An IESA initiative

IGHC — India Green Hydrogen Council

Hydrogen Fuel Cells for Mobility

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Innovation Fellow

India Energy Storage Alliance (IESA)

World Hydrogen Energy Summit 2023

Image: NTB scanpix

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Making India a Global Hub for research and manufacturing of advanced energy storage technologies

SESI — Stationary Energy Storage India Council

Stationary Energy Storage India (SESI) Council is focused on the roadmap and outlook for Stationary Energy Storage in India covering grid-scale storage, behind-the-meter applications as well as microgrids.

IEMC — India Electric Mobility Council

The India Electric Mobility Council (IEMC) is intended to support acceleration of pace of EV adoption in India and to establish India as e-mobility leader and drive R&D and Manufacturing in India. IEMC is also working on improving EV charging infrastructure.

India Battery Manufacturing and Supply Chain Council

India Battery Manufacturing & Supply Chain Council (IBMSCC) works on the complete development of the advanced battery supply chain needed to support upcoming giga factories in India as well as for export.

IGHC — India Green Hydrogen Council

The India Green Hydrogen Council (IGHC) is intended to explore opportunities for India to make the best use of the potential of R&D and manufacturing of green hydrogen technologies and their adoption industrial decarbonization and commercial transportation.

IGHC
India Green Hydrogen Council

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- ThermoFisher Scientific
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- Vena Energy
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International Partner

- giz
- Government of Western Australia
- Green Hydrogen Coalition
- GH2 Green Hydrogen Organisation
- Greenstat
- igef Indo-German Energy Forum
- Innovation Norway
- MENA Hydrogen Alliance – An initiative of Dii Desert Energy
- Scottish Development International

Knowledge Partner

- The World Bank
- World Resources Institute

Worked with Government

- सत्यमेव जयते Department of Science and Technology, Ministry of Science and Technology, Government of India
- Government of India Ministry of New and Renewable Energy
- सत्यमेव जयते DSIR Department of Scientific and Industrial Research
- सत्यमेव जयते NITI Aayog

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Our Activities in Green Hydrogen Space

2019
Launch of MIGHT (Mobility and Infrastructure with Green Hydrogen Technologies) Initiative focused on green hydrogen by IESA

Innovation Norway

BUSINESS FINLAND

02 Nov 2020
Webinar on India - Nordic collaboration on Hydrogen Economy at IESW (With Innovation Norway and Business Finland)

सत्यमेव जयते
Ministry of New and Renewable Energy
Government of India

9th April 2021
Submitted inputs to MNRE on National Green Hydrogen Policy

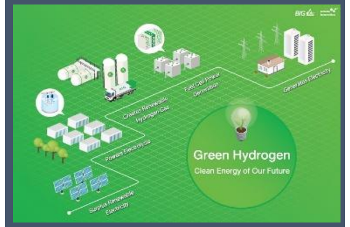
GREENSTAT

MENA Hydrogen Alliance
An initiative of Dii Desert Energy

2020
IESA has signed MOU with MENA Hydrogen Alliance in 2020

IESA has signed MOU with Greenstat Hydrogen India Pvt Ltd in 2020

06 Nov 2020
Session on Technological Readiness of Hydrogen Storage for Stationery and EV Applications



21st April 2021
2nd Roundtable on Green Hydrogen Technology landscape & Applications

7th May 2020
Organized Webinar on Hydrogen & Fuel cell technologies & Opportunities for India

25th March 2021
1st Roundtable on Policy landscape for Green Hydrogen in India

5th May 2021
3rd Roundtable on Green Hydrogen and Hydrogen Mission for India

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Our Activities in Green Hydrogen Space

IESA India Energy Storage Alliance

7-8th June 2021
Participated in Oxford Saïd Executive Networking Forum (OSENF) on Hydrogen Economy

8th July 2021
India Connect Program on Energy storage e-Mobility & Green Hydrogen (in association with Canadian High Commission)

15th June 2022
G20 Indonesian Presidency Webinar on Accelerating Green Hydrogen Technologies and Energy Storage for the Energy Transitions

23rd June 2021
Hydrogen India Conclave (Driving India as an emerging Hydrogen Economy)
Supported by FCDO-UK, Methanol Institute, Ador

8th December 2021
India Connect Program on Green Hydrogen (With Innovation Norway and Hydrogen Center of Excellence)

30th September 2022
IESA supported DST for International Platform on Hydrogen Economy - An Industry-Academia Conclave 2022

NITI Aayog

25th June 2021
Part of Consultative Group on Clean Energy Pathways Hydrogen Economy for India by NITI Aayog

6th May 2022
Organized Conference on Green Hydrogen as part of IESW 2022 (In association with WRI)

9th October 2022
Joined Indo-German Energy Storage Task Force as a member

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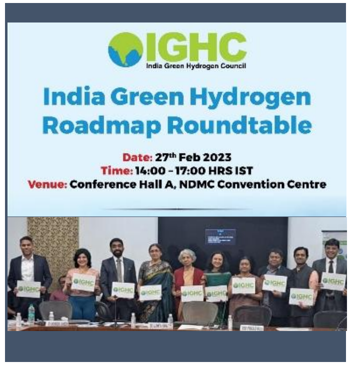
Our Activities in Green Hydrogen Space in 2023

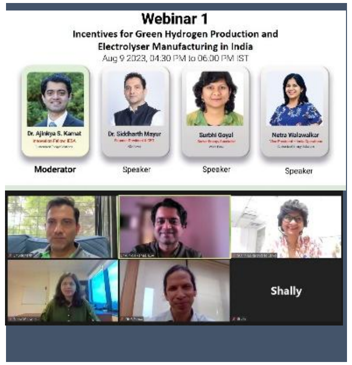
18th January 2023
Virtual roundtable on India's National Green Hydrogen Mission and Opportunities



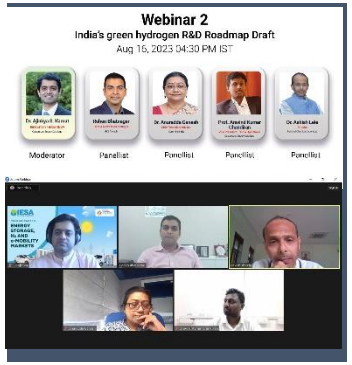
27th February 2023
IGHC Launch and India Green Hydrogen Roadmap Roundtable

14th April 2023
IESW pre-event Global Open Webinar on Manufacturing and Deployment of Green Hydrogen in India

5th May 2023
India Energy Storage Week - Green Hydrogen Day



9th August 2023
IGHC Global Open Webinar on Incentives for Green H2 Production and Electrolyser Manufacturing in India: Focus on SIGHT scheme



16th August 2023
IGHC Global Open Webinar on India's Green Hydrogen R&D Roadmap

24th-25th August 2023
Green Hydrogen Masterclass (theory + lab) with National Chemical Laboratory, Pune

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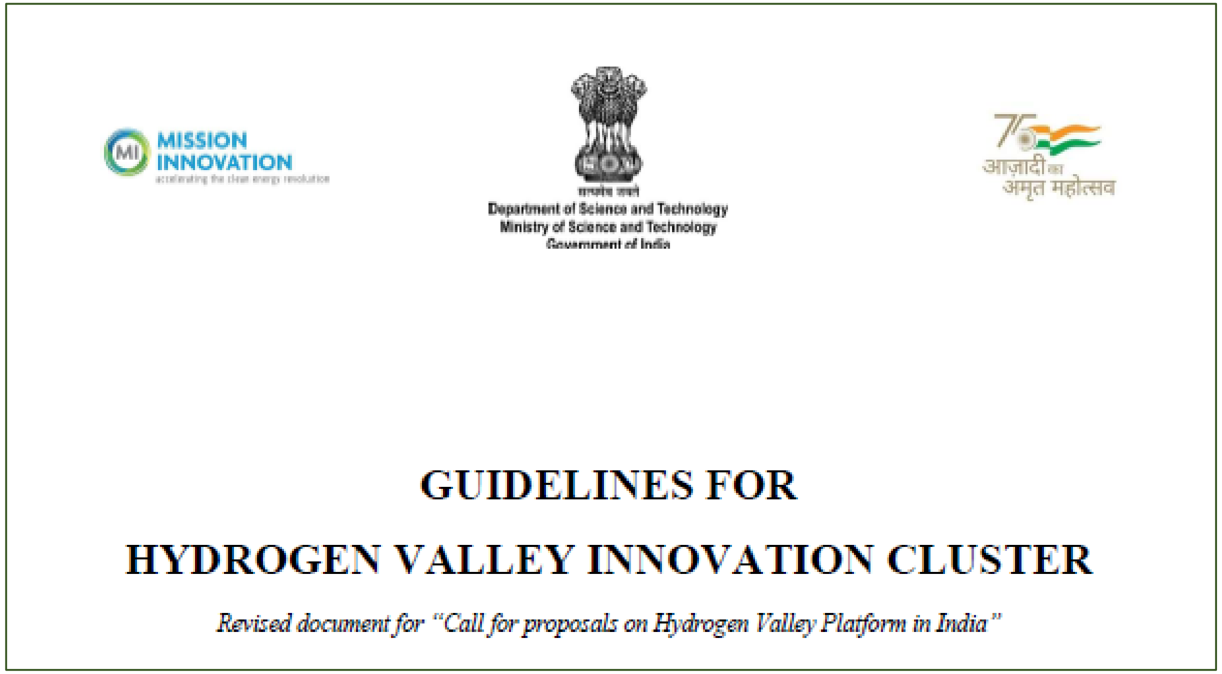
Key Examples of IESA's Contributions in Hydrogen

A member of the **Indo-German Green Hydrogen Task Force**, established by the Indian and German Governments in 2022.


MISSION INNOVATION
Department of Science and Technology
Ministry of Science and Technology
Government of India

GUIDELINES FOR

HYDROGEN VALLEY INNOVATION CLUSTER

Revised document for "Call for proposals on Hydrogen Valley Platform in India"

IESA has been instrumental in developing guidelines for the **Hydrogen Valley Innovation Cluster initiative** – India's flagship program under international **Mission Innovation – Clean Hydrogen Mission**, administered by the Dept of Science & Technology

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Image: NTB scanpix

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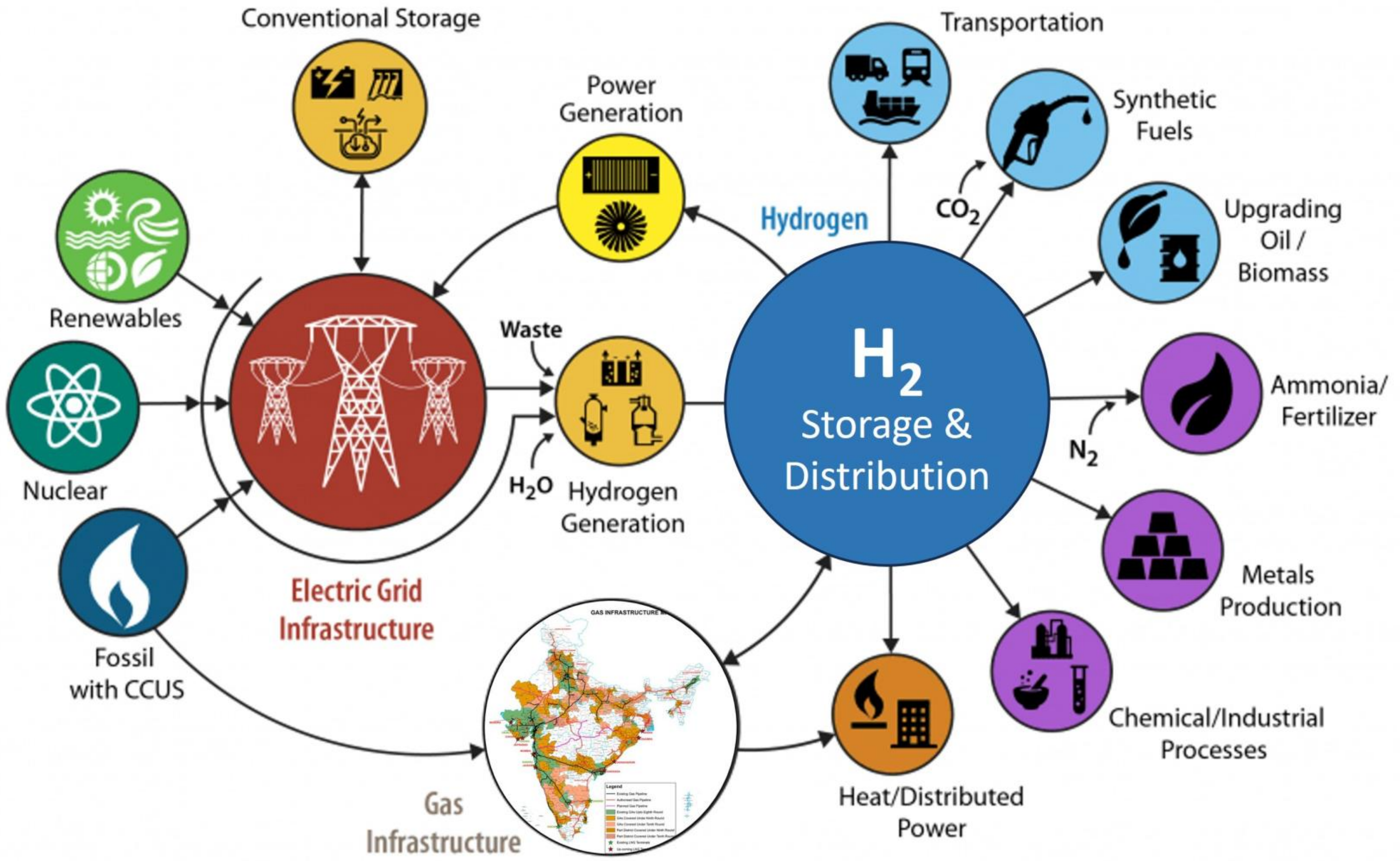
Hydrogen Value Chain Includes Many Industries & Sectors

- Green Hydrogen (GH_2) value chain is complex involving multiple energy sources, sectors, and infrastructures.
- Large-scale GH_2 ecosystem requires large-scale reliable infrastructures
  - Electricity infrastructure
  - Water infrastructure
  - Transportation infrastructure
  - Gas infrastructure.



Adapted from US DOE & India Min. Petroleum & Nat Gas

Outline

1

How hydrogen fuel cells compare with other mobility technologies?

2

What are key drivers of cost reduction in fuel cells mobility?

3

How much would fuel cells vehicles cost in the long term compared to other technologies?

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Fuel Cells vs ICE for Mobility

Fuel cells achieve the same objective as any direct combustion-based power generation system such as coal power plants, thermal plants, gas peakers and diesel generators, which emmits huge quantity of GHG. The main objective is the conversion of chemical energy of the fuel (such as coal, natural gas, diesel) to electric energy.

Advantages

- Diesel engine efficiency ranges from 25%-35%, whereas efficiency of PEM fuel cells ranges from 55% - 60%
- Unlike IC engines, fuel cells don't have any moving parts and don't produce mechanical vibrations
- Unlike IC engines whose tail pipe emits GHG, Tail pipe emissions of a fuel cell is generally water vapour

Challenges

- Market for fuel cells in not well developed yet. Global market for PEM fuel cells is $2B compared to market for IC engines of $55B
- Due to developing nature of the fuel cell industry, annual units sale that results in economies of scale is not achieved
- Fuel cells are yet to demonstrate a robust service life as that of IC engines (20+ years)

Various energy storage present and future technologies have been listed here: Comparison of PEM fuel cell with Li-ion battery

Albatayneh et.al ,"Comparison Of the Overall Engine Efficiency"
Fortune Business Insights ,"PEMFC Market Size"

Source: CES ETR H2 Report 2023

PEM Fuel Cells vs Li-ion batteries

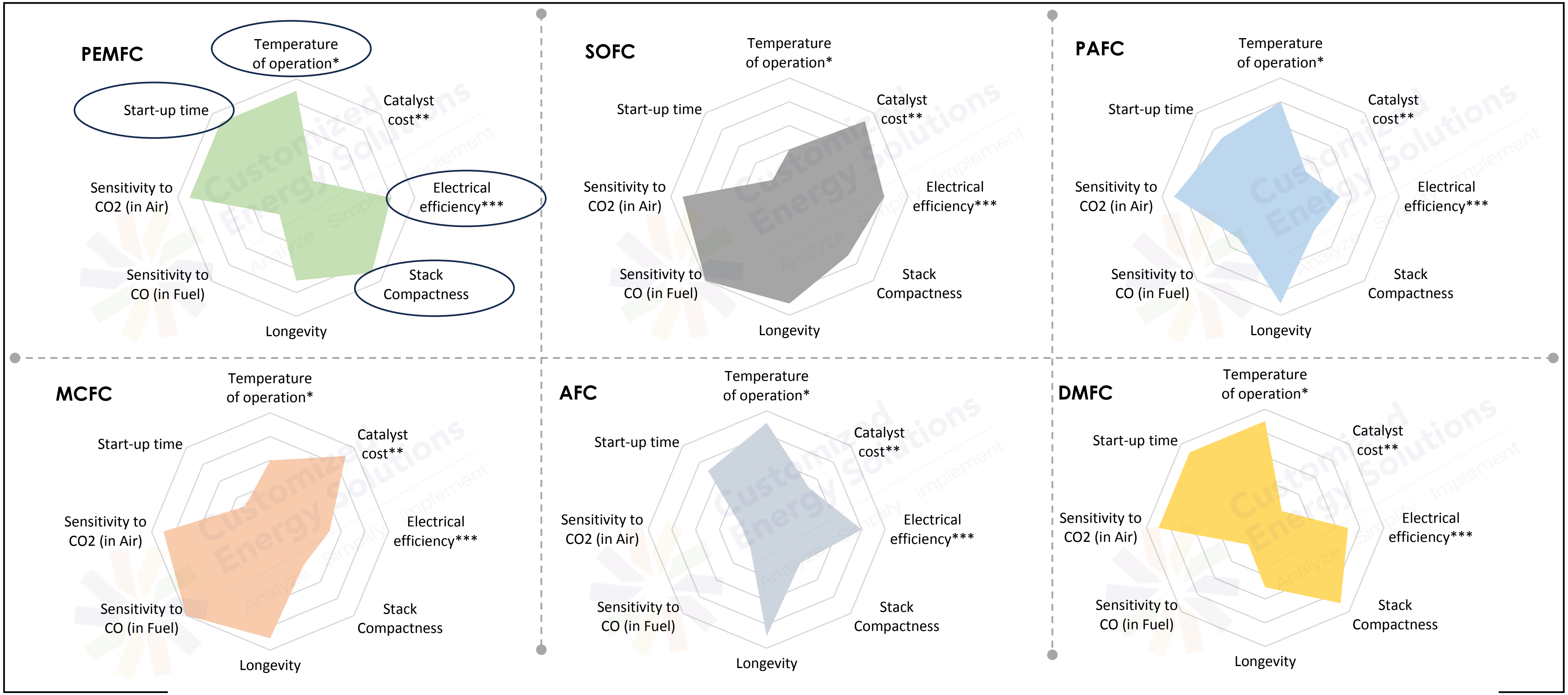
Fuel Cell System (Toyota Mirai)			Battery Pack (Tesla Model S)		
Weight of FC stack =	56	kg	Weight of battery =	590	kg
Weight of Hydrogen Tank =	88	kg	Volume of battery =	195	L
Weight of Hydrogen stored =	5	kg	Energy in battery =	85	kWh
Total weight =	149	kg			
Volume of FC stack =	37	L			
Volume of Hydrogen Tank =	122	L			
Total Volume =	159	L			
Hydrogen req. For 100 Km =	0.91	kg	Energy consumption =	189	Wh/km
Driving Range of car =	550	km	Range of car =	450	km
Weight of Toyota Mirai =	1850	kg	Weight of Tesla Model S =	1890	kg
Gravimetric Energy Density of PEMFC	776	Wh/kg	Gravimetric Energy Density of Battery pack	144	Wh/kg
Volumetric Energy Density of PEMFC	727	Wh/L	Volumetric Energy Density of Battery pack	436	Wh/L
Cost of Hydrogen =	16	$ / kg	Cost of Electricity =	0.247	$ / kWh
Operating Cost =	0.14	$ / km	Operating Cost =	0.05	$ / km

- For the purpose of energy density calculation, the FC system weight consists of the FC stack, Hydrogen Tank, Hydrogen. The Battery pack consists of cells, BMS, thermal management system and other packaging components. Energy content of the hydrogen in the fuel tank is multiplied by the efficiency of the fuel cell stack (63.7%) to calculate the useful energy content of the system.
- The total weight of the two cars are very similar (approx. 1900 kg) and have a similar driving range of 450+ km. However, the weight of the FC system is almost half of the battery pack resulting in a much higher energy density.

Source: CES ETR H2 Report 2023

Toyota ,"Outline of Mirai"
Burgess ,"Air Products Aims to be Vertically Integrated"
Lohse-Busch ,"Toyota Mirai Testing"

Performance matrix of various fuel cells technologies



*Low temperature of operation is desirable from practicality perspective - less component corrosion and degradation, ease of sealing and fast startup time.

**For low temperature option, Platinum is the only known option as the catalyst. At higher temperatures, inexpensive catalysts can be used.

***Electrical efficiency accounts for % conversion of fuel energy to electrical energy. Thermal energy output is not included.

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Source: CES ETR H2 Report 2023

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What are key drivers of cost reduction in fuel cells mobility?

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How much would fuel cells vehicles cost in the long term compared to other technologies?

Drivers of cost reduction in fuel cells mobility

Fuel cell costs

- Platinum-group elements
- Design optimization and integration in membrane electrode assembly
- Bipolar plates
- Balance of plant (compressors, humidifiers, etc.)
- Demand: 5% share in trucks → 5 plants of 1,00,000 stacks/year

Storage tanks costs

- Composite materials costs
- Economies of scale

Hydrogen costs

- 600 km range, $95/kW FC costs at 1,00,000 units/year costs can be cost competitive at hydrogen costs of $7/kgH2

Refuelling infrastructure costs

- 1 station of 50 kgH2/day for 10 cars → $15-25/kgH2.
- 60% of CAPEX is compressor for refuelling at 700 bar.
- Safety and permitting requirements.
- Demand for fleet of 1 million vehicles:
  - FCEVs/ICE: 400 refuelling stations
  - BEVs: 1 million private charging stations + 10,000 fast-charging public stations

Ref: IEA 2019

Effects of economies of scale

Component	Additional info	Scaling	Effect of economies of scale on costs
Bipolar plates + membranes + catalyst + gas diffusion layers	Half of system costs	1,000 units/year to 1,00,000 units/year	65% cost reduction
		1,00,000 units/year to 5,00,000 units/year	Additional 10% cost reduction
Storage system (tank + valves + regulators)	Determined by cost of composites	10,000 units/year to 5,00,000 units/year	$23/kWh to $14-18/kWh
Refuelling station CAPEX	Refuelling at 350 bar	50 kgH2/day to 1,300 kgH2/day	$1.6 million to $1,50,000
	Refuelling at 700 bar		$ 2 million to $6,00,000

Ref: IEA 2019

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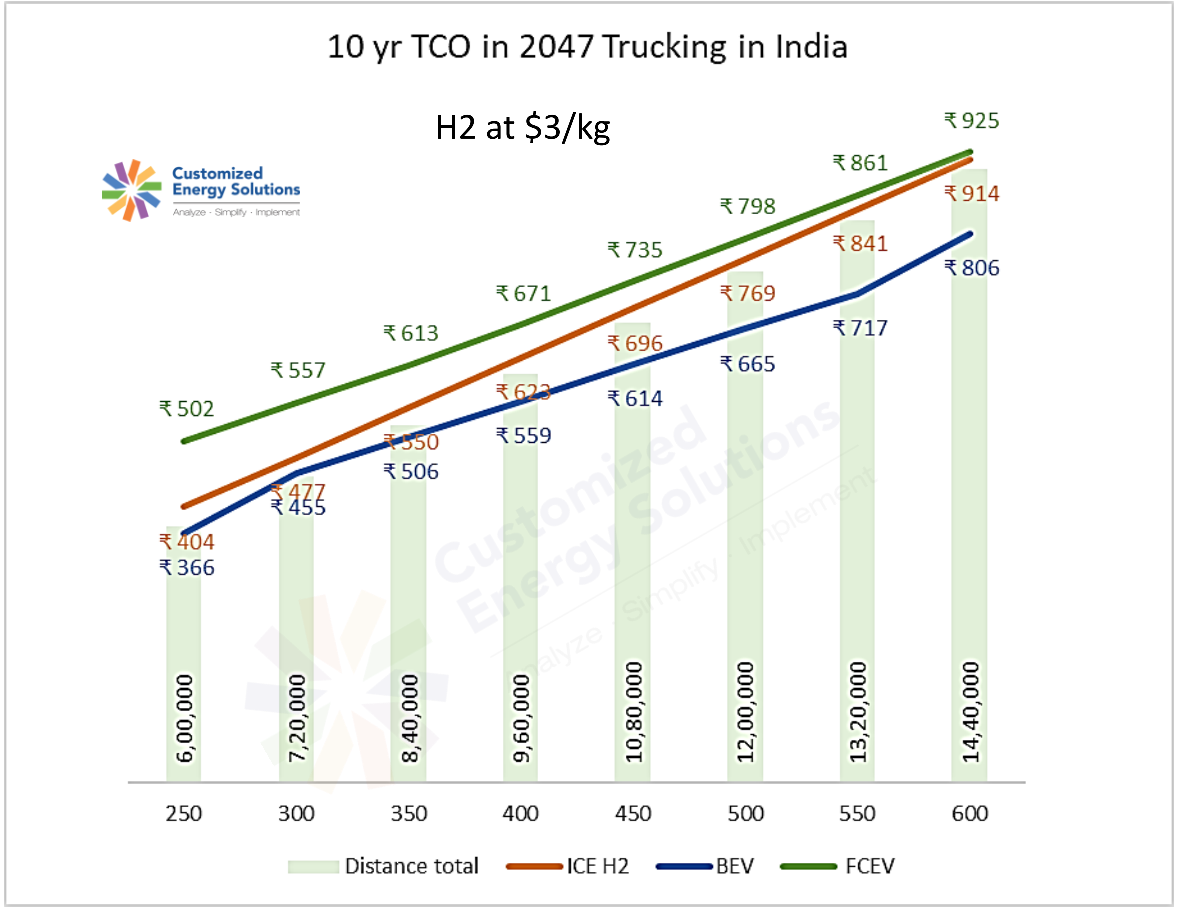
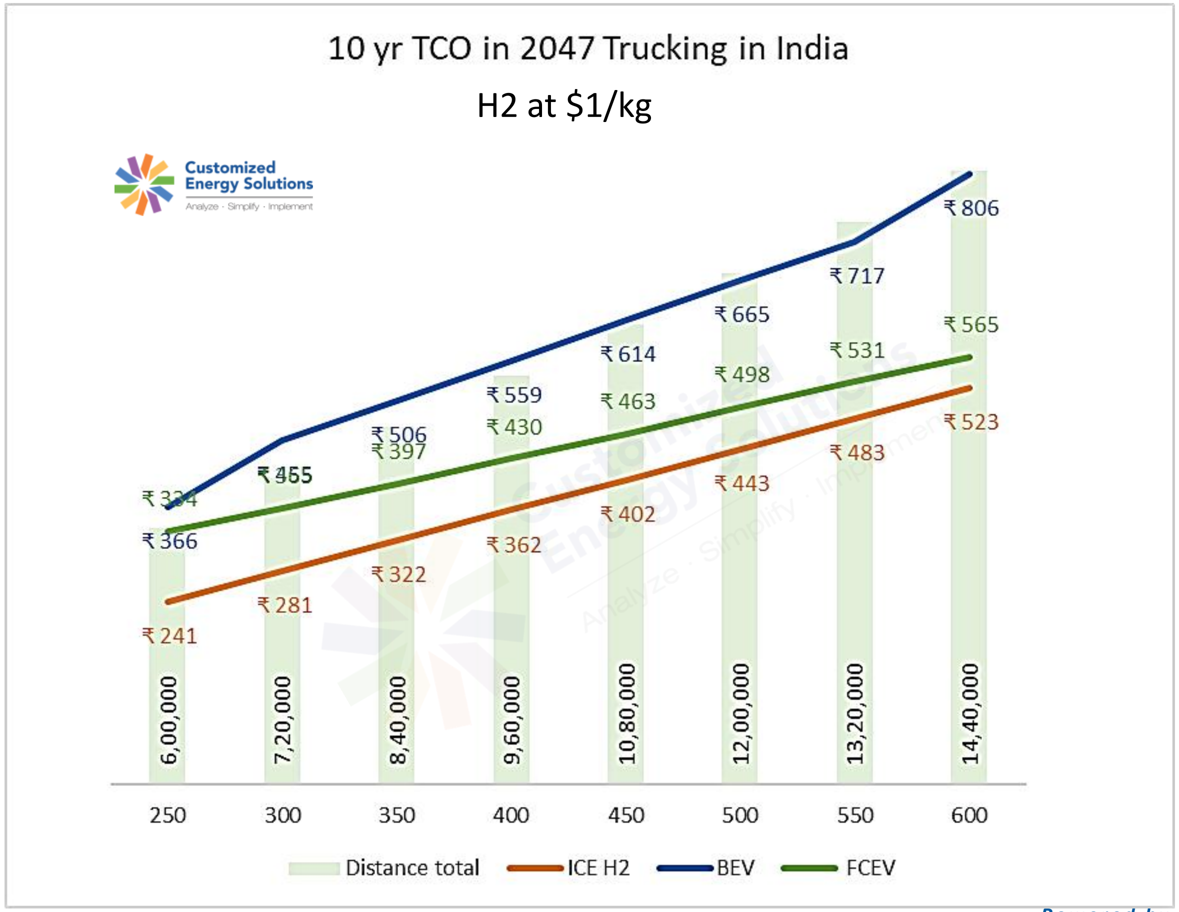
10-yr Total Cost of Ownership of trucks in 2047 Scenario

At 1$/kg, FCEV has TCO lower than ICE H2 or BEV, while at H2 prices of $3/kg, the TCO is high for FCEV.





Source: CES analysis

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1. Fuel cells costs

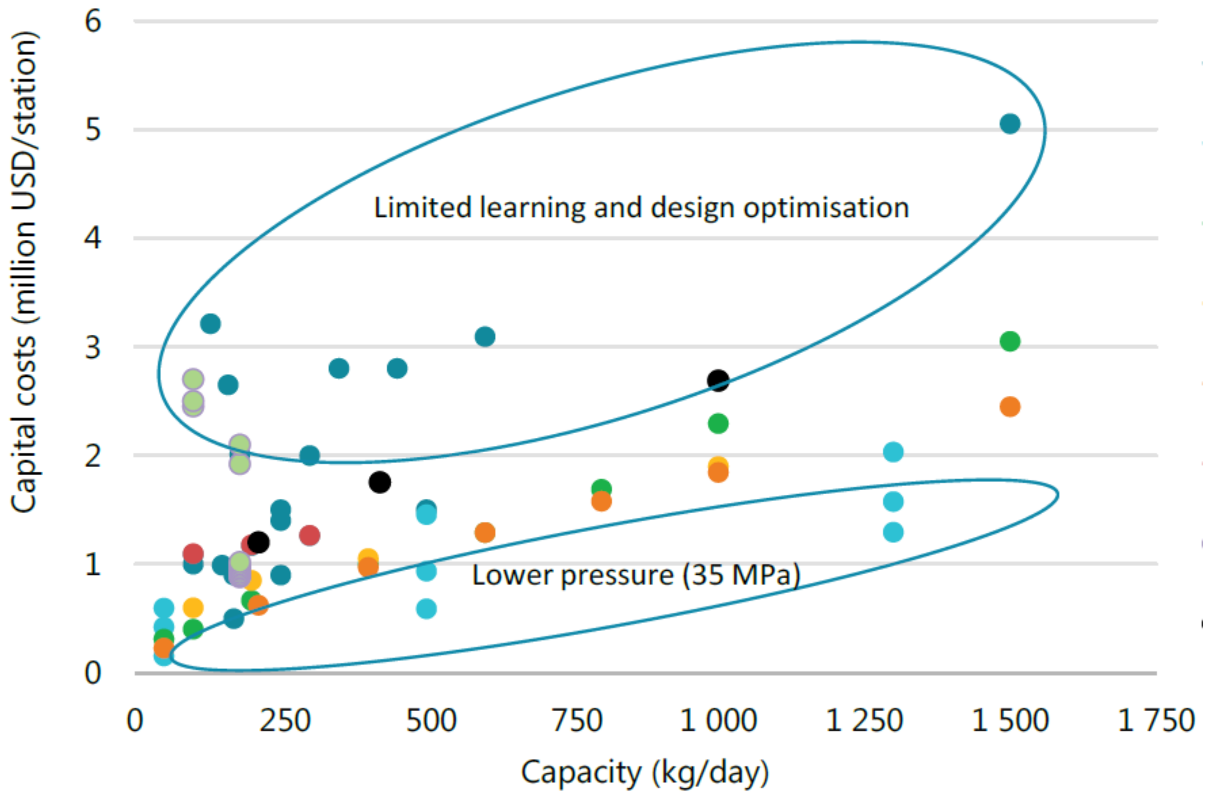
- Reduction or elimination of platinum-group elements content
- Design optimization and integration in membrane electrode assembly
- Costs of bipolar plates
- Costs of balance of plant components (compressors, humidifiers, etc.)
- Economies of scale in manufacturing:
  - 5% share in trucks → 5 plants of 1,00,000 stacks/year
  - 5% share in cars → 40 plants of 1,00,000 stacks/year

2. Storage tank costs

- Economies of scale in manufacturing

3. Refuelling infrastructure costs

- 1 station of 50 kgH2/day for every 10 cars → $15-25/kgH2 delivered price.
- 60% of CAPEX is compressor for refuelling at 700 bar.
- Compliance with safety and permitting requirements.
- Demand for fleet of 1 million vehicles:
  - FCEVs: 400 refuelling stations (similar to ICE vehicles today)
  - BEVs: 1 million private charging stations + 10,000 fast-charging public stations



4. Hydrogen costs

- 600 km range, $95/kW FC costs at 1,00,000 units/year costs can be cost competitive at hydrogen costs of $7/kgH2

- Primary energy consumption by India’s transportation sector in 2050 is expected to be more 3 times that in 2019 – 1278 TWh in 2019 to 3,611 TWh in 2050 [bp].
- Trucks segment, which accounts for 25-30% of transportation energy demand, would contribute 60-65% of the demand in 2050
- Trucks segment has also seen the slowest energy efficiency and hence emissions improvements in the past.

COMPARISON OF FUEL CELL TECHNOLOGIES FOR eMOBILITY

PEMFCs are the best choice for mobility applications among different types of fuel cells for the following three reasons:

- Stack is very compact and lightweight
- Operating temperature is not very high
- Stack size is flexible, can be designed for small or heavy vehicles

- Other types of fuel cells such as SOFC (solid oxide fuel cells), PAFC (phosphoric acid fuel cells), AFC (alkaline fuel cells) and MCFC (molten carbonate fuel cells) are ideal for large scale stationary power generation (1- 100 MW)

Parameter	PEM	SOFC	PAFC	AFC	MCFC	DMFC
Operational Life (h)	10000	15000+	8000+	8000+	10000+	-
Operating Temp. (°C)	< 120	800-1000	150 - 200	< 100	600 - 700	< 100
Electrical Efficiency (%)	55 - 60	60	40	60	50	40-50
Energy density (kWh/kg)	72-500	110-300	-	-	16-26	
Power density (kW/kg)	3-23	3-13	0.5-1.0	0.6	0.6-1	0.4
Stack sizes (kW)	0.2 - 150	1 – 1000	5 - 400	1 - 100	300 - 3000	<0.5
Applications	Stationary, Transportation, Portable	Stationary	Stationary	Stationary, Transportation	Stationary	Portable
Compatible Fuels	Hydrogen	Hydrogen, Natural gas, Biogas	Natural gas	Hydrogen	Hydrogen, Natural gas, Methane	Methanol
Electrolyte Material	Nafion	YSZ	Phosphoric acid	NaOH, KOH, LiOH	Na_2CO_3, K_2CO_3, Li_2CO_3	Nafion
Companies	Ballard Power Systems, Plug Power, Hydrogenics, ITM Power	Bloom Energy, Bosch, Ceres, MHPS, AVL	Fuji Electric, Doosan Fuel cell America	Toshiba, AFC Energy, Ballard, Fuel Cell Energy	Fuel Cell Energy	SFS Energy, Blue World Technologies, Oorja Photonics

Comparison of Fuel Cell Technologies

The operating temperature of the stack has a significant impact on system design, operation and cost:

- **SOFCs and MCFCs** operate at a high temperature (500 – 1000°C), can use inexpensive catalyst materials. However, due to the high operating temperature corrosion issues are more pronounced requiring special materials for stack components and sealing.
- Startup time for **PEMFCs, and AFCs** is less than 1 minute, whereas **MCFCs and SOFCs** take 10 minutes and 60 minutes respectively, for the same.
- Longer startup times for **SOFCs, PAFCs, and MCFCs** is due to gradual heating of the system to operating temperature to attain full power generation. (> 10 hours)
- At the high operating temperatures of **SOFCs,** fuel reforming is not required, and methane and CO can be directly fed to the stack. This reduces system complexity and eliminates reformer cost.
- **PEMFCs, AFCs, and PAFCs** need Platinum as the catalyst in the electrodes as they operate at low temperatures. So far no good substitute for Platinum is available.
- **PAFCs** show a 1.5 percent increased tolerance to fuel impurities like CO, compared to other fuel cell technologies. It broadens the choice of fuels use in PAFC.

The electrical efficiency of fuel cells ranges from 40 – 60 %. Since the exhaust gas coming out of the systems is hot (depends on the stack temperature), it can also be used for space heating applications. The total efficiency (electrical + thermal) is called CHP (combined heat and power) generation efficiency.

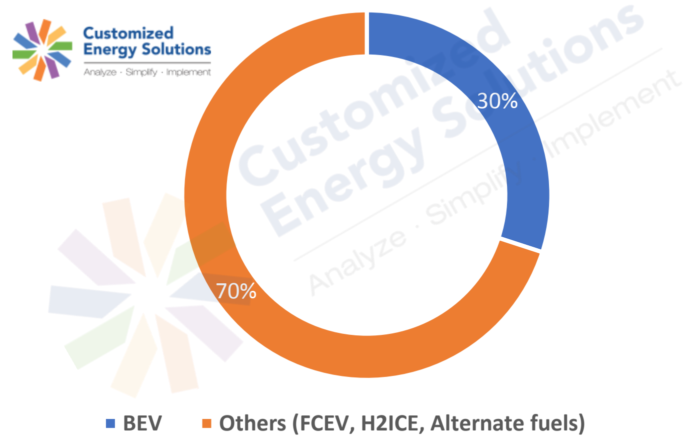
The general design of all fuel cells is similar consisting of a fuel tank, reformer, air-supply, stack, power conversion system, heat exchanger and other BOP components.

Fuel Cells ,"Fuel Cell Basics"
GenCell ,"Comparing Fuel Cell Technologies"

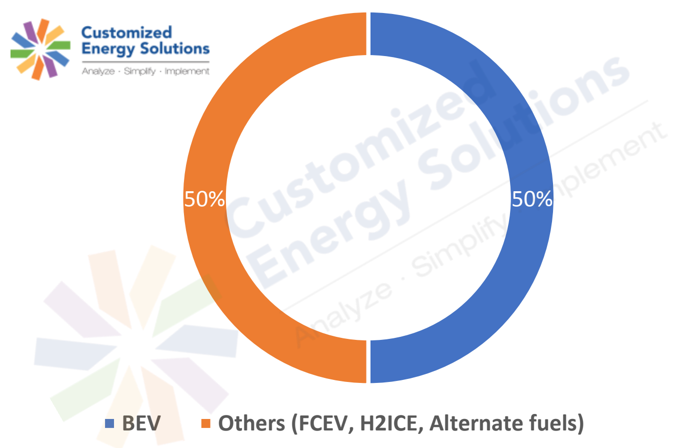
India’s Heavy Transportation Electrification Scenario (2047)

In 2047, CES estimates that electrification would take place in the heavy-duty transportation sector (e-trucks and e-buses) however, there are scenarios where penetration level of BEV vs Others (ICE H2, FCEV and Alternative sustainable fuels) might differ vastly primarily depending on the cost of Hydrogen.

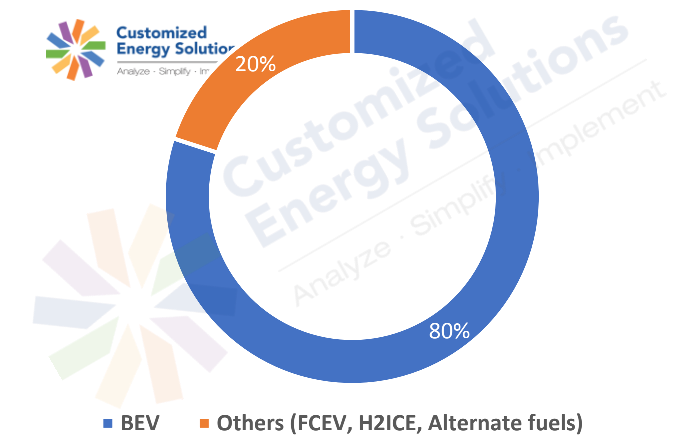
EV penetration in Scenario 1 (H2 < $1/Kg)



EV penetration in Scenario 2 ($1/Kg < H2 < $3/Kg)



EV penetration in Scenario 3 (H2 > $3/Kg)



Key Assumption

- With cost of Hydrogen going below $1/Kg, there is an economic advantage over BEVs when we look at a 10-yr TCO analysis.
- There is a dedicated piping and fueling infrastructure in place.

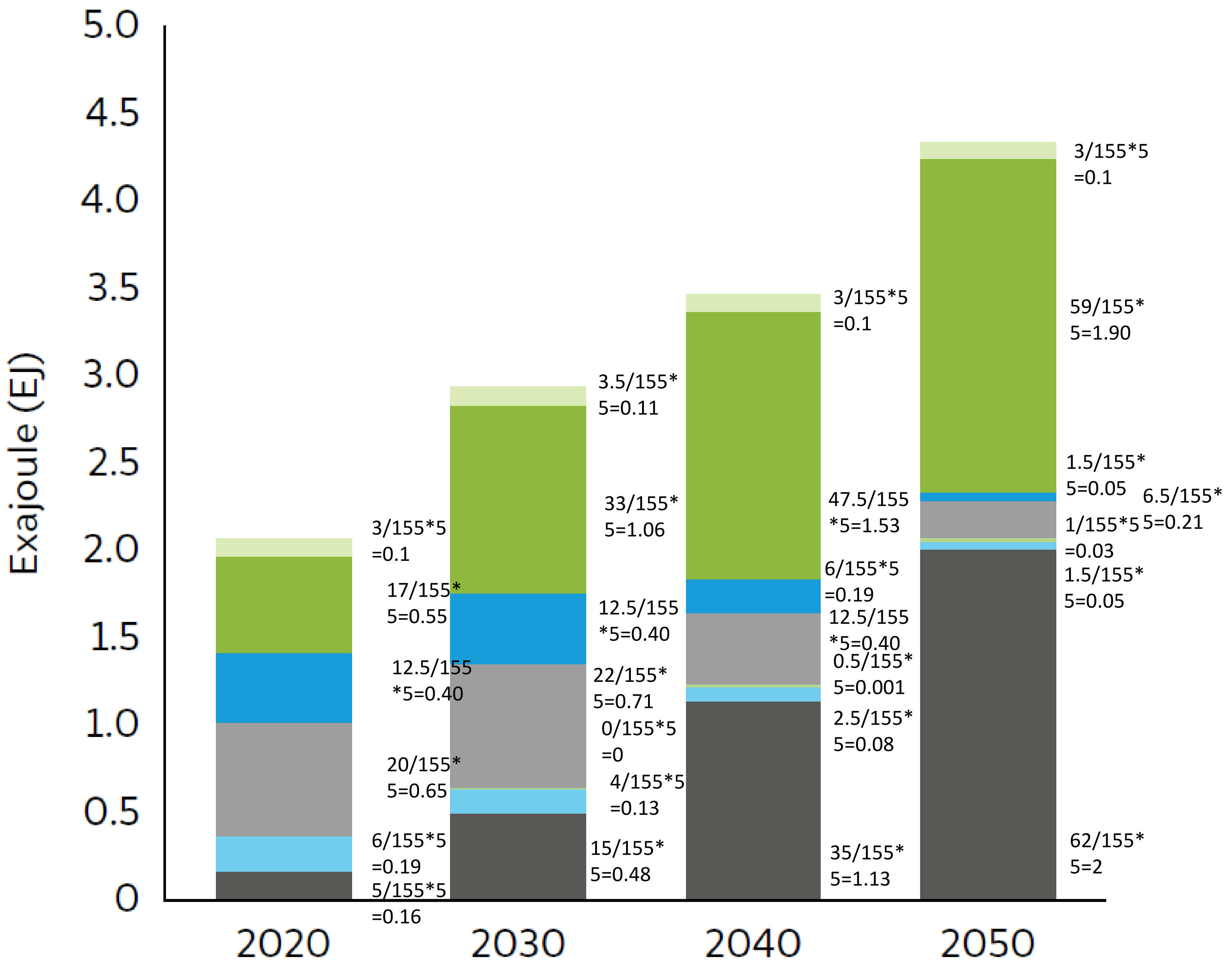
Key Assumption

- As the cost of Hydrogen is between $1-3/Kg we are looking at scenarios where industries might adopt FCEV and ICE H2 in captive use while BEVs are most cost competitive and are used in public and inter-city transport system.

Key Assumption

- As Hydrogen cost remains above $3/Kg, we see BEVs making more economic sense in terms of 10-y TCO analysis.
- There are pantograph-type and DCFC chargers in place with fast charging capabilities in place.

Passenger energy consumption



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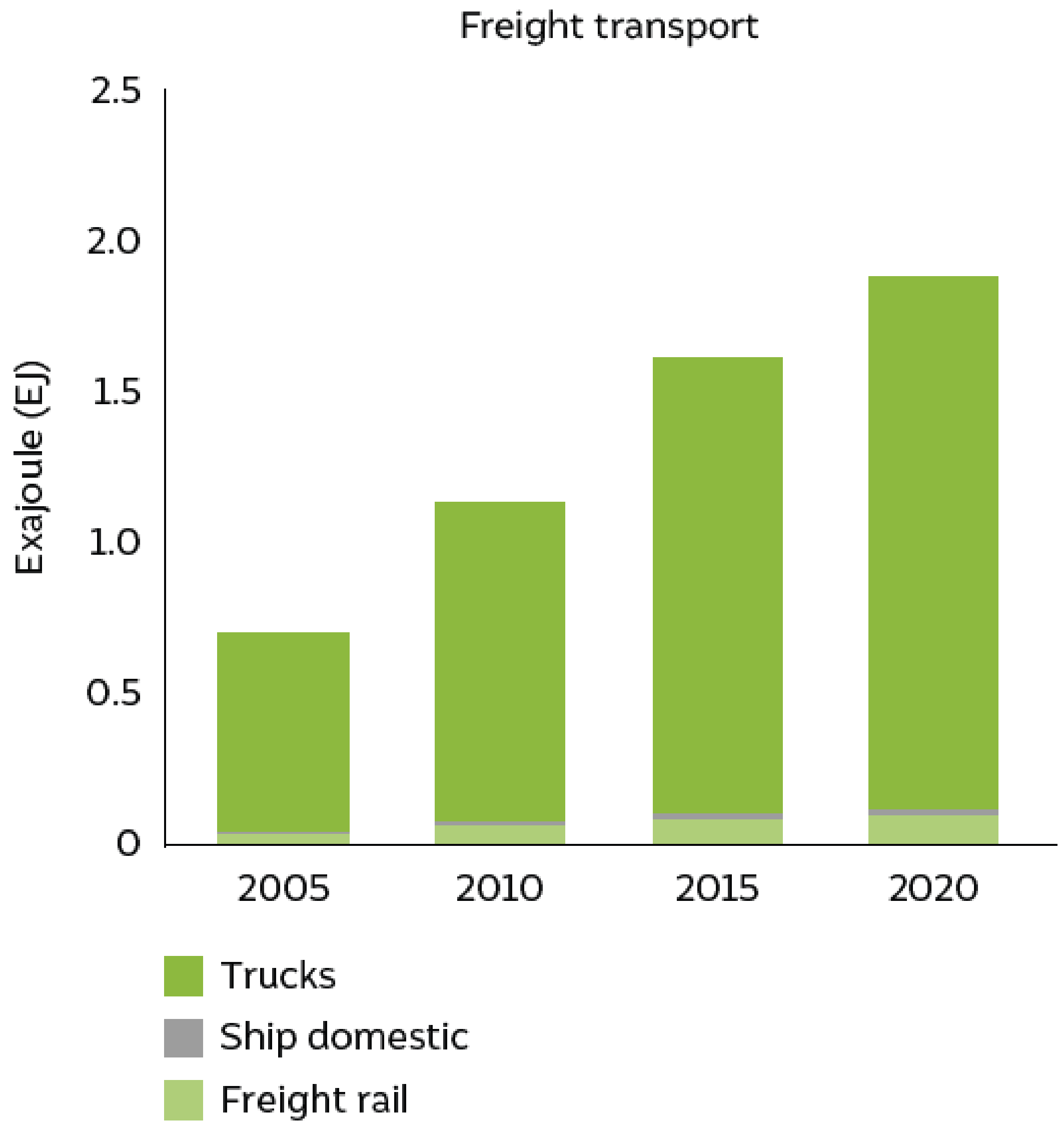
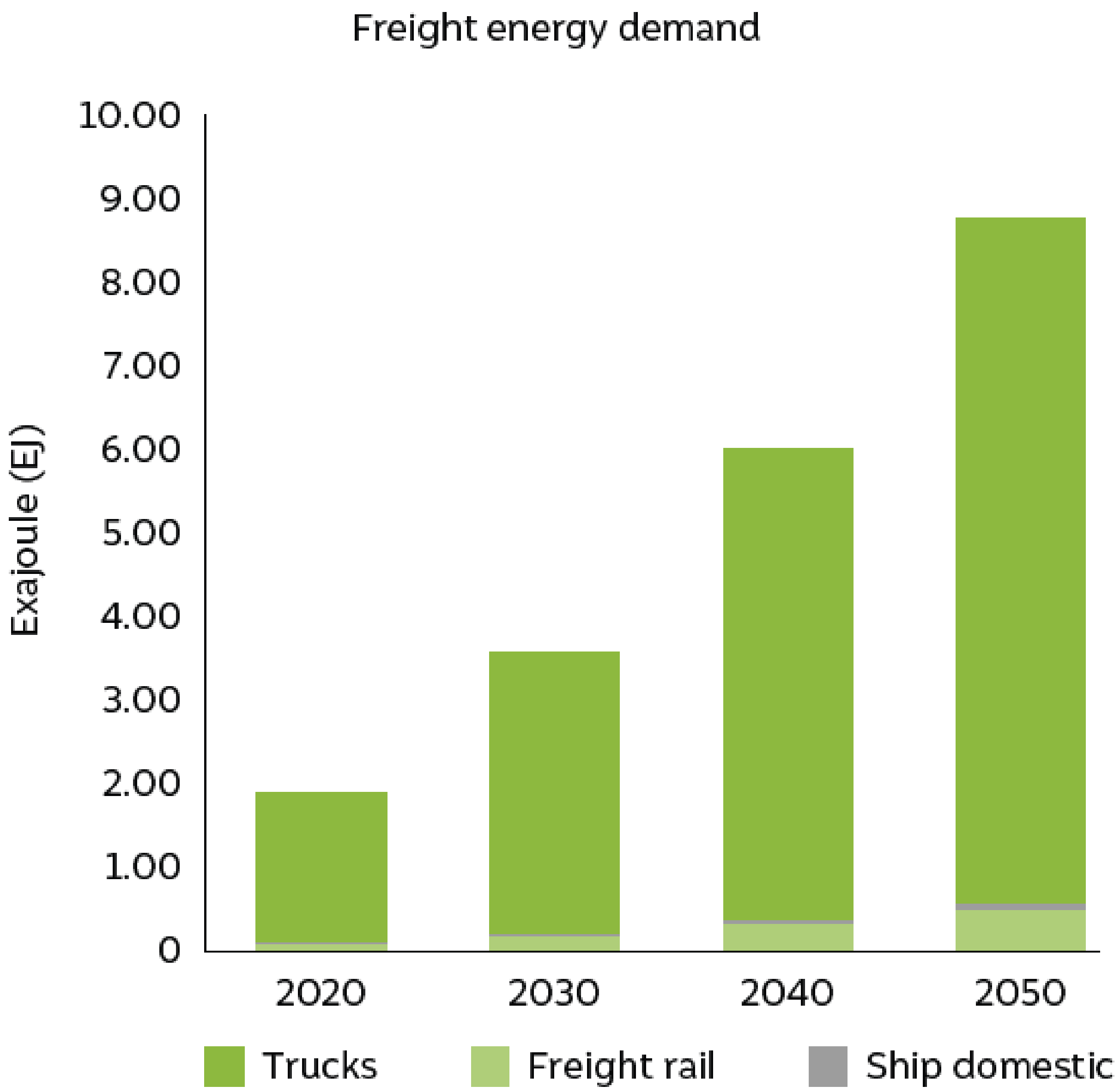

Freight transport
2.5
2.0
1.5
1.0
0.5
0
Exajoule (EJ)
2005
2010
2015
2020
Trucks
Ship domestic
Freight rail

1.25



10/12
0*92=
7.7

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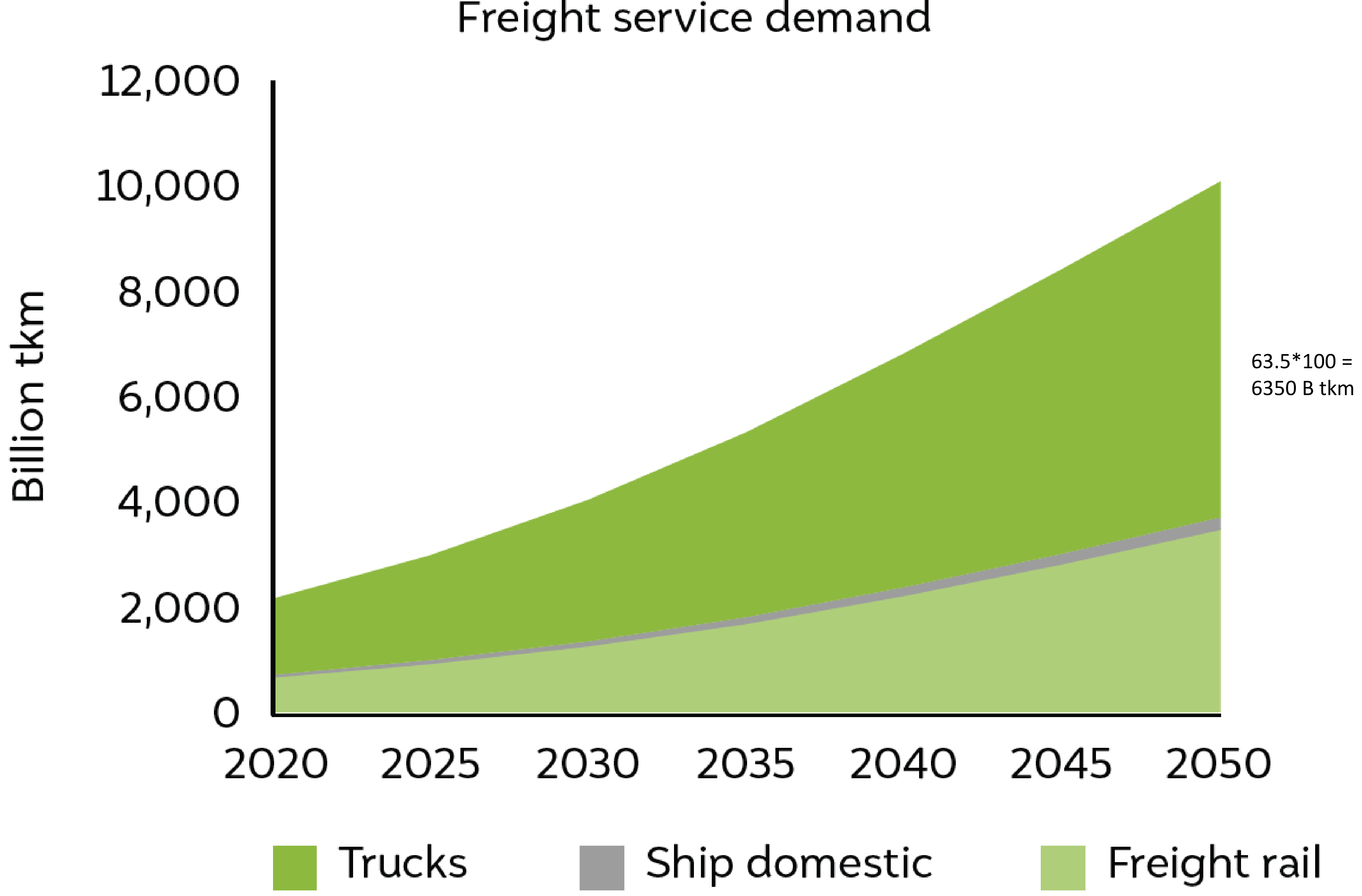

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Figure 11 Liquid fuels and natural gas will become the two primary fuels for the trucks