5th World Future Fuel Summit 2023

Energy Transition with Hydrogen for Sustainable Mobility

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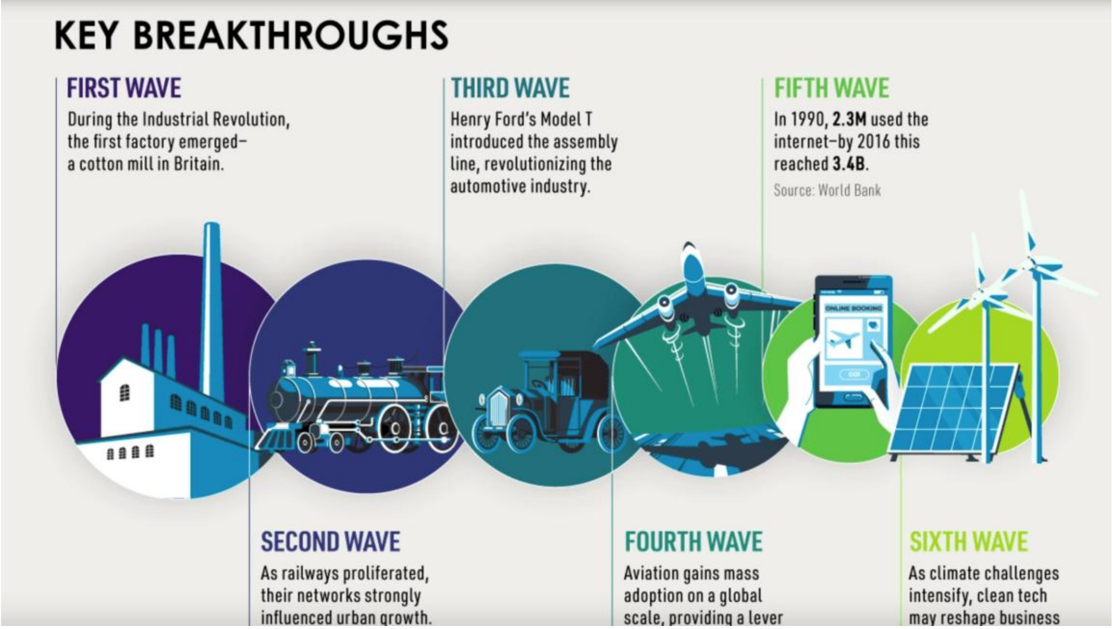
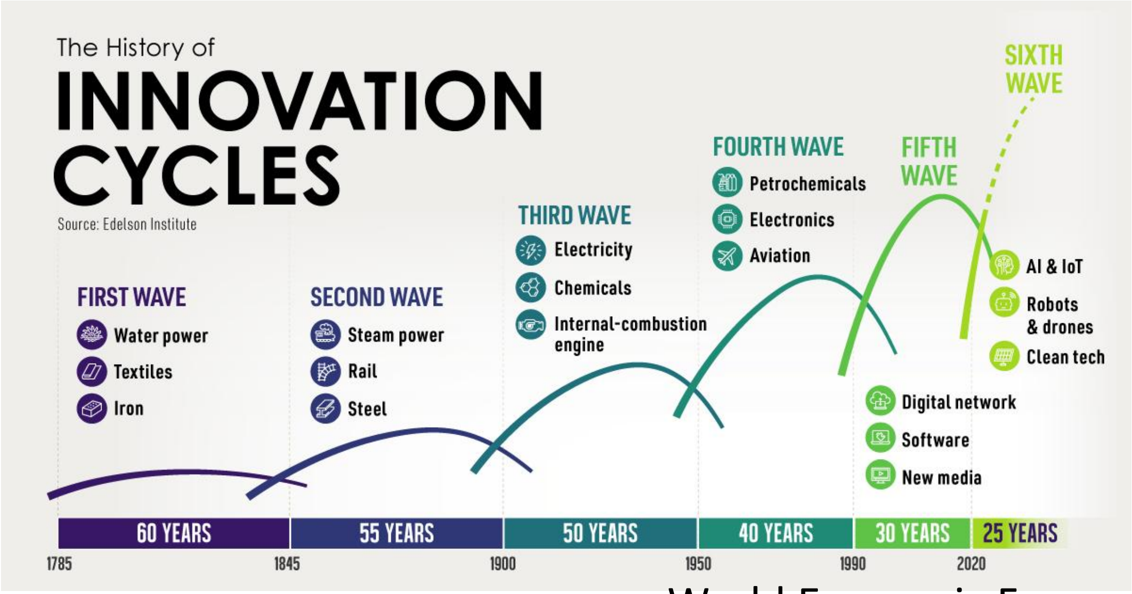
October 16, 2023

Long Waves of Innovation





World Economic Forum

Nikolaus Otto

(He built first four-stroke internal combustion engine in 1876)

Rudolf Diesel

(He patented diesel engine in 1895)

Sir William Robert Grove

(He invented the first fuel cell in 1839)

Renewable Energy and Hydrogen play a critical role to decarbonize Transportation Sectors

Energy Independence

Our honorable Prime Minister speech during the Independence Day 2022:

- To make India *aatmanirbhar* (self-reliant) in the energy sector is one of the key elements of the country's sustainable growth agenda.

- India's journey towards energy independence and its decarbonisation drive for significant economic opportunity.

- The decarbonisation is imperative in order to:
  - achieve climate action goals,
  - substantially reduce the import bill,
  - freeing up resources for other sectors.

Renewable Energy and Hydrogen enhance energy security and achieve climate action goals

Net Zero Emissions

- Net zero means cutting emissions as close to zero as possible, such as moving to green economy, clean and green energy

- Any remaining emissions must be reabsorbed including by healthy oceans and forests

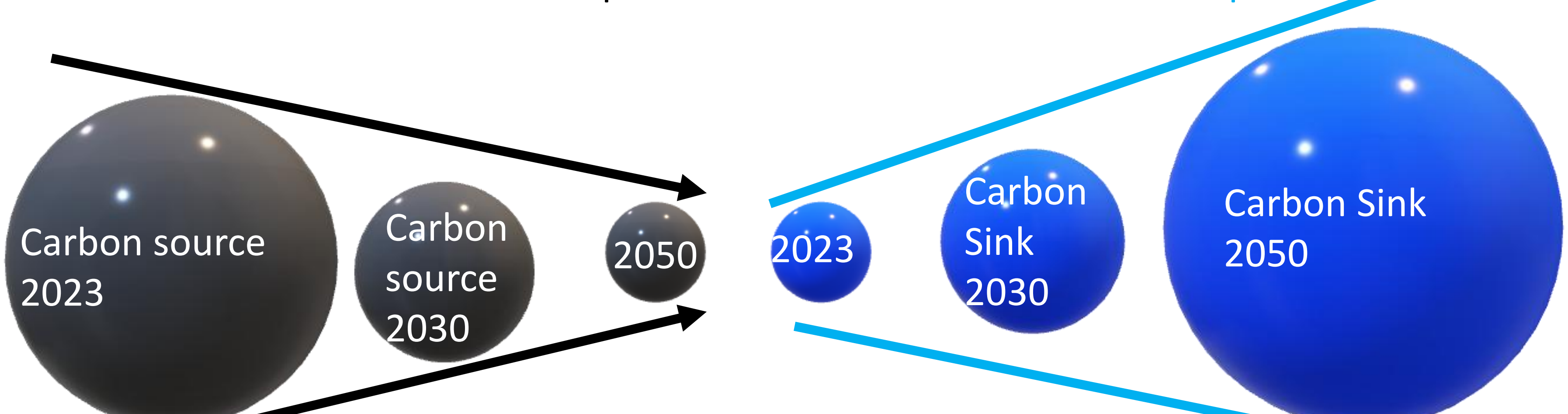
- Shifting to a green economy could yield a direct economic gain of $26 trillion by 2030 compared with business-as-usual. This could produce over 65 million new low-carbon jobs.

United Nations

Net Zero Emissions

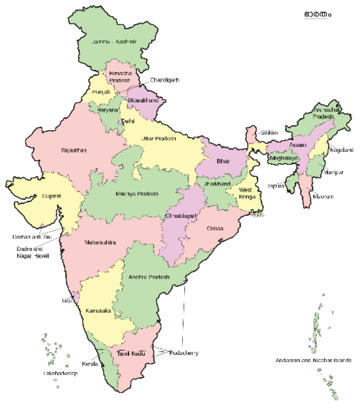
Net zero will happen when the amount of carbon added to the atmosphere lower than the amount removed.

Carbon Addition to atmosphere < Carbon Removal from atmosphere



Biohydrogen is a carbon neutral fuel; Biohydrogen with CCUS contribute to negative

Primary Energy : Total Proved Reserve at End of 2019

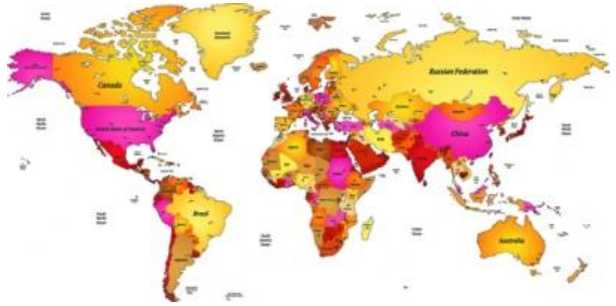


Import of Oil and gas

Import of LPG - 60% of consumption

Import of Crude-87% of consumption

Import of LNG - 47-50% of consumption



	India		World	
	Reserve (MT/TCM)	R/P	Reserve (MT/TCM)	R/P
Crude oil	600	15.5	244600	49.9
Coal	105931	140	1069636	132
Natural Gas	1.3 Trillion SCM	49.4	198.8 Trillion SCM	49.8

Year Oil demand (million bpd) MMTPA

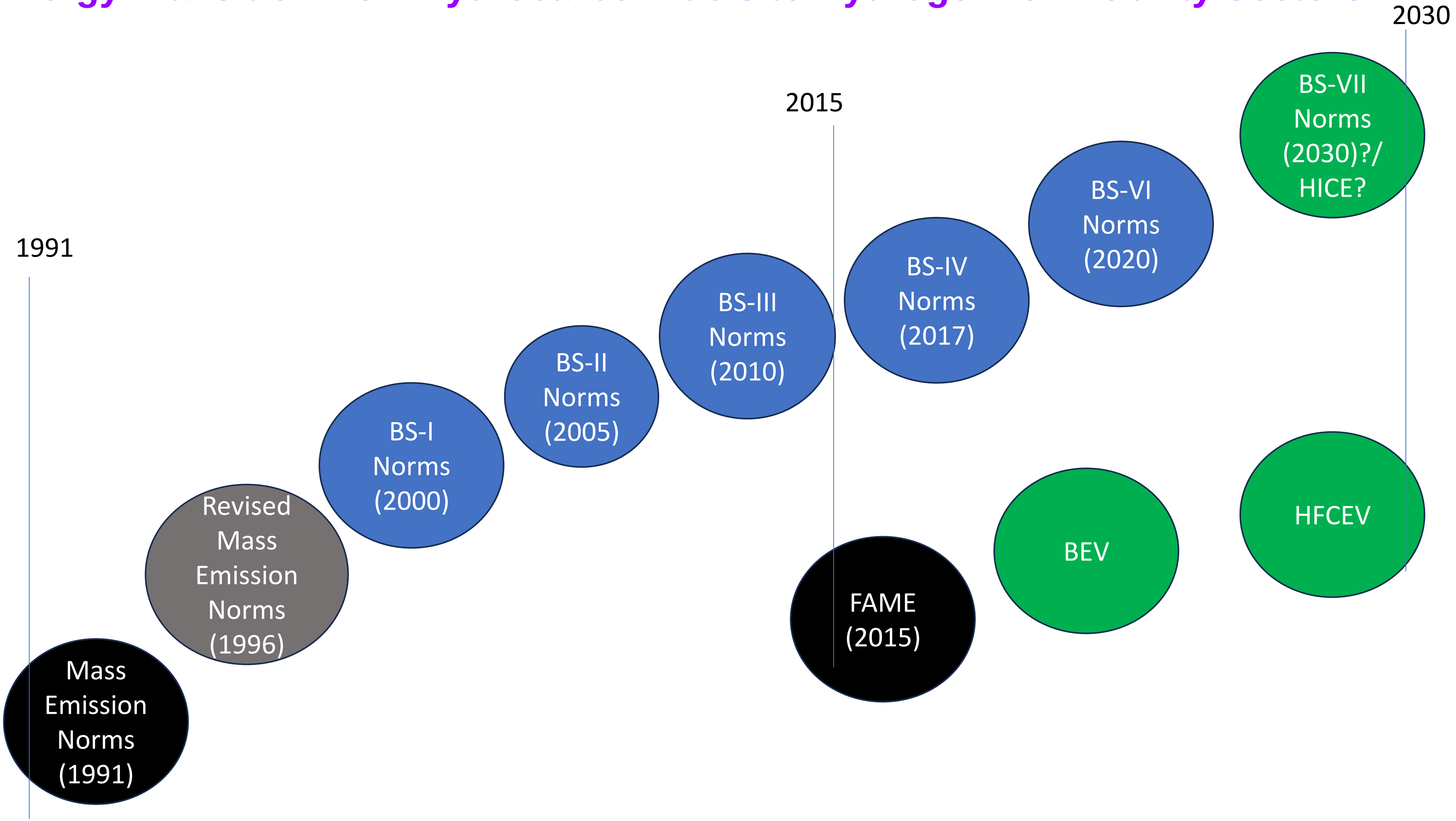
2019 = 4.8 239.04

2022 = 5 249

MT : Million Tonnes
TCM : Trillion Cubic Meter
R/P : Reserve to Production Ratio

Source: International Energy Agency (IEA), World Energy Outlook 2021, BP Statistical Review of World Energy 2020,

Energy Transition from hydrocarbon fuels to Hydrogen for Mobility Sectors



Sustainable Development Goals-7 for Energy

- Affordable
- Reliable
- Sustainable
- Modern

Fossil Fuels

- Energy Security X
- Environment X
- Energy Efficiency
- Energy Economics X
- Energy Equity X

Green Hydrogen

- Energy Security √
- Environment √
- Energy Efficiency √
- Energy Economics √
- Energy Equity √

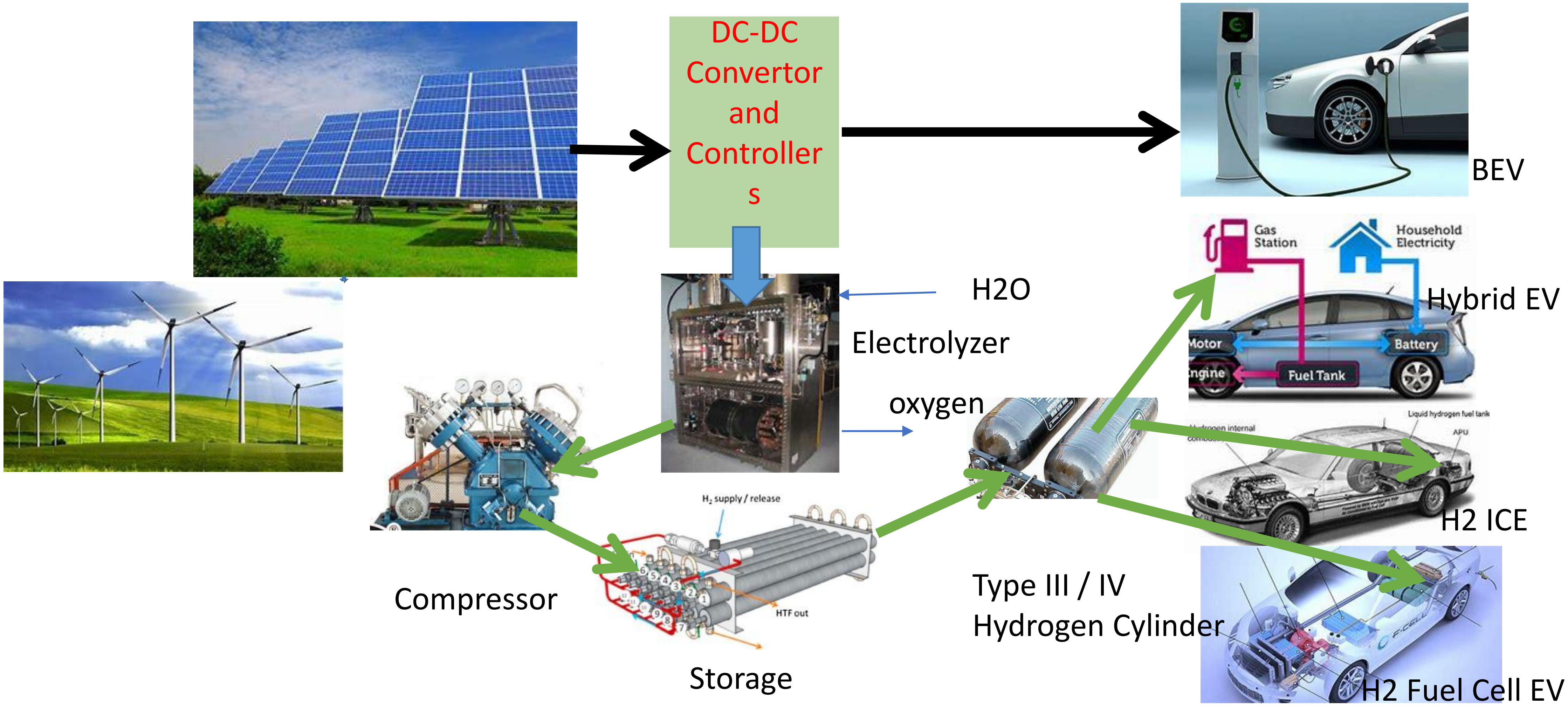
Battery Electric Vehicles

- BEVs are vital for enabling fast decarbonization of transport

Hydrogen Internal Combustion Engine / Fuel Cell Electric Vehicles

- Regions with constrained renewables or grid capacity in the mid to long term
- Vehicle segments with high power and energy demands
- Long-range capability
- Fast refuelling

Electricity / Hydrogen Use in Automotive Vehicles



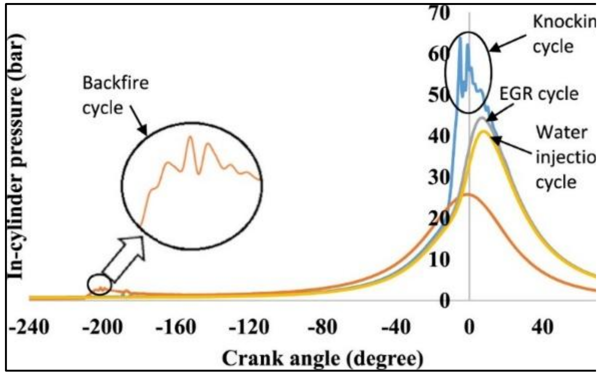
Hydrogen Internal Combustion Engine Vehicle

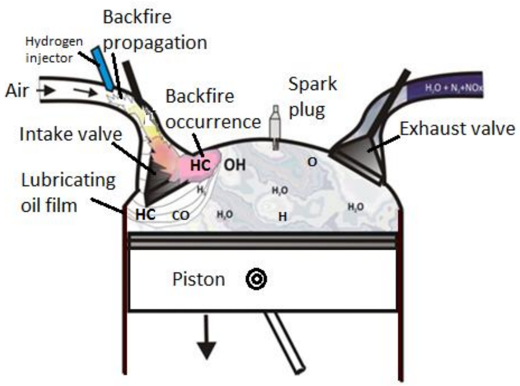
or

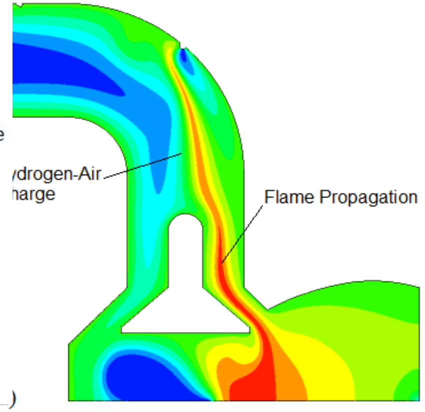
Hydrogen Fuel Cell Electric Vehicles

Major Technical Issues of Hydrogen Fueled Spark Ignition Engines

- ❖ Backfire







- ❖ High NOx emission

Chemical Kinetics of H_2–O_2 Reaction Mechanism

$H_2 + OH \rightarrow H_2O + H$

$H + O_2 \rightarrow OH + O$

$O + H_2 \rightarrow OH + H$

- ❖ Power drop

CV for Gasoline:		CV of Hydrogen
Mass basis :	44 MJ/kg	120 MJ/kg
Volumetric basis :	34.3 MJ/m^3	9.6 MJ/m^3

Suggested Technologies for Development of Hydrogen Fueled Spark Ignition Engines

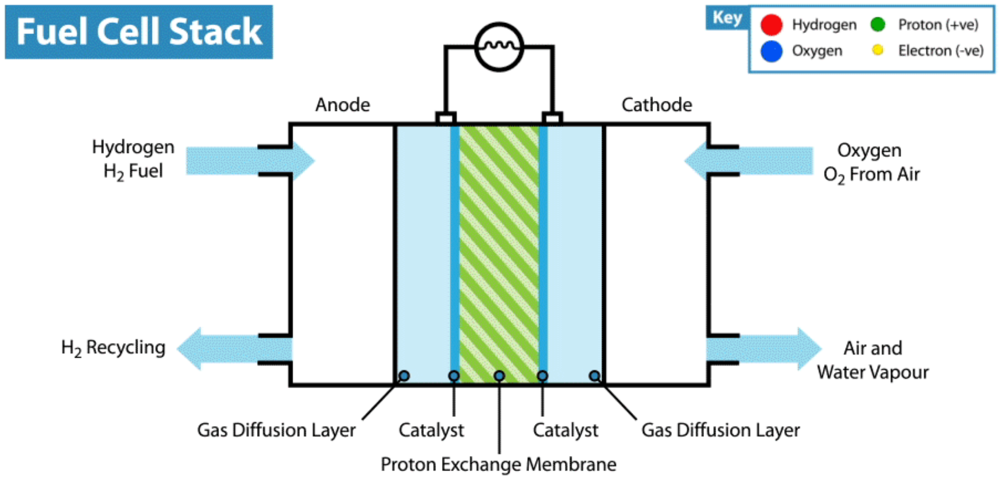
- Three major issues are now resolved :
  - ✓ Backfire – TMHI / DHI + IT_{H2} + ST + EGR / WI / LB
  - ✓ High NOx emission - IT_{H2} + ST + EGR / WI / LB / SCR
  - ✓ Power drop - SC/TC

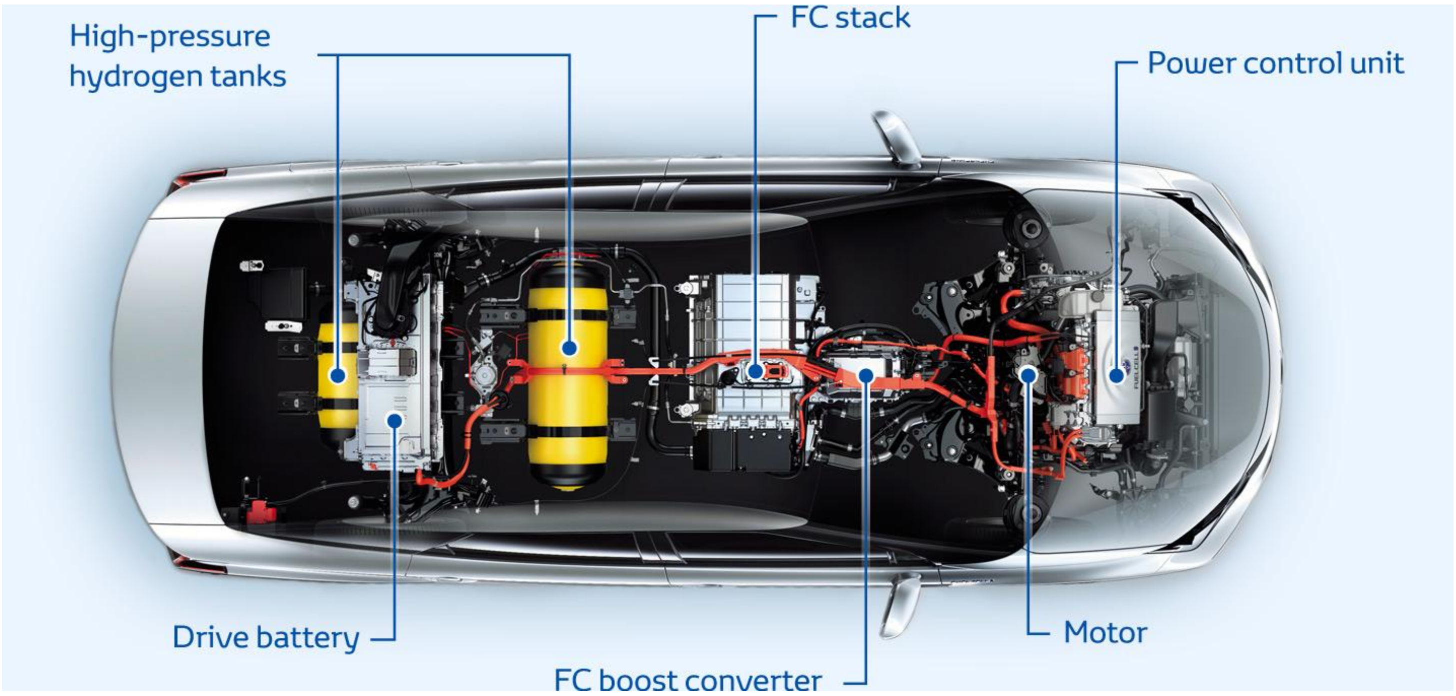
Combinations of technology are suggested to address the above technical issues:

TMHI / DHI + IT_{H2} + ST + EGR / WI / LB / SCR + SC/TC

TMHI	–	Timed Manifold Hydrogen injection using ECU for hydrogen flow rate control
DHI	-	Direct Hydrogen Injection
IT	–	Hydrogen Injection Timing
ST	–	Spark Timing optimization
EGR	–	Exhaust Gas Recirculation
WI	–	Water Injection (Demineralized water)
LB	–	Lean Burn
SCR	–	Selective Catalytic Reduction
SC	–	Supercharging
TC	–	Turbocharging

Fuel Cell Electric Vehicle





Main Materials for Fuel Cells :

- Electrodes: Graphite, Graphene, Titanium
- Membrane : Polymer Electrolyte Membrane
- Catalyst : Platinum
- Bipolar Plate : Graphite
- Current collector : Copper
- End plate : Aluminum

Fuel cell efficiency with respect to power

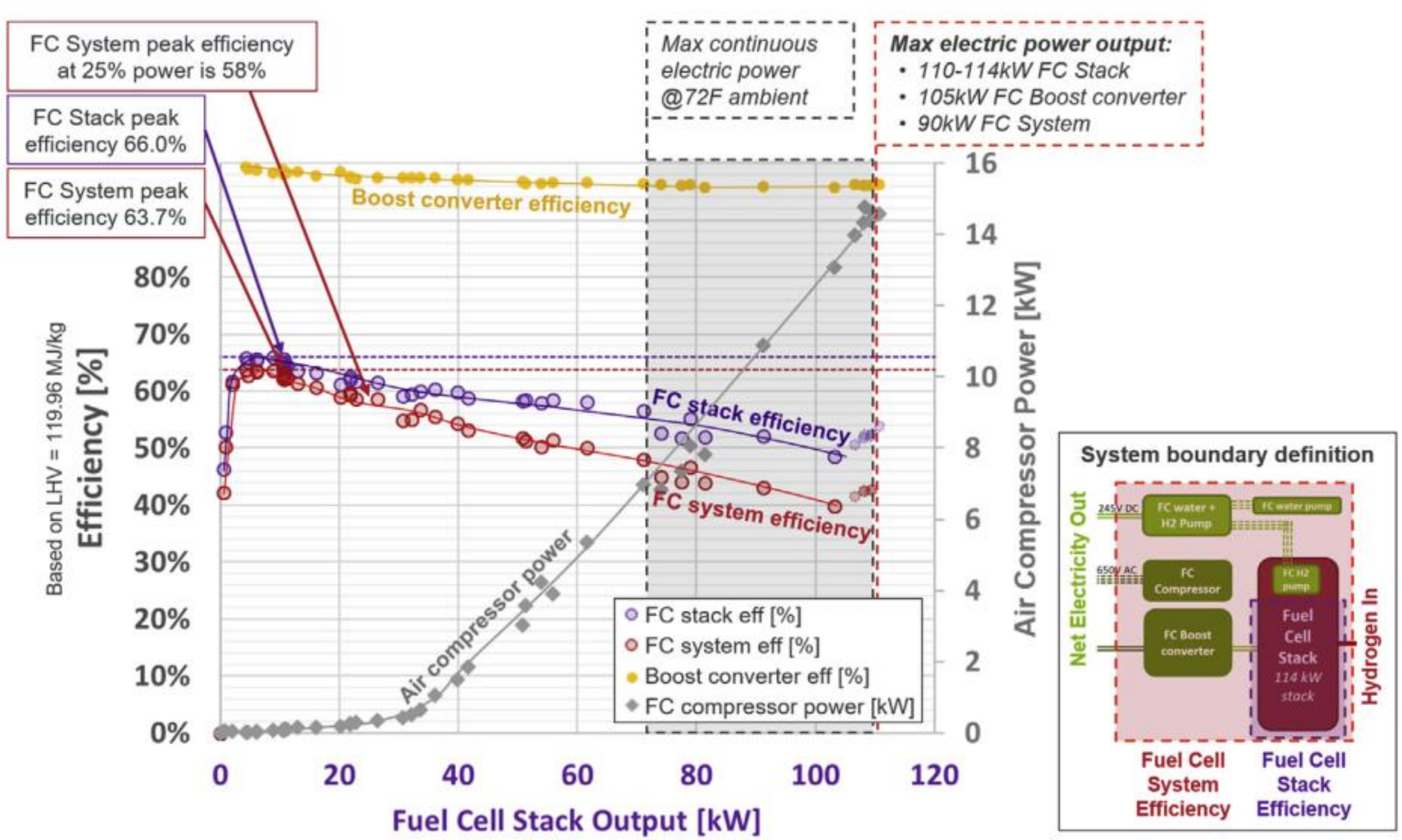


Figure: Fuel cell stack and fuel cell system efficiency as a function of electric power output of the stack

Ref: Lohse-Busch, H., Stutenberg, K., Duoba, M., Liu, X., Elgowainy, A., Wang, M., Wallner, T., Richard, B. and Christenson, M., 2020. Automotive fuel cell stack and system efficiency and fuel consumption based on vehicle testing on a chassis dynamometer at minus 18 C to positive 35 C temperatures. International Journal of Hydrogen Energy, 45(1), pp.861-872.

Technical Targets: 80-kWe (net) Integrated Transportation Fuel Cell Power Systems Operating on Direct Hydrogen

Characteristic	Units	2015 Status	2020 Targets	Ultimate Targets
Peak energy efficiency	%	60	65	70
Power density	W/ L	640	650	850
Specific power	W / kg	659	650	650
Cost	$ / kW_{net}	53	40	30
Cold start-up time to 50% of rated power @—20 ^{o}C ambient temperature	seconds	20	30	30
from +20 ^{o}C ambient temperature	seconds	<10	5	5
Start-up and shutdown energy from -20 ^{o} C ambient temperature	MJ	7.5	5	5
from +20 ^{o}C ambient temperature	MJ		1	1
Durability in automotive drive cycle	hours	3,900	5,000	8,000
Start-up/shutdown durability	cycles		5,000	5,000
Assisted start from low temperature	^{o}C		-40	-40
Unassisted start from low temperature	^{o}C	-30	-30	-30

Ref: https://www.energy.gov/eere/fuelcells/doe-technical-targets-polymer-electrolyte-membrane-fuel-cell-components

Hydrogen fuelled Fuel cell Cars

Specifications	Toyota Mirai [Japan]	Hyundai Nexo [South Korea]	Honda Clarity [Japan]
Stack power	128 kW	95 kW	130 kW
Battery	1.24 kWh	1.56 kWh	1.7 kWh
Motor Peak Power	124 kW (152 hp)	120 kW (161 hp)	130 (174 hp)
Torque	300 Nm	395 Nm	300 Nm
Top Speed	108 mph (174 km/h)	111 mph (179 km/h)	103 mph (166 km/h)
Payload Capacity	4 passengers	5 passengers	5 passengers
Range	647 km	612 km	589 km
Hydrogen tank	5.6 kg (700 bar)	6.33 kg	5.46 kg (700 bar)
Fuel efficiency	0.76 kg/100 km	0.95 kg/100 km	0.95 kg/100 km
Cost	$50,000 to $60,000	$60,000 to $70,000	$58490

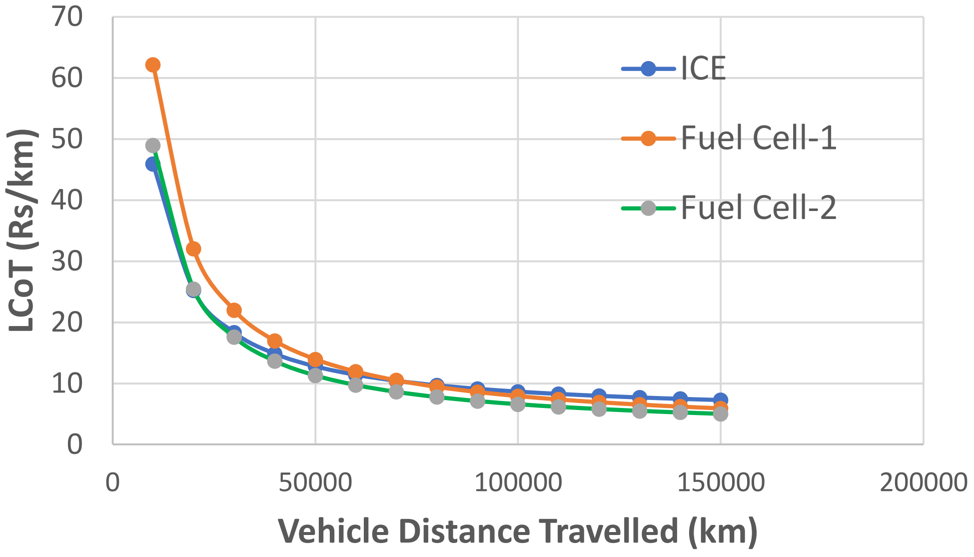
Ref: https://media.toyota.co.uk/wp-content/uploads/sites/5/pdf/210426M-NG-Mirai-Tech-Spec.pdf,
, https://www.hyundaiusa.com/us/en/vehicles/nexo/compare-specs, https://www.hondainfocenter.com/2021/Clarity-Fuel-Cell/Feature-Guide/Specifications/

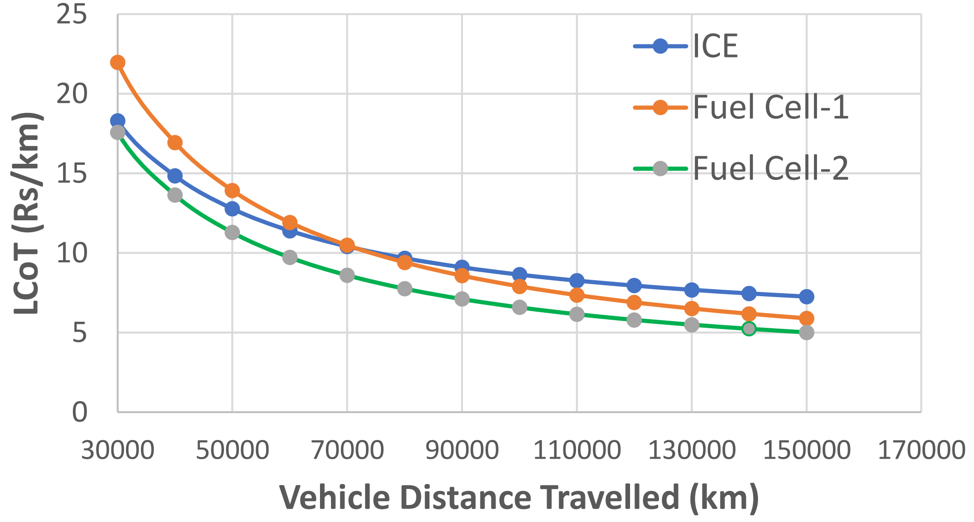
Comparison of ICE and Fuel cell vehicle

Specifications	Ford P2000 2.0l (ICE)	Honda FCX Clarity (Fuel cell)
Rated Power	110 kW	100 kW
Rated Torque	-	395 Nm
Range	96 km	451 km
Fuel efficiency	227.3 km/kg	434.8 km/kg
Life of vehicle	15 years	10 years
Fueling time	5 minutes	5 minutes
Hydrogen storage	1.5 kg H_2 at 248 bar	4.1 kg H_2 at 345 bar
Fuel quality	99.95%	99.9999%
Cost	-	$60,000 to $70,000
NOx (g/km)	0.46	0

Ref: F-S B, J-M T. An environmental analysis of FCEV and H2-ICE vehicles using the Ecoscore methodology. World Electric Vehicle Journal. 2009 Sep;3(3):635-46.

Levelized Cost of Transportation with Hydrogen Fuel Cell and Hydrogen Internal Combustion Engines





Data taken / assumption:
Vehicle Capital Cost :
Rs 10 Lakhs (ICE) - 1 X
Rs 20 Lakhs (FC-1) - 2 X
Rs 15 Lakhs (FC-2) - 1.5 X

Maintenance cost :
1% of CC per year (ICE)
0.5% pf CC per year (FC-1 and 2)

Fuel Economy: 55 km/kg (ICE); 132 km/kg (FC)
Cost of Hydrogen : 250 Rs/kg
Life of Vehicle : 15 years

The cost of Hydrogen Fuel Cell cost shall be at least 1.5 times less than hydrogen internal combustion engines

Challenges in Hydrogen Fuel Cell Electric Vehicles

- **High Cost**
- **Needs High Fuel Quality and Air Quality**
- **Durability**

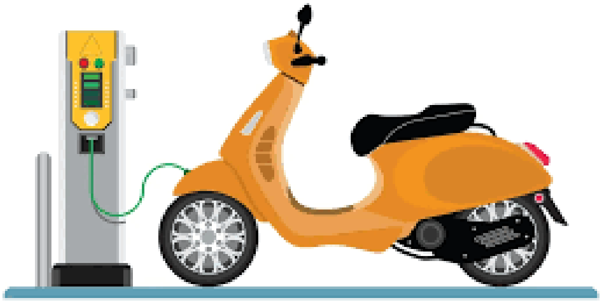
Cost reduction by alternative Materials

- Electrodes: Graphite, Graphene, Titanium, ..?
- Membrane : Polymer Electrolyte Membrane, ..?
- Catalyst : Platinum, …?
- Bipolar Plate : Graphite
- Current collector : Copper
- End plate : Aluminum

A Scenario for Projection of Fuels / Energy for Sustainable Road Transportation towards Net Zero Emissions

- Electricity
- Biofuels
- Hydrogen

Electric two/three-wheeler



Electric / biofuel Car

Hydrogen Vehicle

Sustainable Fuels for Road Transportation for meeting Net Zero Targets

2027 I (33%) | 2037 II(67%) | 2047 III (100%)

Fuel	2022	2025	2030	2035	2040	2045	2050
Fossil (short-term)							
Gasoline Y	Y	Y	Y	Y	N	N	
CNG	Y	Y	Y	Y	Y	N	N
DIESEL	Y	Y	Y	Y	Y	N	N
Ethanol blend (Medium-term)							
E10	Y	N	N	N	N	N	N
E20	-	Y	Y	Y	Y	N	N
ED5	-	Y	Y	N	N	N	N
ED15	-	-	Y	Y	Y	N	N
DME-Diesel	-	-	Y	Y	Y	N	N
Renewable (Long-term)							
Biofuel/E100	-	-	Y	Y	Y	Y	Y
Hydrogen	-	-	Y	Y	Y	Y	Y
Electric	Y	Y	Y	Y	Y	Y	Y

Energy Independence or 100% Energy Security with biofuel, green hydrogen and renewable electricity for Transportation Sectors in 2047

Thank You