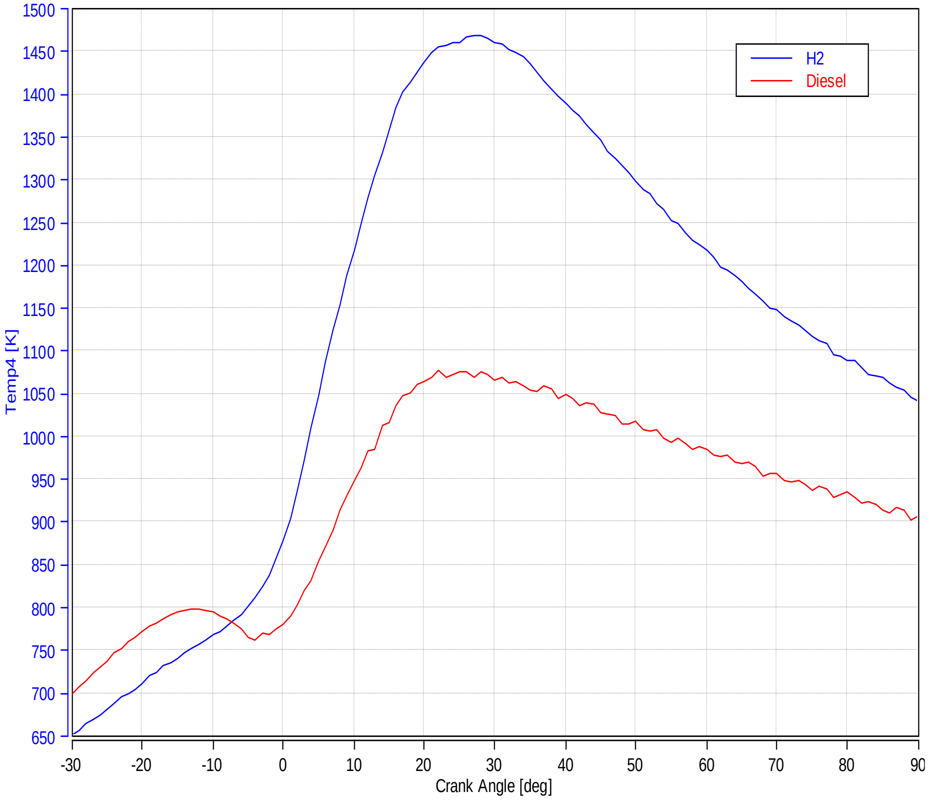


- ➢ Combustion completes faster in H2, due to higher laminar flame speed.
- ➢ Ensure complete combustion in side cylinder.

Mass Burnt Fraction (MBF), %	Diesel	CNG	H2
10	2	-5	1
50	12	8	11
90	37	17	26

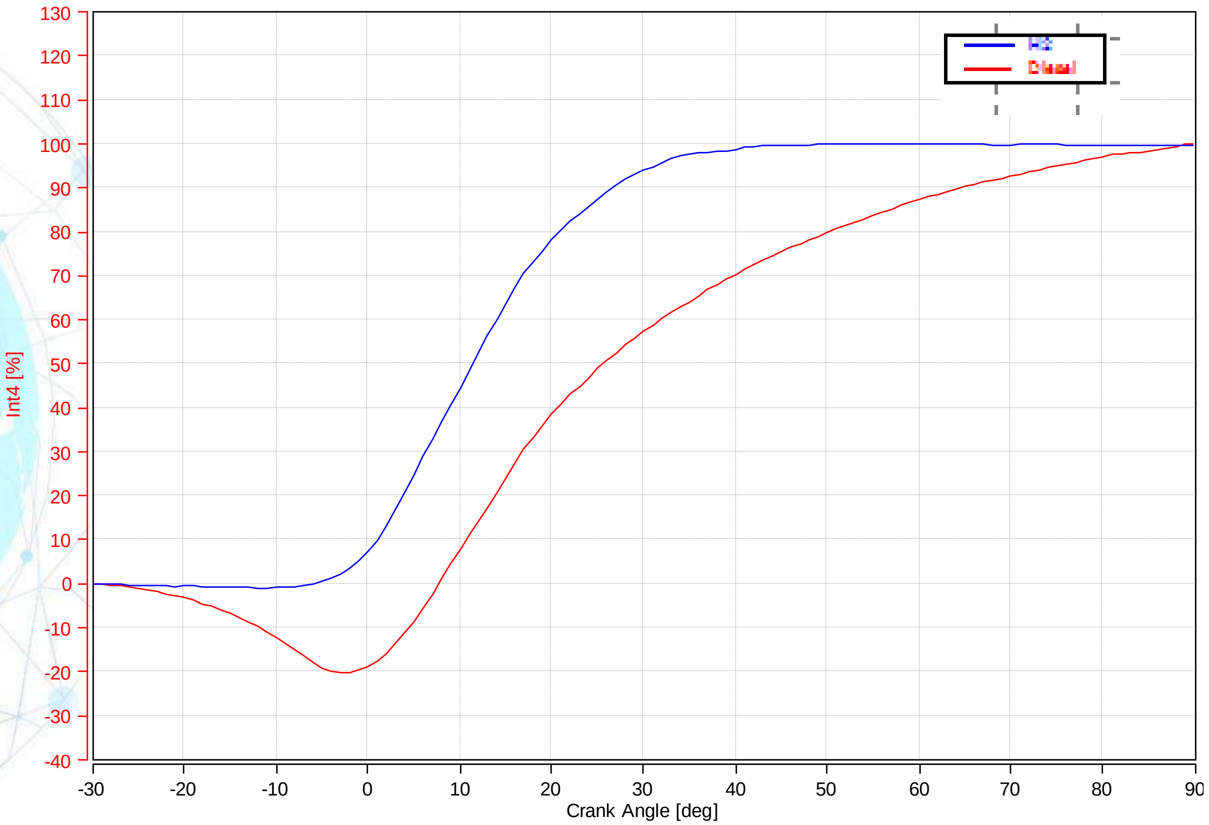
H2 ICE Development – Performance Comparison





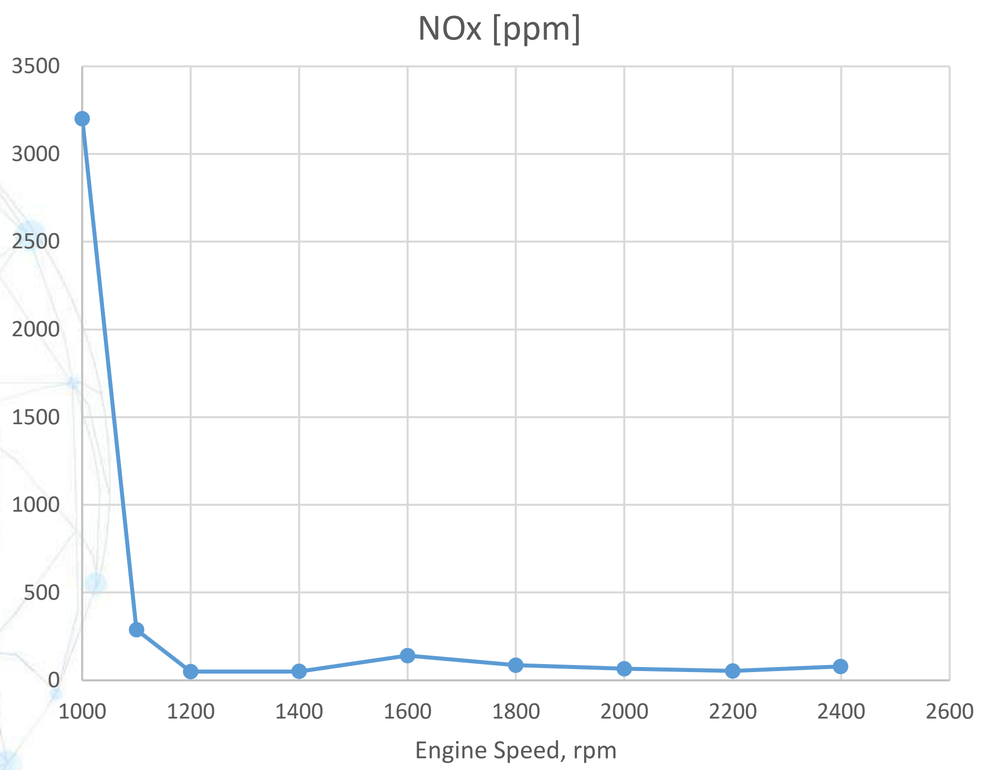
Inference: 1) Peak Pressure is low with H2 ICE compared to diesel
2) In cylinder combustion temp is higher with H2-ICE compared to diesel

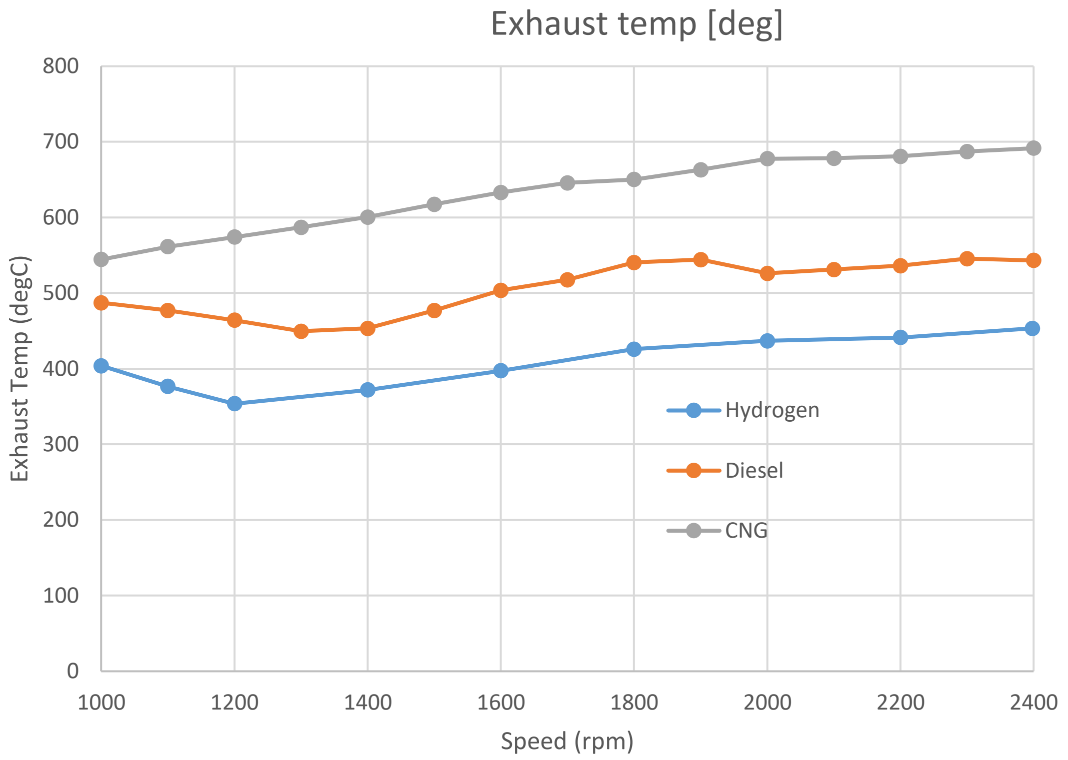
H2 ICE Development – Performance Comparison



Inference: 1) Fuel rate of burning is much faster with H2ICE compared to diesel.

H2 ICE Development – Performance Comparison





Inference:

1) NOx emission is very high at 1000rpm as engine is operated in rich condition (lambda =1.7) to get target torque
2) 2) Exhaust temp is lower by 100 to 250 deg C compared to Diesel and CNG respectively.

LEARNINGS FROM HYDROGEN DEVELOPMENT

H2-ICE

- While enormous progress in developing fuel cells, vehicle systems, and hydrogen storage and generation solutions has been made and continues, challenges remain – but engineers are confident they can be addressed this decade.
- The concept appeals both to diesel-engine manufacturers and some fleet/equipment operators as a near-term step while electrification issues are sorted out.
- Hydrogen ICEs have been a focus of various OEMs, notable Daimler (which offered a limited run of H_2 –fuelled passenger cars), Toyota, and Cummins engine, which is developing its own fuel cells but also sees great promise for hydrogen with its diesel engine platforms
- Veteran Combustion engineering researcher Dr. David Foster at the university of Wisconsin- Madison, notes “. Viewing it as a system Dr. Fo*aspects of hydrogen as a fuel that are really great – No Carbon. Flame speeds are high. You can go very very lean with hydrogen, which is good. NOx is reduced and you may be able to meet NOx emissions without after-treatment. Going very lean, with lots of boost, you can start to recover some, but all, of your max load limiter* admitted “ *The really high energy density that comes with each injection of liquid fuel into a cylinder is very difficult to replicate with hydrogen because you are injecting a gas*. “embrittlement “ *so there are some material issues to deal with. Not trying to belittle the hurdles, but I classify these as engineering challenges. In the end there is nothing that is a stopper for using hydrogen in an IC engine.”*
- *WE as an ICE community can sustain jobs who are in other fuels as on today with carbon less ,neutral etc*

- **Industries Involved in Hydrogen Technology**
- The USA, Germany, and Japan started using fuel cells to produce electricity and to heat homes and buildings. Hydrogen-fueled forklifts started replacing battery-powered forklifts in warehouses. Several countries also started experimenting with Hydrogen-fueled buses (Foton & Mercedes Benz). Major automobile manufacturers around the globe started developing technologies for Hydrogen driven cars (Toyota Mirai/ Hyundai Nexo, Honda Clarity etc.). Railway companies also started experimenting with Hydrogen-fueled locomotives (e.g. China South Rail Corporation/ Alstom). A few cities also started experimenting with trams running on Hydrogen. Even Boeing and Airbus are now studying the feasibility of Hydrogen-fueled passenger planes while a Hydrogen-powered supersonic private plane is also under development. Interestingly, Hydrogen and Electricity are generally considered as opposite sides of the same energy. While Electricity (derived from any source) can be readily used to produce Hydrogen via electrolysis, Hydrogen can only be consumed to produce pollution-free electricity via a fuel cell.

- **Advantages of Hydrogen**
- (1) it can be produced from and converted into electricity at relatively high efficiencies;
- (2) one of the materials to produce it is water (Interestingly water is again formed when Hydrogen is burned to generate electricity), and is available in abundance;
- (3) it is a completely renewable fuel;
- (4) it can be stored in gaseous form (convenient for large-scale storage), in liquid form (convenient for air and space transportation), or in the form of metal hydrides (convenient for surface vehicles and other relatively small-scale storage requirements);
- (5) it can be transported over large distances through pipelines and/ or via tankers;
- (6) it can be converted into other forms of energy in more ways and more efficiently than any other fuel (such as catalytic combustion, electrochemical conversion, and hydriding); and
- (7) it is environmentally friendly when produced from water using renewable energies since its production, storage, transportation, and end use do not produce any pollutants (except for small amounts of nitrogen oxides when it is burned with ambient air), greenhouse gases, or any other harmful effects on the environment.

Details of Hydrogen Types

Sl.	Type Of Hydrogen	Colour	Carbon Neutrality	Details
1	White	⚪	N/A	This Hydrogen Is The Naturally Occurring Hydrogen. N/A
2	Green	🟢	CARBON NEUTRAL	This Hydrogen Is Produced Through Water Electrolysis Process By Employing Renewable Electricity Other Than The Solar Energy. Renewable Electricity ---> Electrolysis (Electricity From Renewable Energy Source Except Solar) $H_2O \longrightarrow H_2 + 1/2\ O_2$
10	Yellow	🟡	CARBON NEUTRAL	This Hydrogen Is Produced Using Solar Power. It Is A New Term. Solar Electricity ---> Electrolysis (Electricity From Solar) $H_2O \longrightarrow H_2 + 1/2\ O_2$
4	Blue	🔵	CARBON NEUTRAL	It's Production Is Similar To Grey Hydrogen, However, The CO_2 Is Captured, Stored And Utilised (CCSU). Fossil Fuel ---> Reforming (CO_2 Is Capture & Stored) $CH_4 + 2H_2O \longrightarrow 4H_2 + CO_2$ (Captured)
5	Turquoise	●	CARBON NEUTRAL	This Hydrogen Can Be Extracted By Using The Thermal Splitting Of Methane Via Methane Pyrolysis. The Process, Though At The Experimental Stage, Remove The Carbon In A Solid Form Instead Of CO_2 Gas. Fossil Fuel ---> Pyrolysis $CH_4 \longrightarrow 2H_2 + C$ (Carbon Black)
6	Grey	●	✗	It Is Produced From Fossil Fuel Utilising Steam Methane Reforming (SMR) Method. During This Process, CO_2 Is Produced. Fossil Fuel ---> Reforming (CO_2 Released Into The Atmosphere) $CH_4 + 2H_2O \longrightarrow 4H_2 + CO_2$
7	Black/ Brown	⚫ 🟤	✗	It Is Produced By Gasification Of Coal & Depending Upon The Type Of Coal Used It Is Called Black (Bituminous Coal) Or Brown (Lignite Coal). It Is A Very Polluting Process, And CO_2 And CO Are Produced As By-Products. Fossil Fuel ---> Reforming (CO_2 Released Into The Atmosphere) $CH_4 + 2H_2O \longrightarrow 4H_2 + CO_2 + CO$
8	Purple	🟣	CARBON NEUTRAL	Purple Hydrogen Is Made Though Using Nuclear Power And Heat Through Combined Chemo Thermal Electrolysis Splitting Of Water. Nuclear Electricity & Heat ---> Electrolysis (Using Combined Chemo Thermal Electrolysis) $H_2O \longrightarrow H_2 + 1/2\ O_2$
9	Pink	●	CARBON NEUTRAL	This Hydrogen Is Generated Through Electrolysis Of Water By Using Electricity From A Nuclear Power Plant. Nuclear Electricity ---> Electrolysis (Electricity From Nuclear Plant) $H_2O \longrightarrow H_2 + 1/2\ O_2$
10	Red	🔴	CARBON NEUTRAL	This Is Produced Through The High Temperature Catalytic Splitting Of Water Using Nuclear Power Thermal As An Energy Source. Nuclear Electricity ---> High Temperature Catalytic Splitting Of Water $H_2O \longrightarrow H_2 + 1/2\ O_2$

Process	Type	Reaction	Desciption
Steam Methane Reforming (SMS)	✖	$CH_4 + H_2O \rightarrow CO + 3\,H_2$/ $CO + H_2O \rightarrow CO_2 + H_2$	H_2 Is Produced Form Natural Gas [Mostly Methane (CH_4)] & Currently The Cheapest Source Of Industrial H_2. Nearly 50% Of The World's H_2 Is Being Produced By This Method.
Methane Pyrolysis	CARBON NEUTRAL	$CH_4 \rightarrow C + 2\,H_2$	Here Also H_2 Is Produced From Natural Gas [Mostly Methane (CH_4)]. H_2 Separation Occurs In One Step Via Flow Through A Molten Metal Catalyst In A "Bubble Column". It Produces Low-Cost H_2 But Requires High Temperatures (1065 °C). It Also Produces The Industrial Quality Solid Carbon Which Is A Green Waste.
Partial Oxidation	✖	$C_xH_y + x/2\,O_2 \rightarrow x\,CO + y/2\,H_2$ [$C_{12}H_{24} + 6\,O_2 \rightarrow 12\,CO + 12\,H_2$ $C_{24}H_{12} + 12\,O_2 \rightarrow 24\,CO + 6\,H_2$]	In This Process H_2 Production Is Done From Heavy Hydrocarbons, Which Are Unsuitable For Above Two Processes. It First Generates H_2 And CO Rich Syngas & Then More H_2 And CO_2 Are Obtained Via The Water-Gas Shift Reaction.
Plasma Reforming	CARBON NEUTRAL	$C_xH_y \rightarrow xC + y/2\,H_2$	Also Knwon As "The Kværner Process (1980)" & Produces H_2 As Well As Carbon Black From The Liquid Hydrocarbons (C_xH_y). CO_2 Is Not Produced In The Process.
Coal/ Petroleum Coke	✖	$3\,C$ (Coal) $+ O_2 + H_2O \rightarrow H_2 + 3\,CO$ $CO + H_2O \rightarrow CO_2 + H_2$	The Process Of Coal Gasification Uses Coal, Steam And Oxygen To Form A Gaseous Mixture Of H_2 And Carbon Monoxide Which Again Is Made To React & Produce More H_2 Along With CO_2.
Electrolysis	CARBON NEUTRAL ✖	$2\,H_2O \rightarrow 2\,H_2 + O_2$	H_2 Is Produced By Splitting The Water Molecule (H_2O) Into Its Components H_2 And O_2 Using Electricity. When The Source Of Electricity Is Green, The H_2 Produced Is Referred As Green H_2. However, This Method Is Generally Expensive Than Fossil Fuel Based Production Methods.
Depleted Oil Wells	✖	N/A	Injecting Appropriate Microbes Into Depleted Oil Wells Allows Them To Extract H_2 From The Remaining, Unrecoverable Oil In The Wells.

- **Hydrogen In ICEVs As Directly Injected Fuel**
- Liquid Hydrogen as stated above, remained a preferred fuel for rocket engines.
- In recent years, the concern for cleaner air, along with stricter air pollution regulation and the desire to reduce the dependency on fossil fuels have reignited the interest in Hydrogen as a vehicular fuel.
- The properties that contribute to use of Hydrogen as a combustible fuel in ICEs are its wide range of flammability, low ignition energy, small quenching distance, as well as its high auto-ignition temperature, high flame speed at stoichiometric ratios, high diffusivity and very low density. Due to this wide flammability range hydrogen injected fuel-air mixture can be combusted in an ICE even when the fuel mixture is lean (i.e. it has lesser fuel than the theoretical, stoichiometric value). That's why it is fairly easy to start an ICE on Hydrogen and also it gives a better fuel economy due to better combustion reaction when a vehicle runs on such a lean mixture. Additionally, with the usage of Hydrogen, the final combustion temperature is generally lower, reducing the amount of pollutants, such as nitrogen oxides, emitted in the exhaust. However, there is a limit to how lean the ICE can be run, as lean operation significantly reduces the power output due to reduction in the volumetric heating value of the air/fuel mixture.
- Hydrogen in ICE brings down the ignition energy enabling these modified HICEs to ignite even the lean mixtures, ensuring prompt ignition. This low ignition energy Hydrogen mixed fuel , even with hot gases and hot spots on the cylinder can cause premature ignition and flashback. Preventing this premature ignition is one of the challenges associated with running an engine on Hydrogen. The wide flammability range of Hydrogen means that almost any mixture can be ignited by a hot spot.

- Hydrogen has a much smaller quenching distance than gasoline, which means Hydrogen flames will travel closer to the cylinder wall before they extinguish making it comparatively difficult to quench a Hydrogen flame than a gasoline flame within the engine. Such a smaller quenching distance can also increase the tendency for backfire since the flames from a Hydrogen-air mixture can more readily reach nearer to the closed intake valve, than a hydrocarbon-air flame. Yet with its relatively high auto-ignition temperature, the HICEs can be designed to have a much higher compression ratio than is being used for hydrocarbon ICEs.
- Apart from these, with the very high diffusivity rate, Hydrogen is somewhat advantageous when used in ICEs for two main reasons – firstly, it facilitates the **formation of a uniform mixture of fuel and air** & secondly, if a **Hydrogen leak develops, the Hydrogen disperses rapidly**.
- Thus, unsafe conditions can either be avoided or minimized. Not but least, Hydrogen has a very low density which results in two more problems when used in an ICE – firstly, very **large volume storage of Hydrogen is necessary for an adequate driving range** & secondly, due to the **lower energy density of a Hydrogen-air mixture, the power output of ICE is reduced**.
- Despite all these challenges, trials to run conventional ICEVs to run on Hydrogen fuel were never stopped. However, Hydrogen can also be used Hydrogen fueled ICE which has higher reliability and cost performance and requires less investment for mass production than fuel cell vehicles.
- Rotary engine (RE) better known as “Wankel Engines”, provide merits such as prevention of pre-ignition of Hydrogen combustion. Mazda has been developing Hydrogen vehicles driven by Hydrogen ICE since the early 1990s.

Safeties Issues In Handling Hydrogen

Hydrogen, molecule is the smallest molecule (120 pm i.e. 120*10^-12 m) and hence has the greatest tendency to escape through openings. This tendency is about 1.26~2.80 times faster than a natural gas leak through the holes or joints of low-pressure pipelines however, since Hydrogen has about 1/3rd the energy density, than natural gas, any Hydrogen leak would result in much less energy release than a natural gas leak. For very large leaks from high-pressure storage tanks, where the leak rate is limited by the sonic speed, Hydrogen would escape 3 times faster than natural gas (due to the higher sonic speed in Hydrogen which is ~1308 m/s compared to the sonic speed in natural gas which is ~450 m/s).

Another good property of Hydrogen is its buoyancy and rapid diffusiveness (compared to gasoline, propane, or natural gas) due to which in any untoward incident, of its leak for whatever reason, it will disperse much faster than any other gaseous fuel, thus reducing the hazard levels associated with Hydrogen.

Though the Hydrogen per is not corrosive, it can assist in the propagation of corrosion fatigue cracks and can also cause sulphide stress corrosion cracking in ferritic and martensitic steels, including the stainless grades. This is called Hydrogen embrittlement, also known as Hydrogen-assisted cracking or Hydrogen-induced cracking, is a reduction in the ductility of a metal due to absorbed Hydrogen since the Hydrogen atoms are small and can permeate solid metals. Thus Bulk Hydrogen storage also needs vessel made of specially treated high-strength steel as regular steel.

Hydrogen flames have low radiant heat because its combustion primarily produces heat and water. Due to the absence of carbon and the presence of heat-absorbing water vapor which is created when Hydrogen burns, a Hydrogen fire has significantly less radiant heat compared to a hydrocarbon fire. Since the flame emits low levels of heat near the flame (the flame itself is just as hot), the risk of secondary fires is lower. This fact has a significant impact on the public and rescue workers.

Like any flammable fuel, Hydrogen can combust. But Hydrogen’s buoyancy, diffusivity, and small molecular size make it difficult to contain and create a combustible situation. In order for a Hydrogen fire to occur, an adequate concentration of Hydrogen, the presence of an ignition source, and the right amount of oxidizer (like oxygen) must be present at the same time. Hydrogen has a wide flammability range (4~74% in air) and the energy required to ignite Hydrogen (0.02mJ) can be very low. However, at low concentrations (below 10%) the energy required to ignite Hydrogen is high – similar to the energy required to ignite natural gas and gasoline in their respective flammability ranges – making Hydrogen realistically more difficult to ignite near the lower flammability limit. On the other hand, if conditions exist where the Hydrogen concentration increased toward the stoichiometric (most easily ignited) mixture of 29% hydro-gen (in air), the ignition energy drops to about one-fifteenth of that required to ignite natural gas (or one tenth for gasoline).

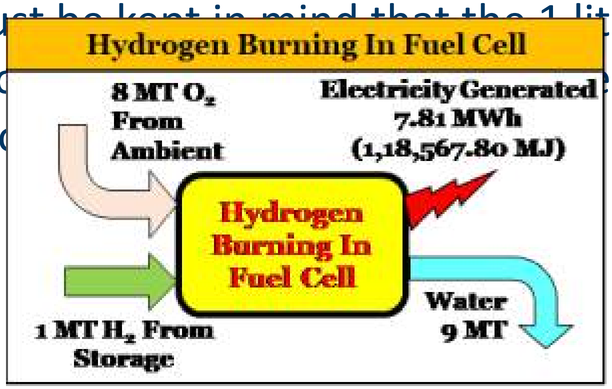
The good part of Hydrogen storage is that no explosion can occur in its tank at any contained location without an oxidizer (i.e. oxygen) which must be present with a certain level of concentration (at least 10% pure oxygen or 41% air). Hydro**gen can be explosive at concentrations of 18.3%~59%** and although the range is wide, it is important to remember that gasoline can present a more dangerous potential than Hydrogen since the potential for explosion occurs with gasoline at much lower concentrations, 1.1%~3.3%. Furthermore, there is very little likelihood that Hydrogen will explode in open air, due to its tendency to rise quickly. This is the opposite of what we find for heavier gases such as propane or gasoline fumes, which hover near the ground, creating a greater danger of explosion.

With the exception of oxygen, any gas can cause asphyxiation. In most scenarios, Hydrogen's buoyancy and diffusivity make Hydrogen unlikely to be confined where asphyxiation might occur. Hydrogen is non-toxic and non-poisonous. It will not contaminate groundwater (it's a gas under normal atmospheric conditions), nor will a release of Hydrogen contribute to atmospheric pollution. Hydrogen does not create "fumes."

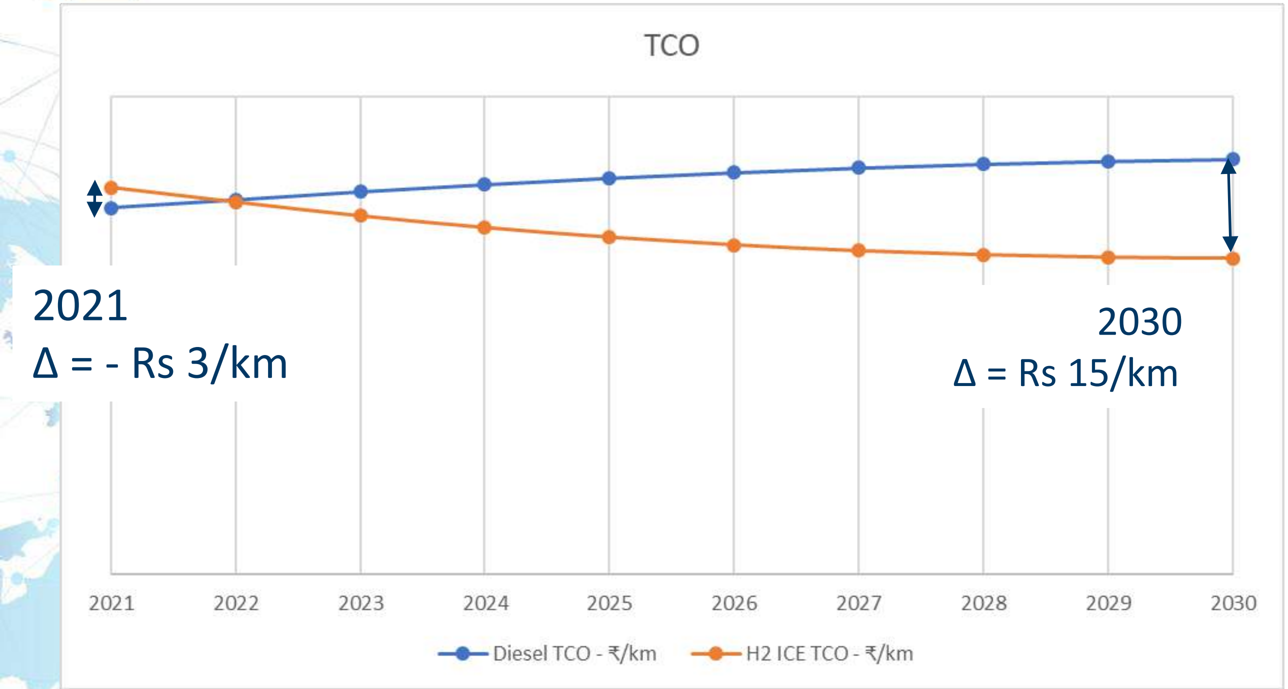
Hydrogen has a flame velocity which is seven times faster than that of natural gas or gasoline but the detonation of Hydrogen in the open atmosphere is highly unlikely, because of its higher stoichiometric ratio of 29.53% against a value of 2% for Gasoline vapors & 9.46% Natural Gas). In order to explode, Hydrogen would first have to get accumulated to reach a minimum of 13% concentration level in a closed space and only then an ignition source, if triggered, can cause an explosion. Should an explosion occur, Hydrogen has the lowest explosive energy per unit stored volume, and a given volume of Hydrogen would have 22 times less explosive energy than the same volume filled with gasoline vapor.

Hydrogen by electrolysis process requires a large amount of electricity yet on reverse side, the burning of Hydrogen gas (in fuel cell) also releases an similar amount of energy as shown below.

The energy in 1 kilogram of Hydrogen gas is about the same as the energy in 2.91 kilograms of gasoline (Considering the Avg Calorific values of Hydrogen as 142.50 MJ/kg vs. 49 MJ/kg of Gasoline), which is about 3 times more, however since the Hydrogen has a low volumetric energy density, it needs to be stored onboard a vehicle as a compressed gas to achieve the driving range of vehicles. However, considering the cost comparison it mu ter of Petrol contains about 30 MJ of energy which at present rate costs abo ergy approximately 126.50 (=30,000,000/237,160) moles of Hydro



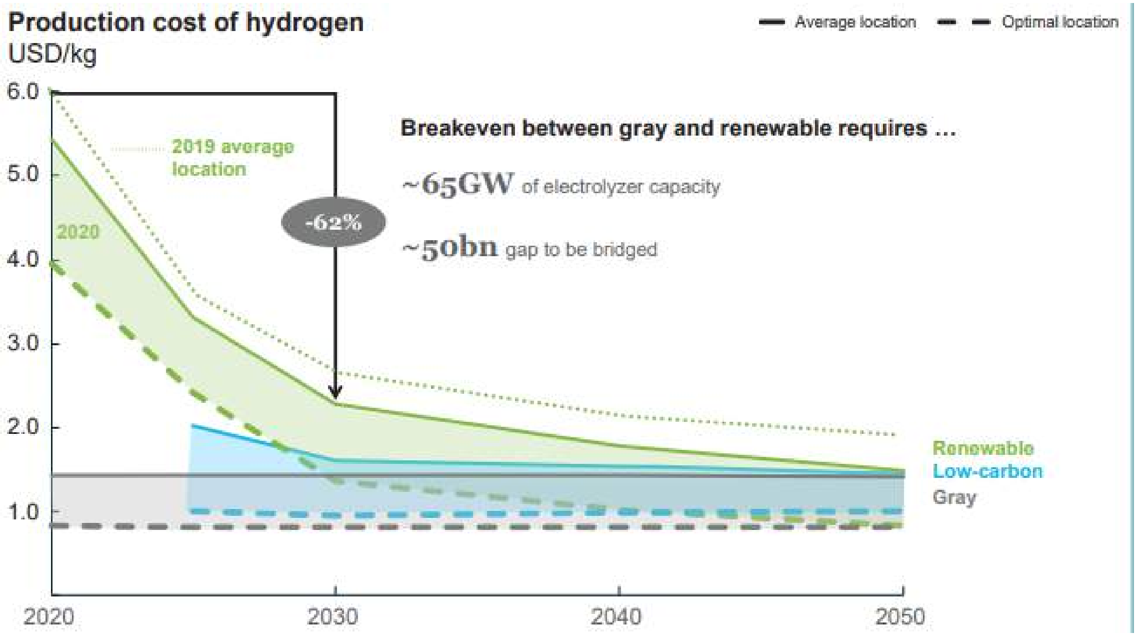
Total Cost of Ownership – Diesel vs H2 ICE



2021
Δ = - Rs 3/km

2030
Δ = Rs 15/km

Reference: AL Internal Report on TCO (Haulage application)



Breakeven between gray and renewable requires ...

~65GW of electrolyzer capacity

~50bn gap to be bridged

Reference; Hydrogen Insights: A perspective on hydrogen investment, market development and cost competitiveness, February 2021, Hydrogen Council & McKinsey

The TCO scenario is dependent on the cost of green H2 which is $5/kg currently and is expected to reduce to $1/kg by 2030 due to multiple reasons viz; declining cost of renewable electricity, electrolysers getting better and cheaper and increase in production capacity (current hydrogen demand of 90m MT to grow to 130m MT by 2030).

Hydrogen National Green Mission – 2023 (Mission Components)

DEMAND CREATION

Export Markets
Capturing Global Demand

Substituting imports
Fossil Fuels and Fertilizers

Domestic demand
Multiple Sectors

INCENTIVISING SUPPLY

Strategic Interventions for GH2 Transition

Direct Financial Incentives for:
- Electrolyzer Manufacturing
- Green Hydrogen Production

KEY ENABLERS

Resources
Finance, renewable energy - banking & storage, transmission, land, water

R&D
Result oriented, time-bound, including through PPP, grand challenges

Ease of doing business
Simpler procedures, taxation, SEZ, commercial issues

Infrastructure & Supply Chain
Ports, Re-fueling, Hydrogen Hubs, pipelines

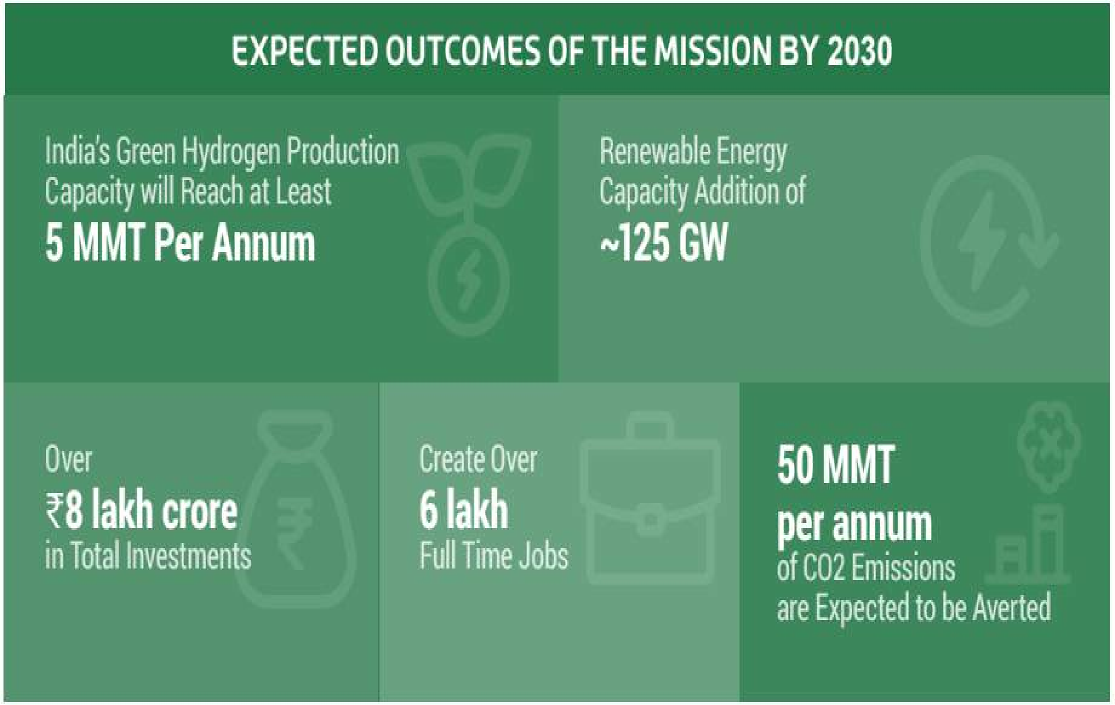
Regulations & Standards
Testing facilities, standards, regulations, safety & certification

Skill Development, Public awareness
Coordinated Skilling programme, online portal

INCENTIVES PROPOSED UNDER SIGHT

Support for Domestic Manufacturing of Electrolysers

Incentives on Production of Green Hydrogen



EXPECTED OUTCOMES OF THE MISSION BY 2030

India's Green Hydrogen Production Capacity will Reach at Least
5 MMT Per Annum

Renewable Energy Capacity Addition of
~125 GW

Over
₹8 lakh crore
in Total Investments

Create Over
6 lakh
Full Time Jobs

50 MMT per annum
of CO2 Emissions are Expected to be Averted

Hydrogen National Green Mission – 2023 (Risk Management)

Type of Risk	Risk categorisation	Risk Management/Mitigation Measures
Strategic Risks	Supply Chain Disruptions in Critical Inputs	Diversification in Supply Chains
Technological Risk	Technology Disruptions and Unforeseen Developments	Diversification of technology options, Technology agnostic approach in funding support. Funding of multiple R&D and pilot threads, Collaborative platforms for industry, academia and startups
Operational/Project Level Risks	Water Availability	Optimizing location of Renewable Energy and Green Hydrogen production plants
	Land Availability	States to be requested to create land banks for Renewable Energy and Green Hydrogen deployment
	Safety Concerns	Rigorous safety standards and regulatory mechanisms
Financial and Market Risks	Sustainable Demand	Demand creation efforts in identified sectors
	Availability of Affordable Renewable Energy (RE)	Integrated planning of RE capacity addition
	Availability of Electrolysers and other key components	Incentives to create domestic manufacturing ecosystem
	Additional infrastructure costs and capital expenditure	Ramp up of capacities to achieve economies of scale
	Availability of accessible Credit	Risk sharing framework in procurement, Facilitating projects to access FDI, bond markets, MFAs