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# Reducing Emissions in Off-Road Equipment Used

## in Agriculture, Mining, and Construction Through Green Hydrogen and its Derivatives

# List of Abbreviations

CAPEX - Capital Expenditure
CNG - Compressed Natural Gas
CO2 - Carbon Dioxide
DMFC- Direct Methanol Fuel Cell
EV - Electric Vehicle
FCEV - Fuel Cell Electric Vehicle
GH2 - Green Hydrogen
GHG - Greenhouse Gas
H2ICE - Hydrogen Internal Combustion Engine
H-CNG - Hydrogen Compressed Natural Gas
HDT - Heavy Duty Truck
HP - Horsepower
ICE - Internal Combustion Engine
IEA - International Energy Agency
INR - Indian Rupee
kg - Kilogram
kWh - Kilowatt-hour
MJ - Megajoule
MT - Metric Ton
NPV - Net Present Value
OEM - Original Equipment Manufacturer
OPEX - Operational Expenditure
R&D - Research and Development
RPM - Revolutions Per Minute
TCO - Total Cost of Ownership
TRL - Technology Readiness Level
VGF - Viability Gap Funding

# Table of Contents

# Executive Summary

Manufacturers of off-road vehicles in mining, agriculture, and construction have long been facing decarbonization pressure from customers. Recently, government initiatives have also started to move beyond the on-road consumer segment to promote emissions reductions in the off-road vertical. In light of this, major mining companies have set ambitious decarbonization targets, aiming for Scope 1 and 2 neutralities, even as commitments from the construction and agriculture sector have not been as forthcoming. On the whole, the pressure to develop zero-emissions equipment in these sectors is growing.[1]

A major source of emissions in these sectors is diesel use in off-road equipment. Approximately 30% of a mine's Scope 1 and 2 greenhouse-gas (GHG) emissions, for example, are caused by diesel engines.[1] Fuel requirements of the off-road segment in agriculture, construction, and mining sectors are easy to predict, and simpler to decarbonize, owing to consistency in demand arising from predetermined routes.

This report gives clear pathways for higher penetration of low emission vehicles (i.e. tractors, construction equipment, and wheel loaders) in these industries It compares the total cost of ownership, a key determinant for comparison among low carbon alternatives. Emissions reduction potential and technology maturity levels are also factors contributing to identifying the focus areas for government and private sector participation.
There are three zero emission technologies to power off-road vehicles – green hydrogen internal combustion engines (ICEs), green hydrogen-based fuel cell electric vehicles (FCEVs), and green methanol. [2] In addition to these technologies, we considered hydrogen blending in compressed natural gas engines (H-CNG) with 20% blending by volume as a bridge technology. These technologies have unique advantages and disadvantages, which are highlighted in this report with regards to their applications for the off-road segment.

**Key Results**
The key results of this study are as follows:

• Methanol-based tractors are economical compared to all other alternatives due to lower upfront and operational cost. On-site production of green methanol, produced from bio genic route, is an even more viable alternative to diesel tractors.

• In excavators used for construction and mining , hydrogen-based ICEs are most suitable due to lower weight of on-board fuel storage, despite lower cost of ownership of methanol. Hydrogen-based ICEs present a viable alternative due to similar engine specifications as diesel vehicles and higher efficiency. If storage, transportation and refueling of hydrogen can be achieved at lower cost, hydrogen-based ICEs are an attractive emissions reduction alternative.

• In mining for haul truck-based transport operations, methanol is the identified least-cost alternative to diesel. M100 (100%

1 Heid. B, Martens. C, Orthofer, A. (2021). How Hydrogen combustion engines can contribute to zero emissions. McKinsey & Company. Retrieved from: https://www.mckinsey.com/industries/automotive-and-assembly/our- insights/how-hydrogen-combustion-engines-can-contribute-to-zero-emissions

2 Battery Electric Vehicles are not part of this study owing to established research on this technology for reference.

methanol) engines are available commercially in China and Europe, they have demonstrated performance for heavy duty applications. They also offer significant cost and emission reduction potential for mining operations.

• Methanol's versatility offered as fuel makes it a viable option for both ICEs via blending or 100% fuel (M100) engines, or as a fuel in EVs. IRENA predicts that renewable methanol will make up about half of the methanol produced, globally by 2050.[3]

• Cost of renewable energy, availability of green hydrogen, transportation, and storage infrastructure green hydrogen and green methanol, and other local market conditions determine the optimization of TCO of these alternative technologies.

• H-CNG as a bridge fuel alternative for decarbonization of the off-road sector, is cost-effective, however, the emissions reduction potential is limited to the volume of blending of green hydrogen in the fuel.

• The infrastructure necessary for transportation and storage of green hydrogen and its derivatives is a necessary investment. These alternatives are complementary and not competing technologies as they rely on the same ecosystem. Cost of fuel at point of fueling or refueling is the biggest concern in transitioning to these technologies. For example, fuel tanks for green hydrogen for both ICE and FCEV technologies are the same, which is a significant contributor to the powertrain costs.

• Allowing OEMs and other private players in the ecosystem to amortize their R&D and capex over a fleet of vehicles and over a short/medium timeframe will help bridge the cost parity with diesel.

• Table below highlights the viability gap funding (VGF) requirements per vehicle deployed among these technologies.

| Lifetime VGF Funding Support in INR Lakh/Vehicle | | | | |
|---|---|---|---|---|
| **INR Lakh** | **H2ICE** | **H2FCEV** | **HCNG(20% blend)** | **Methanol** |
| **50 HP tractor** | 31.0 | 64.6 | NA | 2.7 |
| **110 HP tractor** | 54.6 | 128.6 | NA | 6.0 |
| **100 HP JCB Excavator** | 166.6 | 227.5 | NA | 85.0 |
| **250 HP Mining Haul truck** | 2747.6 | 2281.7 | 295.7 | 1635.0 |

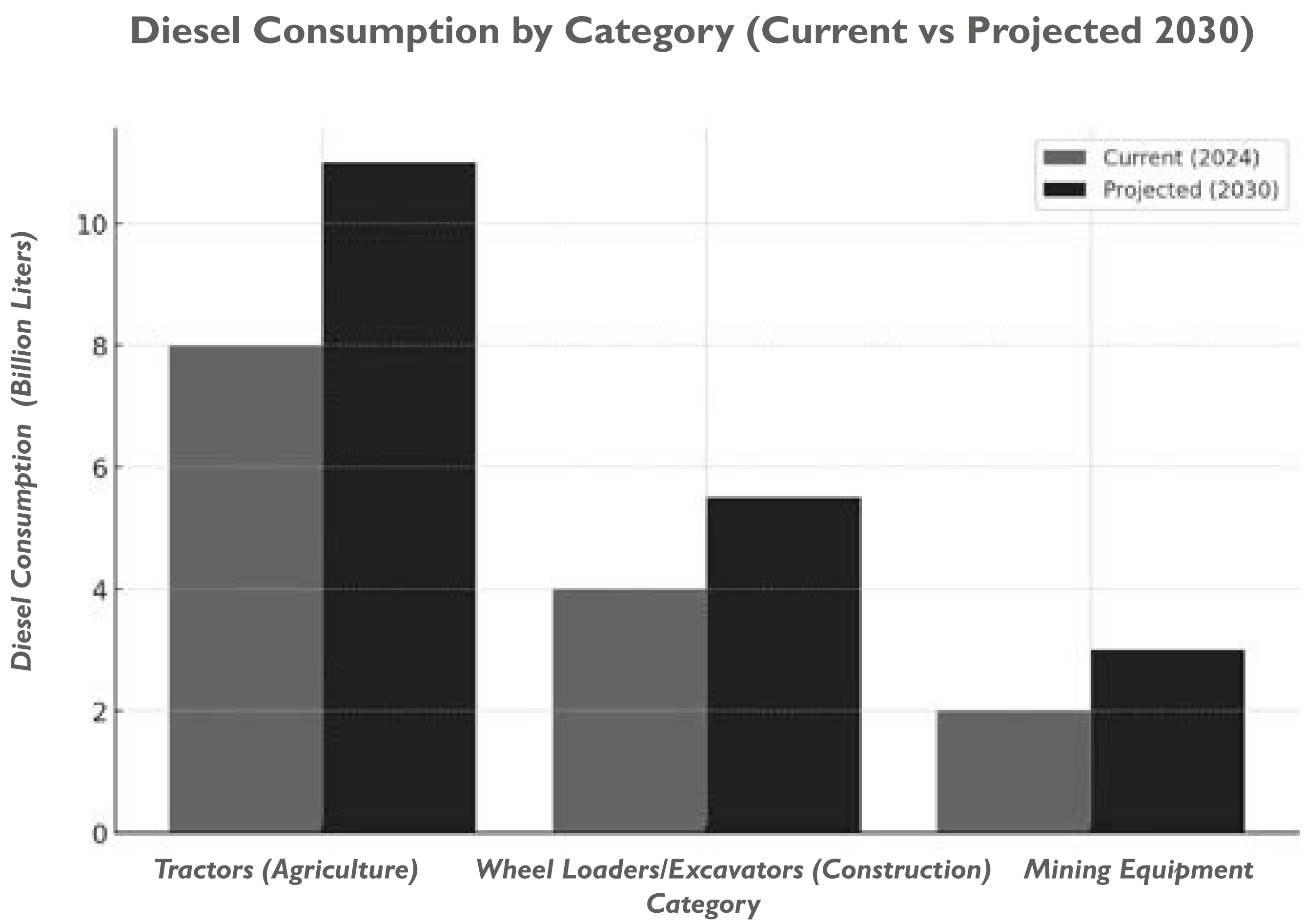
*Lifetime Viability Gap Funding (VGF) funding support.*
**NA ( not considered ) because the benefits of GHG reduction are very low.*

3 IRENA AND METHANOL INSTITUTE (2021). Innovation Outlook : Renewable Methanol.
International Renewable Energy Agency, Abu Dhabi. Retrieved from:https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf.

# Introduction

By 2030, India's GDP (Gross Domestic Product) is expected to double, leading to an increase in construction, mining, and agricultural activities to cater to growing demand.This study focuses on agriculture, construction, and mining, which are key sectors driving economic growth. Driven by increasing uptake for mechanized approach to farming, rapid urbanization leading to multi-fold growth in construction, and growing energy needs met by new mining exploration has increased the focus on these sectors, particularly when the focus of the government has been on decarbonization or low-carbon alternatives. Fuel consumption is among the key indicators of GDP, International Energy Agency (IEA) forecasts indicate diesel consumption in India is expected to grow at 4.5% annually between 2023 and 2030, in comparison China's consumption flattened, OECD, and the rest of the world are projected to have negative growth.[4]

This analysis is focused on the agriculture, construction, and mining sectors and their potential for reducing carbon footprint using alternative fuels/technologies. The consumption of diesel by tractors, excavators, and mining equipment in India is expected to grow substantially, given the extensive use of these machines in agriculture, construction, and mining sectors. The graph below highlights the projections for diesel consumption for crucial equipment.




*Annual diesel consumption for tractor, excavators, and mining equipments*

**1.Diesel Consumption by Agriculture Sector:** Agriculture sector in India consumes around 8 billion liters of diesel annually. Increase in penetration of solar pumps point to future demand majorly driven by farm machinery, primarily tractors. Diesel consumption for this sector is projected to reach 11 billion liters by 2030.
Sector Share: Agriculture, where tractors are primarily used, accounts for approximately 12.5% of the total annual diesel consumption in India.[5]

**2. Diesel Consumption by Construction Sector:** Annual Diesel Consumption: Wheel Loaders/Excavators, which account for 90% of the sales for construction equipment are estimated to consume around 4 billion liters of diesel annually[6,7]. Diesel Consumption in 2030 is expected to be 5-6 billion liters based on the growth rate projected by IEA for this sector.
Sector Share: Construction and infrastructure equipment, including excavators, account for about 4.5% of the total annual diesel consumption.[8]

**3. Diesel Consumption by Mining Equipment:** Annual Diesel Consumption: Mining equipment, including large excavators, dumpers, and loaders, is estimated to consume around 2 billion liters of diesel annually. The Projected Diesel Consumption in 2030 is 3 billion liters based on the growth rate projected by IEA.
Sector Share: The mining sector is responsible for about 2.2% of India's total annual diesel consumption. [9]
These three categories combined account for approximately 14-15 billion liters of diesel annually. This represents a significant portion of the country's total diesel consumption, which is around 90 billion liters per year.
This study is focused on the key machinery/vehicles/equipment used in off-road sectors mentioned above. Consumption of tractors in agriculture, wheel loaders/excavators in construction, and haul trucks in mining are the key equipment.

**Key Diesel Consumption Trends in Off-Road Segment:**
If the segment is unaddressed, off-road vehicles could become a major contributor to emissions due to heavy focus on decarbonisation of passenger and on-road vehicles.[10] Projected with high growth, rapid decarbonisation of this segment is the only path to limit emissions and limit its contribution to global warming. One key attribute about off-road segments is they have repetitive paths/operations and are operated in fleets. If this growing fleet continues to rely on fossil fuels, they will further pollute the air, worsen public health risks, increase energy costs, and raise emissions, even as many countries strive to reduce their carbon footprints. India has the opportunity to bypass fossil fuels and expand low-carbon alternatives like green hydrogen and its derivatives.

4 International Energy Agency. (2024). Indian Oil Market: Outlook to 2030. IEA, Paris. Retrieved from: https://www.iea.org/reports/indian-oil-market
5 International Energy Agency. (2024). Indian Oil Market: Outlook to 2030. IEA, Paris. Retrieved from: https://www.iea.org/reports/indian-oil-market
6 EPC World. (2022). Volvo CE India takes a big leap forward with adoption of Bio-diesel blends to power its range of construction equipments. Retrieved from: https://www.epcworld.in/p/post/volvo-ce-india-takes-a-big-leap-forward-with-adoption-of-bio-diesel-blends-to-power-its-range-of-construction-equipments
7 Mining sector consumption, Retrieved from: https://iced.niti.gov.in/energy/fuel-sources/oil/consumption#sector-wise-consumption
8 Based on annual fuel consumption compared to total sector consumption, Retrieved from: https://iced.niti.gov.in/energy/fuel-sources/oil/consumption#sector-wise-consumption
9 India Climate and Energy Dashboard, Mining Sector share, Retrieved from: https://iced.niti.gov.in/energy/fuel-sources/oil/consumption#sector-wise-consumption

The case for green hydrogen as a fuel of preference for achieving zero emissions transport is outlined below.

**1. Refueling time:** Refueling time is an important factor in off-road vehicle operations, particularly, mining haul trucks and construction equipment. The time taken to refuel and downtime of equipment are optimized to save costs in operations. Alternative fuels/technologies that can provide similar refueling time or faster can provide added benefits in cost savings.

**2. Consistent demand justifies investments into the infrastructure:** Cost of transportation and storage of green hydrogen is a drawback in comparison to battery operated vehicles. However, for medium/heavy duty applications with consistent demand, this is an opportunity to invest in the supply chain, allowing OEMs and tank suppliers to amortize R&D and capex over a larger number of vehicles will help bring down the cost curve for all vehicles and support the competitiveness of solutions based on hydrogen and its derivatives.

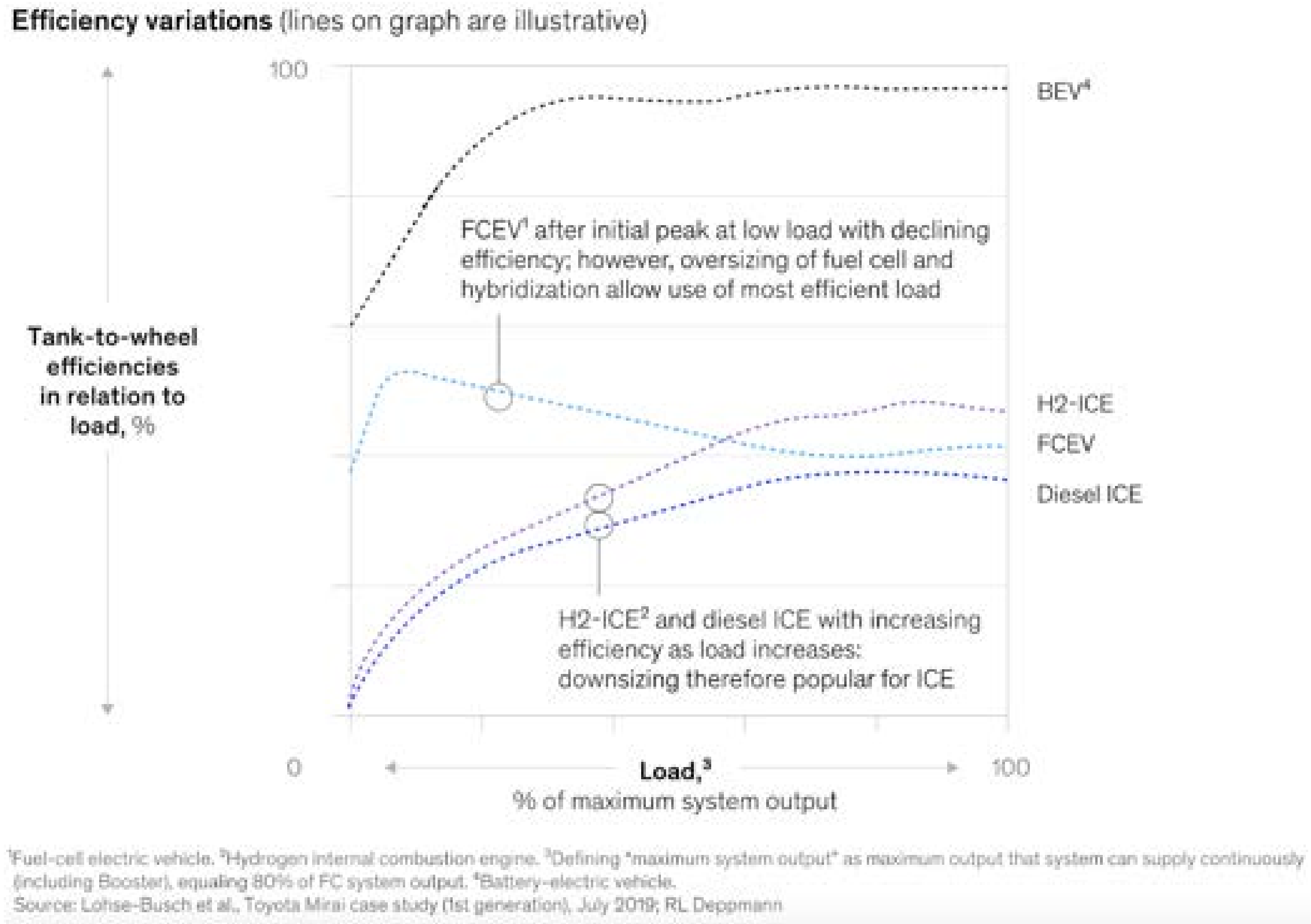
**3. Clean transport:** Green hydrogen fuelled vehicles emit water and heat as by-products, making it a clean mode of transport.

**4. Familiar design and architecture for Green Hydrogen-ICE:** Integrating green hydrogen combustion engines into off-road vehicles is an attractive option, as it builds on well-known design principles and existing architecture. Moreover, the cooling transmission and hydraulic systems are like diesel engines, as are the repair and maintenance costs. ICEs have demonstrated their capability to cater to the requirements of off-road sectors like round-the-clock operations with minimal downtime, extreme vibrations, heat development, high exposure to dirt, and high power required on board the vehicles. FCEVs are yet to meet these requirements in harsh conditions due to limited technical innovation, however green hydrogen based ICEs can meet these requirements. The illustration below best highlights the performance comparisons at different loads on the engine.[11]

The challenges of displacing diesel engines with green hydrogen combustion engines or fuel cells is the high cost of vehicles and higher fuel costs, majorly due to transporting and storage of hydrogen to the site. Lack of infrastructure to support and nudge users through policies to shift their fuel consumption can be a probable cause of this segment's premature demise. An attempt has been made to better understand the cost components for total cost of ownership for alternative fuels/technologies.

10 Kubsh, J. (2017). Managing emissions from non-road vehicles. The International Council on Clean Transportation. Retrieved from: https://theicct.org/wp-content/uploads/2021/06/Non-road-vehicle-management_ICCT_consultant-repor_24042017_vF.pdf

11 Heid. B, Martens. C, Orthofer, A. (2021). How Hydrogen combustion engines can contribute to zero emissions. McKinsey & Company. Retrieved from:




*Performance comparisons at different roads on the engine*

## Methodology

With advancements in fuel cells, the future of green hydrogen applications looks promising. This study focuses on potential for decarbonization of off-road vehicles used in three sectors - agriculture, construction, and mining. The key objectives of this study are outlined below

1. Assess the application of green hydrogen and fuel cell technologies for equipment applications in the heavy-duty (HD) off-road markets, initially focusing on the agriculture, construction, and mining market sectors
2. Understand current technology gaps
3. Estimating the total cost of ownership (TCO) for off-road diesel operated vehicles used in agriculture, construction, and mining
4. Identifying the applications of green hydrogen and green methanol in Internal Combustion Engines (ICEs), and mapping their Technology Readiness Levels (TRLs)
5. Estimating the TCO for alternative fuels like green hydrogen, green methanol, and CNG with hydrogen blending in above mentioned sectors
6. Comparing the TCO and emissions mitigation potential of these alternative fuels
7. Recommending an approach for testing above mentioned alternative fuels and estimating the funding model for Government of India (GoI) to promote pilots in these sectors.

https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/how-hydrogen-combustion-engines-can-contribute-to-zero-emissions

## Key Assumptions

This exercise involved understanding the cost components of alternative fuel technologies for off-road applications, listed below.

1. Diesel-based ICEs (Base case)
2. Green hydrogen-based ICEs
3. Green hydrogen-based fuel cell electric vehicle (FCEVs)
4. CNG engines blended with 20% (by volume) green hydrogen.
5. 100% Green Methanol (M100)

The approach for estimating the TCO and common assumptions are discussed below.

- **Capital Costs:** Upfront costs for certain classes of vehicles are not publicly available, and are derived by applying specific ratios to available prices of heavy-duty vehicles of the same fuel type. The debt-to-equity ratio for all vehicle categories is assumed at 80:20. Nominal interest rates were assumed, varying based on vehicle category. The loan payback period was consistently set to five years. Taxes and insurance rates are combined in the total capex estimates.
- **Fuel Costs:** Annual operating hours for different vehicle categories are well outlined in existing literature, assuming nominal fuel efficiencies for respective fuels, the fuel costs are estimated over a 10-year operational lifespan. The cost escalation for diesel is assumed based on historical prices trends.
- **Operating and Maintenance Costs:** Operating and maintenance costs for all vehicle classes were assumed as a share of the listed vehicle prices.
- **Fuel Efficiency:** Mileage for all vehicles was assumed to be constant throughout the 10–year period of assessment for the total cost of ownership.

# 1. Non-Fossil Fuel Based Tractors For Agriculture

## 1.1 Technology Readiness

Advantages for green hydrogen in agricultural applications are high because of the low refueling time and lighter powertrain in comparison to battery operated vehicles (for heavy duty tractors) among zero emissions transportation technologies. Green hydrogen-based methanol and ICEs deliver efficiency in the range of 40-45%, using a conventional powertrain while green hydrogen-based Fuel Cell Electric Vehicle (FCEV) deliver efficiency in the range of 45-55% with an electric powertrain.

*Fendt e100 Vario, methanol-based tractor developed through a collaboration between AGCO Power and Blue World Technologies*

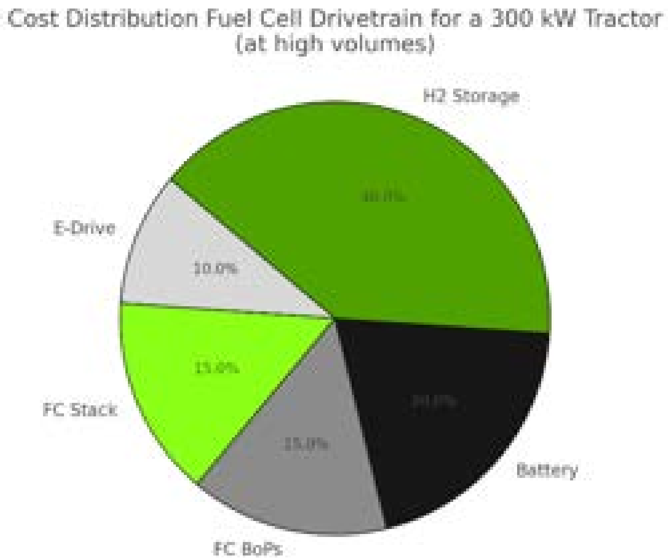
• Fendt e 100 Vario is one of the first direct applications of green methanol for tractors. This product is in the early development stages.[13]

• Thermax Ltd has successfully developed a 5 KW green methanol-based reformer in India on a Direct Methanol Fuel Cell (DMFC). This module is being tested to replace DG sets in mobile towers.Kirloskar Oil Engines Ltd has converted a 5 KW generator set to run on 100% green methanol for direct electricity generation. Kirloskar is working towards converting generator sets of 150-300 KVA/ KW capacity in collaboration with Dor Chemicals, Israel.[14]

Apart from green methanol-based tractor, fuel cell drivetrains have undergone field testing in the USA, Australia, and Europe.

Key learnings which emerged from the fuel cell-based trials are outlined below:

• Storage of green hydrogen-based fuel locally is challenging. Gaseous hydrogen storage is about 2 tons heavier than diesel and liquid green hydrogen is about 500 kg heavier. However, the primary barrier to achieving similar runtime is the system's volume, as even liquid hydrogen would require a storage system appropriately seven times larger in volume than a diesel fuel storage system.[12]




*Cost of Green Hydrogen storage and transportation is the biggest contributor to drivetrain costs for FEV contributing to 60% of the total FCEV drivetrain costs. Other major costs include the balance of plant systems (BoPs) including compressor, DC-DC converter, and fuel cell stacks.*

• Cooling requirement for tractors is high, necessitating larger radiator capacity on board and also increasing the load on the fuel cell.

• The challenge of fuel cell life for agricultural applications is projected at 10,000 hours, but based on initial pilots, the life of FCEVs can be lower with varying operating conditions and loading of tractors.

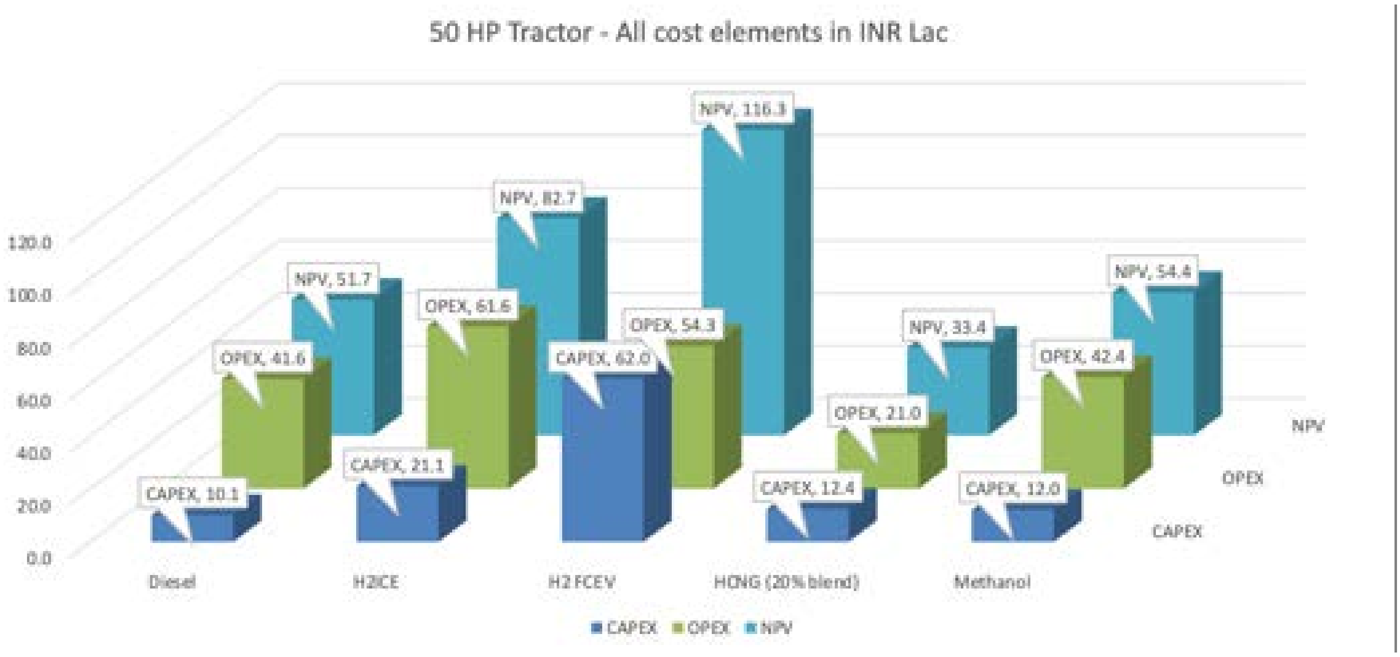
| Technology/fuel for Tractors | TRL (out of 10) | Description |
|---|---|---|
| H-CNG (20% Blend) | 7 | Commercial model and readiness not proven |
| Green Methanol | 6 | Undergoing field demonstration in USA |
| Green Hydrogen-based FCEV | 5 | Applications for low-HP tractors yet to be demonstrated |
| Green Hydrogen ICEs | 4 | |

*A table showing the TRL of the technologies for tractors*

12 CNHi Team. (2021). Technology Challenges for Hydrogen Fuel Cells in Agricultural Applications. CNHi Industrial. Retrieved from: https://www.energy.gov/sites/default/files/2021-12/922-11-mission-innovation-CNH.pdf
13 Blue World Technolgies (2023). Fuel cell manufacturer Blue World Technologies in collaboration with AGCO Power on electric Fendt tractor to run on methanol. Retrieved from: https://www.blue.world/fuel-cell-manufacturer-blue-world-technologies-in-collaboration-with-agco-power-on-electric-fendt-tractor-to-run-on-methanol/
14 NITI Aayog. Methanol Economy. Retrieved from: https://www.niti.gov.in/methanol-economy

## 1.2 Total Cost of Ownership

Results from estimation of the total cost of ownership (TCO ) for 50 HP tractors indicate that green methanol and CNG blended with 20% green hydrogen are the most attractive options in comparison with the existing option of diesel vehicles.



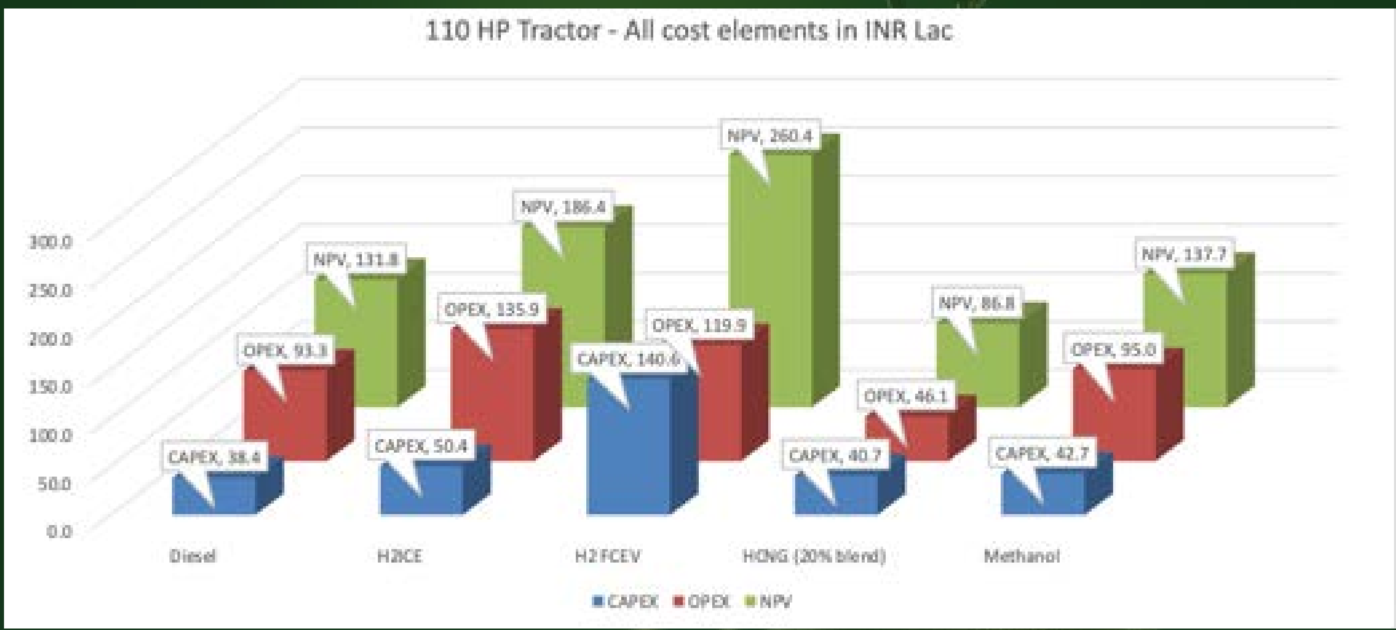

*An estimation of the TCO for 50 HP tractors*

| Lifeltime Cost (TCO) per Vehicle | | | | | |
|---|---|---|---|---|---|
| 50 HP Tractor | | | | | |
| **INR Lakh** | **Diesel** | **H2ICE** | **H2FCEV** | **HCNG(20% blend)** | **Methanol** |
| **CAPEX** | 10.1 | 21.1 | 21.1 | 12.4 | 12.4 |
| **OPEX** | 41.6 | 61.6 | 61.6 | 21.0 | 21.0 |
| **NPV** | 51.7 | 82.7 | 82.7 | 33.4 | 33.4 |

*Lifetime Cost (TCO) per Vehicle*

While the capital expenditure for both green methanol and H-CNG are about 19% and 22% higher in comparison with diesel-operated vehicles, higher fuel efficiencies in tractor engines and lower fuel costs result in lower operating costs over a 10-year period of assessment.[15] Established research indicates about 50% and 40% in fuel cost savings respectively, for green methanol and -green hydrogen-CNG in comparison to diesel engines. However, green methanol derived from electrolysis using renewable energy sources is more than double the cost of biogenic methanol. Green methanol emerges as the strongest alternative source of energy and could prove cost effective compared to diesel with the right policy backing and industry response.

High capital costs and fuel costs of both the Green Hydrogen based technologies, fuel cells and green hydrogen ICEs, make them cost prohibitive despite their high efficiencies. Any cost efficiencies achieved in the green hydrogen storage and transportation will result in significant savings over the TCO comparison with diesel vehicles. The estimations do not account for degrading fuel efficiency of a vehicle in its lifetime.
The graphs below highlight the TCO comparison of both 50 HP and 110 HP tractors across fuel types.




*An estimation of the TCO for 110 HP tractors*

| Lifeltime Cost (TCO) per Vehicle | | | | | |
|---|---|---|---|---|---|
| 110 HP Tractor | | | | | |
| **INR Lakh** | **Diesel** | **H2ICE** | **H2FCEV** | **HCNG(20% blend)** | **Methanol** |
| **CAPEX** | 38.4 | 50.4 | 140.6 | 40.7 | 42.7 |
| **OPEX** | 93.3 | 135.9 | 119.9 | 46.1 | 95.0 |
| **NPV** | 131.8 | 186.4 | 260.4 | 86.8 | 137.7 |

*Lifetime Cost (TCO) per Vehicle*

15 Schröder, J., Müller-Langer, F., Aakko-Saksa, P., Winther, K., Baumgarten, W., & Lindgren, M. (2020). Methanol as motor fuel: Summary Report. Advanced Motor Fuels Technology Collaboration. Retrieved from: https://iea-amf.com/app/webroot/files/file/Annex%20Reports/AMF_Annex_56.pdf

## 1.3 Viability Gap Funding Requirements

The viability gap funding (VGF) requirements are projected for deployment per vehicle, with the total cost of diesel vehicle ownership as the benchmark. The VGF requirements along with their emissions reduction potential is shown in the table below.

| 50 HP *Tractor* | | | | |
|---|---|---|---|---|
| **INR Lakh** | **H2ICE** | **H2FCEV** | **HCNG(20% blend)** | **Methanol** |
| **VGF Funding Suppourt in INR Lakh** | 31.0 | 64.6 | NA | 2.7 |
| **Emissions reduction potential** | 91% | 93% | 65% | 98% |

*Viability Gap Funding Requirements for 50 HP Tractor*
**NA Not considered for VGF due to low emission reduction potential*

| 110 HP *Tractor* | | | | |
|---|---|---|---|---|
| **INR Lakh** | **H2ICE** | **H2FCEV** | **HCNG(20% blend)** | **Methanol** |
| **VGF Funding Suppourt in INR Lakh** | 54.6 | 128.6 | NA | 6.0 |
| **Emissions reduction potential** | 91% | 93% | 65% | 98% |

***Viability Gap Funding Requirements for 110 HP Tractor***
****NA Not considered for VGF due to low emission reduction potential***

While methanol as a fuel to power tractors presents a strong proposition for investment support, ensuring consistent fuel supply and its safe storage are crucial for farmers/co-operatives to invest in tractors run on alternative fuels. Supporting this ecosystem with a robust supply chain will reduce cost of the fuel and increase demand for green methanol or green hydrogen based tractors.

# 2. Non-Fossil fuels based Excavators for Construction

## 2.1 Technology Readiness

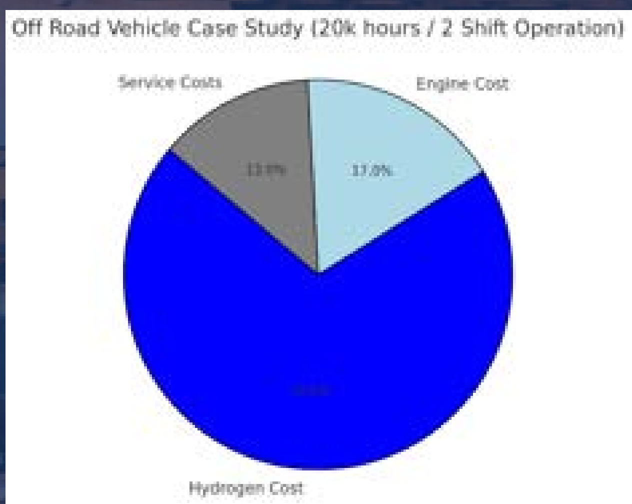
Construction sector decarbonization using green hydrogen and its derivatives as a fuel is at a relatively nascent stage. Early prototypes are being tested; the engine capabilities are being developed for different applications by established electrolyzer and fuel cell manufacturers. The requirements associated with both green hydrogen fuel-based ICEs and FCEVs for onboard storage tanks are challenging for construction equipment like excavators. Further, continuous operations for fuel cell based excavators beyond twelve is challenging. Fuel cell plus battery-powered engines, FCEVs, loose tank-to-wheel efficiency at higher loads, and continuous operations with FCEVs could result in efficient use of fuels.[16]

High pressure Green Hydrogen based fuel cell is an upcoming techology for excavators. The key cost drivers for off-road vehicle in construction using Nuvera fuel cells, based on the case study.[17] Nuvera tested their E-series fuel cell engine for 2-day off-road shift operation depand on:

- Total cost of ownership
- Minimum power requirements
- Durability of the fuel cell engine
- Hydrogen fuel usage over lifetime

The chart below showcases the following data:
- Hydrogen Cost contributes 70% of the total cost.
- Engine Cost contributes 17%.
- Service Costs contribute 13%.


Liebherr R 9XX H2 Excavator: Liebherr introduced the R 9XX H2, a crawler excavator powered by a green hydrogen combustion engine.




Case study of Nuvera fuel cells, a US-based green hydrogen company

| Technology/fuel for construction | TRL (out of 10) | Description |
|---|---|---|
| Green HydrogenICE | 3 | Applications for excavators and other construction machines yet to be demonstrated |
| Green Hydrogen-basedFCEV | 4 | |
| H-CNG (20% blend) | 5 | Commercial model and readiness not proven |
| Green Methanol | 5 | Usage of green methanol as a fuel will prove challenging inconstruction machinery, given the vibration and other stresses witnessed by the vehicles |

***A table showing the TRL for construction sector machinery***

This case study highlights that the cost of hydrogen is a major factor in the overall cost distribution for this off-road application.

The table below shows the technology readiness levels for construction sector machinery.

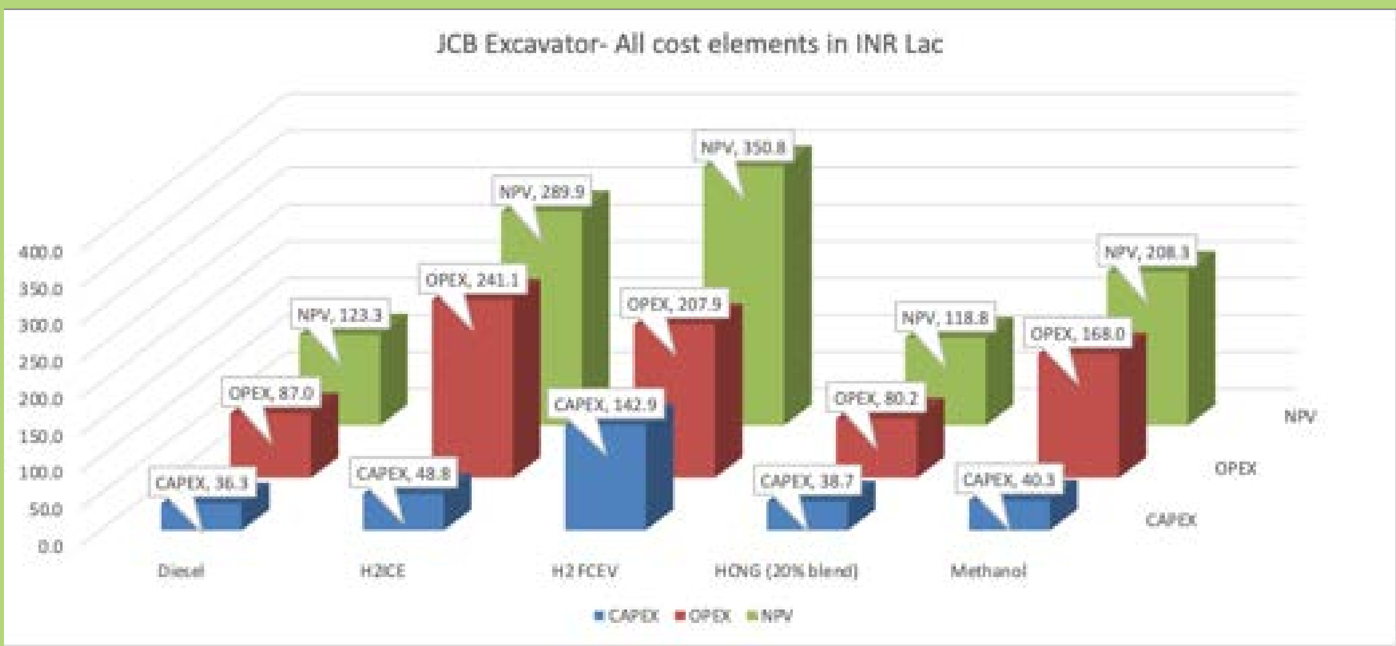
16 Heid. B, Martens. C, Orthofer, A. (2021). How Hydrogen combustion engines can contribute to zero emissions. McKinsey & Company. Retrieved from: https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/how-hydrogen-combustion-engines-can-contribute-to-zero-emissions 17 Nuvera Fuel Cells (2021). Retrieved from: https://www.energy.gov/sites/default/files/2021-12/923-10-mission-innovation-nuvera.pdf.

## 2.2 Total Cost of Ownership

The share of mid-size engines (50-175 HP) is highest in the construction equipment market in India. We assumed a 100 HP excavator as reference equipment for this study. Results from the estimation of TCO for 100 HP excavators indicate high operational costs involved primarily driven by diesel consumption. The commercial scope for FCEVs and green hydrogen-ICEs will become attractive with lower fuel costs.

Vehicle costs are a small share of the total costs with their share ranging from 4-12%, with the highest being FCEVs. Interestingly, the difference in upfront costs between FCEV and diesel vehicles contributes to higher Net Present Value (NPV) for diesel vehicles. Technology maturity will drive down the TCO and make FCEVs an attractive option.
Green methanol and green hydrogen blended-CNG are the most cost-effective alternatives to diesel fuel. However, the availability of e-methanol and the capability of conventional engines to blend green hydrogen fuel beyond 20% is limited. This limits the capability to invest despite their low TCO.

The significant opportunity offered by green hydrogen ICEs, given their familiar powertrain, to reduce emissions from the construction segment is a viable alternative despite its high costs. With reduced storage and transportation costs, and likelihood of higher adaptability within the sector, green hydrogen ICEs are the best alternative fuel. Several OEMs, engine suppliers, engineering-service companies, and H2-ICE start-ups are investigating hydrogen combustion as part of their off-road zero-emissions solution offerings. The lower R&D costs involved in developing green hydrogen ICEs in comparison to fuel cells is also a key determining factor for the market leaning towards this technology.




*An estimation of the TCO for JCB Excavator*

| Lifeltime Cost (TCO) per Vehicle | | | | | |
|---|---|---|---|---|---|
| **100 HP JCB Excavator** | | | | | |
| **INR Lakh** | **Diesel** | **H2ICE** | **H2FCEV** | **HCNG (20% blend)** | **Methanol** |
| CAPEX | 36.3 | 48.8 | 142.9 | 38.7 | 40.3 |
| OPEX | 87.0 | 241.1 | 207.9 | 80.2 | 168.0 |
| NPV | 123.3 | 289.9 | 350.8 | 118.8 | 208.3 |

*Lifetime Cost (TCO) per Vehicle*

## 2.3 Viability Gap Funding Requirements

Like the agriculture sector, viability gap funding (VFG) requirements are projected per vehicle, with the total cost of diesel vehicle ownership as the benchmark. The VGF requirements, along with their emissions reduction potential, is shown in the table below.

| 100 HP JCB Excavator | | | | |
|---|---|---|---|---|
| **INR Lakh** | **H2ICE** | **H2FCEV** | **HCNG (20% blend)** | **Methanol** |
| VGF funding support in INR Lakh | 166.6 | 227.5 | NA | 85.0 |
| Emissions reduction potential | 82% | 86% | 31% | 96% |

*Viability Gap Funding Requirements for 100 HP JCB Excavator*
**Not considered for VGF due to low emission reduction potential*

Construction activities emit more than 23% of global GHG emissions. Decarbonization of construction machinery, which is the major consumer of diesel in the construction sector, is a policy priority. India has a robust market for manufacturing construction equipment machinery, the strategies to decarbonize the sector must involve the manufacturers in the supply chain. For example, in China, the manufacturers laid out R&D initiatives for the demonstration of alternative fuels for electric excavators, loaders, truck cranes, forklifts, etc.

Demand for stronger ecosystem support, particularly in procurement policies for construction equipment or favorable conditions in public works for zero emissions equipment, will enhance the use of alternative fuels for this machinery. The supply chain for manufacturing can be incentivized to invest in developing an R&D base and product prototyping for testing alternative fuels.

# 3. Non-Fossil Based Excavators for Mining

## 3.1 Technology Readiness

There is tremendous pressure for the mining sector to decarbonize its operations. Poor environmental performance is linked to the ability to leverage capital at lower rates. Lowering emissions incentivizes mining companies to improve their financial and operational performance. Hauling extracted resources accounts for 35% of mining emissions with electricity used for processing contributing another 30%.[18] Replacing diesel haul trucks with low-carbon alternatives is essential for mining companies to decarbonize their operations.

**Mining haul truck (250HP)**

Both, green hydrogen ICEs and Fuel Cell Electric Vehicles (FCEVs) are expected to be commercially available by 2028, with pilot vehicles available currently. The table below shows the technology readiness levels for construction sector machinery 11.

| Technology/fuel for construction | TRL (out of 10) | Description |
|---|---|---|
| Green HydrogenICE | 5 | Pilots for heavy duty trucks already conducted using GH2 ICEs and FCEVs |
| Green Hydrogen-basedFCEV | 5 | |
| H-CNG (20% blend) | 5 | Commercial model and readiness not proven |
| Green Methanol | 7 | M100 heavy duty trucks are commercially available in China and Europe. They are yet to be proven in India. Further, the supply chain for e-methanol is not established yet. |

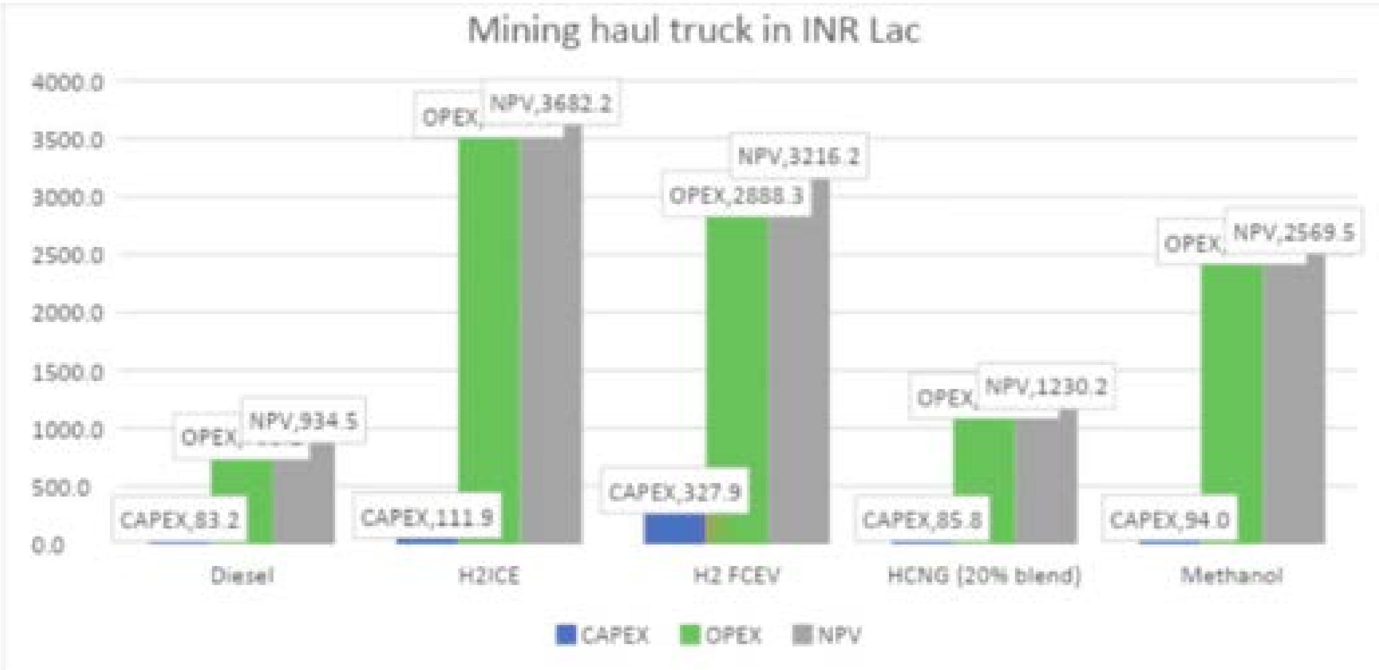
***A table showing TRL for construction sector machinery***

18 Muralidharan, R., Thomas, K., Blank, T,. (2019). Pulling the Weight of Heavy Truck Decarbonization: Exploring Pathways to Decarbonize Bulk Material Hauling in Mining. Rocky Mountain. Retrieved from: https://rmi.org/insight/pulling-the-weight-of-heavy-truck-decarbonization/

## 3.2 Total Cost of Ownership

Mine haulage trucks are designed to operate for long stretches with only refueling breaks. The operational costs of haulage trucks dwindle the upfront costs of vehicles in comparison. The total cost of ownership (TCO) analysis indicates operational costs of green hydrogen ICEs and FCEVs are about three times the costs of diesel vehicles, owing to high fuel costs, primarily for storage and transportation. Local storage and generation can significantly reduce the costs of green hydrogen-based alternatives.

Green methanol offers a viable alternative in this segment given its proven track record for heavy duty trucking applications. On site production and storage of green hydrogen can significantly tilt the scales to favor ICEs or FCEVs for mining haulage trucks. The TCO analysis assumes 250 HP trucks for hauling in mines.
The graph below highlights the TCO comparison of 250 HP mine haulage trucks across fuel types.




*An estimation of the 250 HP mine haulage trucks*

**Lifeltime Cost (TCO) per Vehicle**

| 250 HP HDT Mining truck | | | | | |
|---|---|---|---|---|---|
| **INR Lakh** | **Diesel** | **H2ICE** | **H2FCEV** | **HCNG (20% blend)** | **Methanol** |
| CAPEX<br>OPEX<br>NPV | 83.2<br>795.2<br>934.5 | 111.9<br>3570.2<br>3682.2 | 327.9<br>2888.3<br>3216.2 | 85.8<br>1144.4<br>1230.2 | 94.0<br>2475.5<br>2569.5 |

*Lifetime Cost (TCO) per Vehicle*

## 3.3 Viability Gap Funding Requirements

The viability gap funding (VGF) requirements are projected for a deployment per vehicle, with the total cost of diesel vehicle ownership as the benchmark. The VGF requirements, along with their emissions reduction potential, is shown in the table below.

| 250 HP Mine haul truck | | | | |
|---|---|---|---|---|
| **INR Lakh** | **H2ICE** | **H2FCEV** | **HCNG (20% blend)** | **Methanol** |
| VGF funding support in INR Lakh | 2747.6 | 2281.7 | 295.7 | 1635.0 |
| Emissions reduction potential | 75% | 80% | 2% | 94% |

***Viability Gap Funding Requirements for 250 HP mine haulage trucks***
****Not considered for VGF due to low emission reduction potential***

Mines must take significant action in order to stay within their carbon budget. Even with conservative assumptions the drivers of growing demand compound into a total growth in trucking demand of 125% for mining sector.[19] Hauling minerals from mines to processing units using trucks make up 30%–50% of their mines' total energy use. Together, these mining trucks emit 68 million tons of CO2 (MtCO2) per year. The opportunity to decarbonize does not get bigger than the mining sector.

About 50,000-60,000 mining haul trucks were sold in the financial year 2023-24.[20] While the mining sector presents an opportunity to both reduce diesel consumption and consequently decarbonise the fleet, the volume of fuel required for on-site operations is huge. The viability gap funding should focus on ensuring that the supply chain linkages can support supply of alternative fuels like green hydrogen and green methanol to scale across the fleet of operations. This will provide the mine owners or operators to invest in alternative technologies to decarbonise their operations.

# Conclusion

Recognizing the economic and environmental advantages of Zero Emission Transport (ZET), nations are shifting away from fossil fuels. ZETs present India an opportunity to distinguish itself in the global market for achieving emissions reduction in the off-road segment. The demand for off-road vehicles has rapidly increased leading to higher emissions from the sector.

Alternative fuel options (e.g. green methane, green methanol and other green hydrogen derivatives) using different resources – mainly renewables – and conversion technologies are being explored as a green fuel. Providing renewable fuels for combustion engines does not reduce the need for adaptation of advanced technologies, such as green hydrogen fuel cell based electric powertrains.

Green methanol could be a key solution for addressing global warming and air pollution in sectors and regions where powertrain electrification is difficult. Renewable green methanol offers significant greenhouse gas reduction potential, and its physical properties enable clean and efficient combustion. Green Methanol is a multipurpose fuel and can be used straight and as a blended fuel. Combustion with 100% methanol (M100) releases very low particulate and NOx emissions. Engines dedicated for M100 can increase wheel efficiency compared to diesel engines. Primary challenges in growth of M100 as a priority fuel include limited R&D focus by the auto industry, production capacity of renewable methanol, and safe transportation and handling. It can be used in internal combustion engines, and in hybrid and fuel cell vehicles and vessels. It is a liquid at ambient temperature and pressures, and so is straightforward to store, transport and distribute. It is compatible with existing distribution infrastructure and can be blended with conventional fuels.

The analysis underscores the critical importance of focusing on green methanol as a viable alternative fuel. Numerous indicators highlight its advantages, including low capital expenditures and operational costs. Green methanol is poised to play a pivotal role in the shift to cleaner energy, as evidenced by China's emergence as the top consumer for automotive use and Europe's exploration of its potential in fuel cell electric vehicles.[21] To fully realize this potential, strong support from policymakers and industry stakeholders is essential.

19 Muralidharan, R., Thomas, K., Blank, T,. (2019). Pulling the Weight of Heavy Truck Decarbonization: Exploring Pathways to Decarbonize Bulk Material Hauling in Mining. Rocky Mountain. Retrieved from: https://rmi.org/insight/pulling-the-weight-of-heavy-truck-decarbonization/

20 Assuming 20% of the heavy-duty trucks sold are for hauling at mines. https://www.autocarpro.in/news/case-construction-equipment-to-introduce-6-new-products-at-excon-2023-117853

21 Schröder, J., Müller-Langer, F., Aakko-Saksa, P., & Winther, K. (2020). Methanol as Motor Fuel. Retrieved from: https://iea-amf.org/app/webroot/files/file/Annex%20Reports/AMF_Annex_56.pdf

22 Accelerating the Net-zero transition, Methanol institute, 2024, https://www.methanol.org/wp-content/uploads/2024/06/240607AramcoMI-Joint-Report-release.pdf

About half of the cost of producing renewable methanol comes from the cost of renewable energy. Approximately one-third of the cost is for synthesis of the fuel, remaining costs are for sourcing the carbon. Leveraging low-cost renewable energy in India can help bring down the cost of e-methanol significantly.[22] The capital investment for a green methanol synthesis unit using CO2 and H2 is estimated to be about the same as that for a conventional syngas-based plant. The technology to produce green methanol is thus already mature and very similar to the one used in traditional fossil fuel-based plants.[23]

Green hydrogen based technology alternatives are complementary as they rely on the same ecosystem as green methanol. The infrastructure required for transportation and storage of green hydrogen and its derivatives is necessary investment.

The aim of this analysis is also to solicit recommendations from industry, government, and independent agencies to ensure we have a holistic approach to investing in decarbonization of off-road sectors in India. Therefore, the results of the analysis will form the basis for a larger discussion on viable alternatives, approach for policy, investment, and industry involvement in the path to decarbonization.

23 IRENA AND METHANOL INSTITUTE (2021). Innovation Outlook : Renewable Methanol.
International Renewable Energy Agency, Abu Dhabi. Retrieved from: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf.

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