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A comparison of the life-cycle greenhouse gas emissions from combustion and electric heavy-duty vehicles in India

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EXECUTIVE SUMMARY

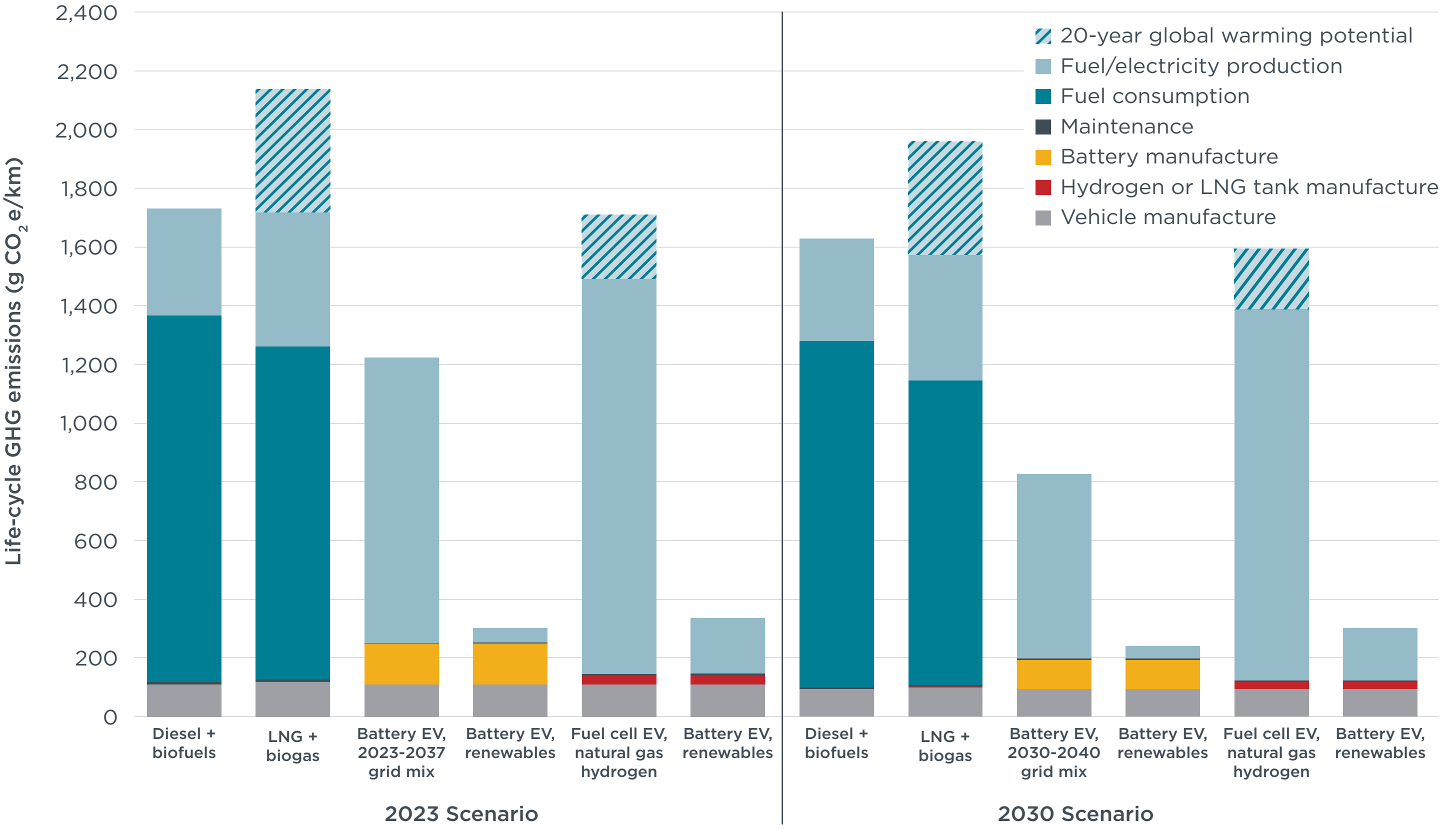
The heavy-duty vehicle (HDV) sector accounts for a majority of India's on-road transport emissions and is one of the largest contributors to total greenhouse gas (GHG) emissions in the country. Though Indian authorities have implemented efficiency standards for HDVs and proposed ambitious biofuel blending mandates, HDV emissions are still expected to as much as double by 2050, which would be incompatible with national and international climate commitments. To meet its decarbonization goals, India must reduce HDV emissions.

This study evaluates the life-cycle GHG contribution of different HDV vehicle technologies and fuel pathways in India. Examining three representative HDVs—a 12-tonne rigid truck, a 55-tonne tractor trailer, and an urban bus—we evaluate a mix of different powertrain technologies, including best-in-class diesel HDVs, natural gas-fueled HDVs, battery-electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs). For each, we estimate GHG emissions across the vehicle's entire life cycle, including upstream emissions (e.g., manufacturing and fuel production). To assess technology improvements and shifts in fuel and electricity mixes over time, we model the life-cycle emissions of new vehicles entering the fleet in 2023 and in 2030.

As a representative example, Figure ES1 illustrates the GHG emissions of 55-tonne tractor-trailer HDVs manufactured in 2023 and 2030. The figure shows emissions from diesel and natural gas internal combustion engine (ICE) vehicles, BEVs, and FCEVs. Diesel and natural gas pathways account for reductions in GHG emissions from biofuel blends. In addition, we estimate emissions from using either grid or 100% renewable electricity in the BEV and the FCEV using either hydrogen made from liquified natural gas (LNG) or 100% green hydrogen (hydrogen made using electrolysis powered by renewable electricity).

Figure ES1

Comparison of GHG emissions of 55-tonne tractor-trailers produced in 2023 and 2030, by powertrain and fuel type.



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This analysis leads to five conclusions:

1. **Battery-electric HDVs produced in India today offer the greatest GHG emissions reductions of current vehicle technologies, but their impact can be increased significantly by a faster phaseout of coal in India's electricity grid.** Across vehicle categories, we estimate that the life-cycle GHG emissions of BEV HDVs produced in India in 2023 are approximately 17%–29% lower than diesel ICE HDV counterparts when fueled by grid-average electricity over their lifetimes. However, when powered with dedicated renewable electricity, their emissions are between 78%–83% lower. The primary factor limiting potential GHG reductions from BEVs in India is the relatively large share of coal in India's electricity grid mix (around 70% in 2021). Greater deployment of renewables and reduced transmission and distribution losses can meaningfully improve the emissions of BEVs already on the road.
2. **Biofuel blending in India's HDVs has a limited emission reduction impact.** Even with a proposed government target of 5% blending by 2030, the lifetime emission reduction is estimated at only around 1% over diesel HDV. Similarly, increasing biomethane blending to 10% by 2040 only reduces emissions by approximately 1% for natural gas-fueled HDVs. Transitioning to zero-emission vehicles offers greater emission reduction benefits, even with the current electricity grid.
3. **At best, natural gas-fueled HDVs provide modest GHG savings compared to their diesel counterparts. The GHG emissions worsens from natural gas when considering near-term impact.** Even assuming more biomethane deployment into the natural gas grid, natural gas-fueled HDVs only provide a marginal benefit in the best of circumstances. An LNG-fueled 55-tonne tractor-trailer generates approximately the same emissions as its diesel counterpart; a natural gas-fueled 12-tonne truck and urban bus produced in 2023 generate approximately 11%–12% lower life-cycle GHG emissions than their diesel ICE counterparts. However, using a 20-year global warming potential (GWP) factor for methane greatly increases the life-cycle emissions of vehicles fueled by natural gas and grey (natural gas-derived) hydrogen compared to diesel-fueled counterparts. The use of a 20-year GWP negated the relative emissions savings from grey hydrogen-fueled FCEVs entering the fleet in 2023 compared to diesel trucks, while natural gas vehicles entering the fleet in 2023 generated life-cycle emissions between 9%–23% higher than their diesel counterparts.
4. **Blending hydrogen in natural gas has a limited impact on GHG emissions.** We find that the GHG impact of direct hydrogen blending in natural gas for consumption in ICE vehicles is limited by the source of the hydrogen, the efficiency of natural gas-fueled trucks, and the relatively low energy density of hydrogen. For an 18% hythane blend using green hydrogen, we estimate a further 10% decrease in emissions for a 55-tonne tractor trailer compared to a standard LNG mix.
5. **The overall life-cycle impact of hydrogen fuel cell HDVs varies considerably based on the source of hydrogen used.** FCEV HDVs fueled with grey hydrogen entering the fleet in 2023 and 2030 have only moderately (11%–18%) lower life-cycle emissions than diesel ICE HDVs. To achieve deeper GHG reductions from FCEVs, vehicle deployment must be accompanied by the deployment of renewable electricity-derived green hydrogen. Green hydrogen-fueled FCEV HDVs generate life-cycle GHG emissions roughly comparable to green electricity-powered BEVs (81%–83% lower than diesel), though they consume more electricity over their lifetime due to conversion losses.

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INTRODUCTION

Heavy-duty vehicles (HDVs) play a vital role in India's economy, which is currently the sixth largest globally and is on pace to be the third largest by 2030. The road transport sector accounts for 8.6% of India's annual greenhouse gas (GHG) emissions, with HDVs accounting for 58% (206 metric tons) of GHG emissions from on-road transport emissions in 2020 (MoEFCC, 2021; Singh & Yadav, 2024). As demand for HDVs continues to rise, GHG emissions from HDVs are projected to increase at rate of 6% per year to more than 350 metric tons of CO_2 by 2050, unless steps are taken to decarbonize the sector (Singh & Yadav, 2024). Such growth would be incompatible with India's ambitious climate commitments, including its pledges to reduce the emissions intensity of its gross domestic product by 45% by 2030 compared to 2005 levels and reach net-zero emissions by 2070 (PIB, 2022b).

India has taken important steps to decarbonize its transport sector, which can be achieved through a combination of fuel efficiency improvements, the deployment of alternative fuels with lower climate impacts, and fleet replacement with new vehicle technologies such as battery electric and fuel cell powertrains. In 2023, the government implemented the first fuel consumption norms for HDVs (MoRTH, 2022). Under Phase II of the Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles in India (FAME India) program, the Ministry of Heavy Industries aims to incentivize the adoption of nearly 7,000 electric buses by 2024, among other goals (Ministry of Heavy Industries, 2021). In 2022, according to the government's Vahan database, electric buses accounted for 4.2% of all new bus registrations in India (MoRTH, 2023). However, there are currently no battery or fuel cell powertrain models available for either rigid trucks or tractor-trailers, with zero sales across these categories.

To reduce emissions from the existing fleet, India also has introduced several policies to increase the use of alternative fuels in road transport. For instance, the government has adopted a target to raise the share of natural gas in the energy mix from 6.3% in 2022 to 15% in 2030 (PIB, 2022c). It also has publicly advocated for the use of compressed natural gas (CNG) and liquified natural gas (LNG), describing them as cleaner and more cost-effective alternatives to diesel for HDVs, and has been strengthening refilling infrastructure for same (PIB, 2020). The government's National Policy on Biofuels, published in 2018 and amended in 2022, sets out a target to blend 20% ethanol in petrol (E20) by 2025–2026 and 5% of biodiesel in diesel by 2030 (PIB, 2022a) and outlines government support for increasing biofuel availability in-country with a goal to reduce petroleum imports.

Moreover, in January 2023, the government launched a National Mission on Green Hydrogen which earmarks financial resources in the national budget towards pilot projects and research and development for promoting hydrogen production technologies such as water electrolysis, steam methane (CH_4) reforming, and biomass gasification. The Mission aims to develop domestic capacity to produce 5 million tonnes of green hydrogen annually by 2030 to advance decarbonization in mobility and other sectors (PIB, 2023). India is also a member of the Clean Energy Ministerial, a global forum to accelerate the shift to clean energy with programs for hydrogen fuel as well as electric vehicles (Clean Energy Ministerial, 2023).

With decarbonization of HDVs in India in its early stages, it is important to compare the emissions performance of different powertrains and fuels. But analyzing tailpipe emissions alone may overlook important upstream emissions sources. A comprehensive life cycle assessment (LCA) is critical to better understand how different technologies align with India's climate objectives and assess the full range of emissions associated with particular technologies on a consistent, per-kilometer basis across vehicle categories.

This study evaluates the life-cycle GHG emissions of three representative HDVs in India—a 12-tonne rigid truck, a 55-tonne tractor-trailer, and an urban bus—with a mix of different powertrain technologies, including best-in-class diesel trucks, natural gas-fueled trucks, battery-electric vehicles (BEVs), and fuel cell electric vehicles (FCEVs). It takes into account the lifetime average carbon intensity of the fuel, including both upstream emissions from fuel extraction and downstream emissions from fuel consumption. Based on India's stated policy aims, it also accounts for changes in the carbon intensity of these fuel and energy pathways during the useful lifetime of the vehicles. Our goal is to compare the GHG emissions of different HDV powertrain and fuel technologies that could be used to decarbonize the HDV sector in India.

The next section summarizes the methodology used in this analysis. We first present the goal and scope of this study, illustrating the life-cycle boundaries used for the vehicle and fuel cycles. We then summarize the characteristics of the three vehicle categories assessed and the data sources and assumptions used to characterize their emissions. We next describe our assumptions and data sources for both the fuel policies and composition of the fuel mix in this study and our assumptions for estimating life-cycle emissions attributable to the fuel cycle. We then present the results of our analysis, before closing with a discussion and key takeaways.

METHODOLOGY

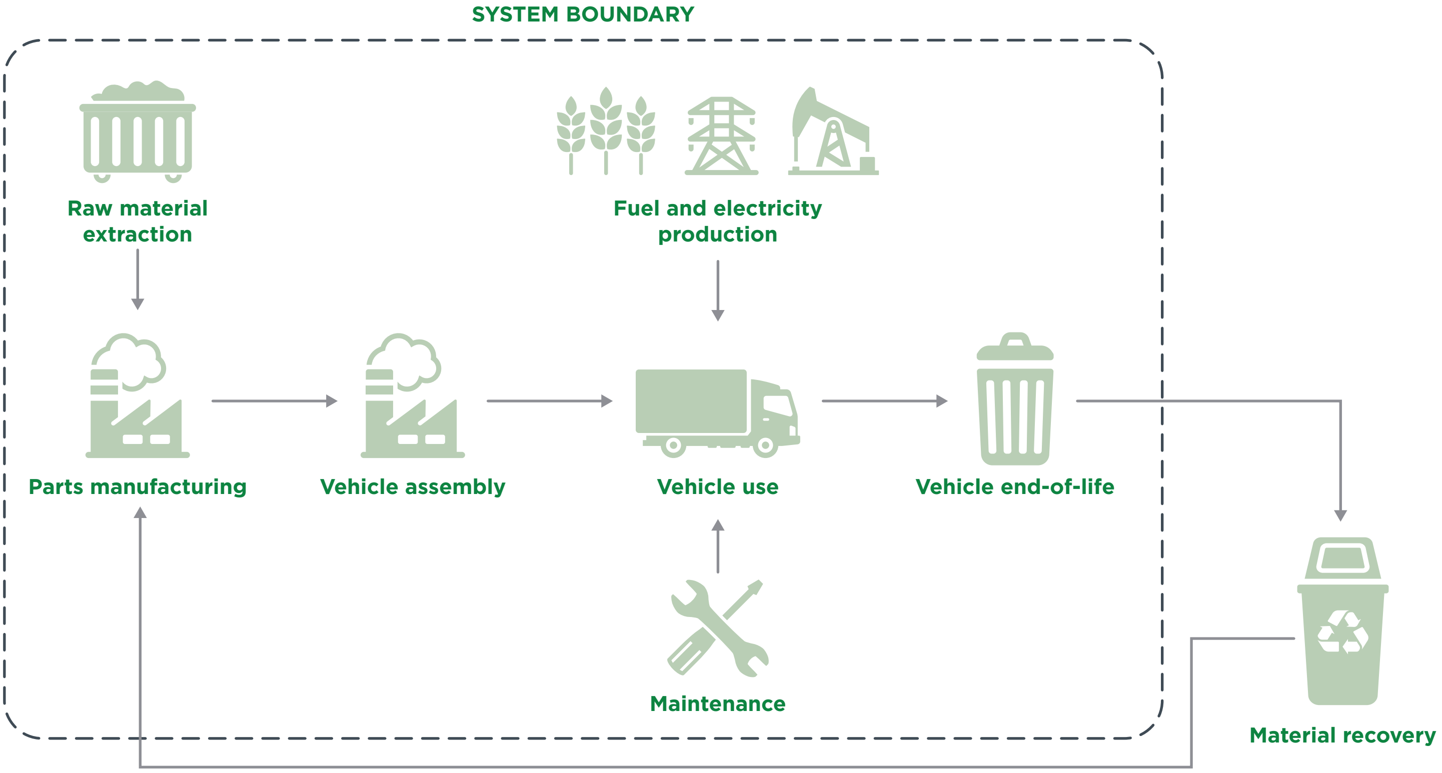
GOAL AND SCOPE

The study estimates the life-cycle GHG emissions of diesel- and natural gas (CNG and LNG)-powered ICE HDVs, along with battery electric HDVs and hydrogen fuel cell electric HDVs. It considers the best-in-class HDVs available in India in 2023 and compares them with estimates of equivalent HDVs expected to be available in 2030.

This study uses a life-cycle approach which includes GHG emissions from vehicle production, maintenance, and recycling (i.e., the vehicle cycle) and from fuel and electricity production and consumption (i.e., the fuel cycle). These emission sources are combined into a single value based on the functional unit of gCO_2e per kilometer traveled throughout a vehicle's lifetime. Emissions from the construction and maintenance of the infrastructure for vehicle production and recycling, fuel transport and distribution, vehicle charging, and road infrastructure are not included, as these are similar for the different powertrain types or have a small influence on total life-cycle GHG emissions.

Figure 1

Life-cycle scope and system boundary for the vehicle and fuel cycle in this study.



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This study principally follows an attributional LCA approach, which examines the average GHG emissions attributable to each vehicle and fuel path during their useful working life. Natural gas emissions are expressed as CO_2e based on their global warming potential (GWP). This study primarily considers a 100-year GWP for natural gas, in which each gram of CH_4 equates to 30 gCO_2e (Stocker et al., 2013). We also examine the effects of using a 20-year GWP factor, which weighs near-term warming more heavily; in this case, the GWP of one gram of CH_4 is almost three times higher, at 85 gCO_2e (IPCC, 2013). This study focuses on the main sources of CH_4emissions, which are the production and transport of natural gas, either for direct use in natural gas vehicles or to produce hydrogen. In addition, in-use CH_4 emissions from the vehicles themselves are considered.

For renewable electricity, we assume that the electricity used to fuel vehicles and produce green hydrogen comes from a new, additional supply, thus avoiding calculating the displacement effects that would result from removing renewable electricity from existing uses and replacing it with a new source. We note that supplying genuine and additional renewable electricity to power the transport sector may require safeguards in the form of additionality certifications and power purchase agreements (Malins, 2019). For grid average electricity, we assume GHG emissions reflect the average mix of energy sources to supply the grid. This study does not factor in marginal emission intensities or consequential effects of new electricity demand on the per-kWh emissions of grid electricity.

VEHICLES STUDIED

Our study focuses on three types of HDVs: a 12-tonne rigid truck, a 55-tonne tractor-trailer, and a 16-tonne, 12 meter urban bus. These vehicle segments covered 51% of total HDV sales in India in 2020–21 (Sathiamoorthy et al., 2021). We selected the top selling models among each of these segments as reference models for this study. Engine and weight characteristics for the diesel powertrain for all three reference models are sourced from manufacturer product detail catalogues (Ashok Leyland, 2023; Tata, 2023a, 2023b).

Table 1
Vehicles studied.

	Rigid truck	Tractor-trailer	Urban bus
Representative diesel model	Tata 1212	Ashok Leyland 5525	Tata LPO 1618
Gross vehicle weight (in tons)	11.9	55	16.2
Emission standard	BS VI	BS VI	BS VI
Annual VKT (in kms)	55,843	59,300	70,000
Lifetime VKT (in kms)	837,645	889,500	840,000
Lifetime (in years)	15	15	12

Emission standards in India do not cover CH_4 and nitrous oxide (N_2O) emissions from HDVs. Therefore, we assume values for CH_4 and N_2O similar to those of the European Union (EU), due to the similarity of the current Bharat Stage (BS) VI norms to EU VI standards (Dallmann & Bandivadekar, 2016). This assumption may result in an underestimation of the true emissions levels for conventional vehicles; the real-world emissions of vehicles in India are likely to be higher than in the EU, due to differences in driving behavior—such as more start-stop in India, resulting in lower average speed (TCI & IIMC, 2015)—and the propensity for Indian trucks to be overloaded (CRRI, 2008).

VEHICLE CYCLE

The vehicle cycle comprises the "cradle-to-grave" GHG emissions of vehicle production, maintenance, and recycling. Vehicle production and recycling primarily involve three categories of components: the battery of the battery electric HDVs, the hydrogen system of fuel cell HDVs, and the rest of the vehicle (glider and powertrain). Due to limited technological advancements and data on the second life of batteries and hydrogen component recycling, such impacts are not covered. Average annual kilometers for all vehicle types are derived considering the full vehicle age and annual degradation factor.

Table 2

Scope of GHG emissions considered in vehicle cycle.

Glider and powertrain	• Vehicle production, including raw material extraction and processing • Component manufacture and assembly • Recycling of vehicle components
Battery	• Battery pack production, including raw material extraction and processing • Cell production and pack assembly • *Not included:* second-life reuse and recycling
Hydrogen system	• Hydrogen tank and fuel cell production • Raw material extraction and processing and component manufacture • *Not included:* component recycling/disposal
Maintenance	• In-service replacement of consumables, including tires, exhaust/aftertreatment, coolant, oil, urea and others

In India, original equipment manufacturers (OEMs) and testing agencies are not mandated to share fuel consumption values of HDVs in the market. Hence, in this study, we use vehicle simulations to determine fuel or energy consumption values. Simulations were performed in Simcenter Amesim, a multiphysics simulation software (Simcenter Amesim, 2022). For each vehicle and powertrain variation, we created a virtual model and ran it on a real-world duty cycle to reflect real-world fuel or energy consumption.

To create virtual models for diesel powertrains, we used vehicle details from OEM specification sheets and brochures. We then did simulation runs to assess fuel consumption. The models were validated and calibrated to within 5% error using a real-world dataset as detailed in Yadav et al. (2023). As trucks in India tend to be overloaded, we assumed a 75% average payload for the energy consumption values of the rigid truck and tractor-trailer, considering operation while empty (e.g., when returning from payload drop) and cases of overloading. The diesel fuel consumption value for the urban bus was evaluated by running the virtual bus on an urban bus duty cycle for India (Jin et al., 2020).

No models of battery electric trucks, fuel cell trucks, or fuel cell buses, are yet publicly available in the Indian market; therefore, we used simulations to estimate the energy consumption performance of all three under Indian driving conditions. For uniformity, we also used simulations for battery electric buses. For these powertrains, the ICE powertrain components of the diesel models were replaced by battery or fuel cell powertrain components while keeping the rest of the vehicle (glider) the same. The power and range required were selected such that the battery electric or fuel cell vehicle had similar operational performance as a diesel truck. For the 12-tonne truck, we assumed a return-to-base operation with a range of 200 km. For the 55-tonne tractor-trailer, we assume the battery would meet two-thirds of the daily operation range of 400 km in a single charge. For the urban bus, we use a 200 km range based on available models. Informed by stakeholder consultations, we assume that lithium iron phosphate (LFP) battery chemistry would be used for BEVs in India, and hence we used same in these virtual trucks. For the modelled fuel cell vehicles, we assume a 350 bar hydrogen gaseous storage system.

Since no engine fuel consumption map for natural gas-based engines was available for use in our simulation, we converted diesel fuel consumption performance to natural gas vehicle performance. For this, we used a differential between diesel vehicles and natural gas vehicles drawn from the U.S. Environmental Protection Agency's (EPA)

MOVES model and applied it proportionally based on vehicle class (United States Environmental Protection Agency, 2022).

Table 3

Summary of assumptions and data sources for vehicle parameters.

Parameter	Vehicle category	2023	2030	Notes
Unladen weight (kg)	12 t truck	4,400	4,400	All vehicle unladen weights assumed to be the same in 2030. Data sources: OEM product brochure and sales database.
	55 t tractor-trailer	15,000	15,000	
	Urban bus	10,500	10,500	
Battery energy density (Wh/kg)	All	160	234	LFP battery. Data source: Mao et al., 2021.
Battery capacity (kWh)	12 t truck	115	105	200 km range, 75% payload. Data source: Simulation based on Yadav et al., 2023.
	55 t tractor-trailer	455	405	270 km range, 75% payload. Data source: Simulation based on Yadav et al., 2023.
	Urban bus	355	242	200 km range. Data source: Simulation based on Yadav et al., 2023.
Hydrogen tank capacity (kg)	12 t truck	8	8	200 km range, 75% payload. Data source: Simulation based on Mao et al., 2021.
	55 t tractor-trailer	40	38	270 km range, 75% payload
	Urban bus	18	18	200 km range

Table 4 summarizes the fuel and energy consumption values used for each of the three vehicle categories in 2023 and 2030. To account for improvements in vehicle technology by 2030, we assume a 4% cumulative reduction in fuel consumption by 2030 for diesel and natural gas vehicles considering business-as-usual technology advancement as mentioned in previous ICCT research on India (Yadav et al., 2023).

HDVs in India tend to have smaller engines and fewer safety and comfort features like HVACs, resulting in lower kerb weight than models in the United States or EU (Delgado et al., 2016). As the Indian market matures by 2030, safety and comfort are expected to be a priority for OEMs and owners. Accordingly, no overall weight reduction is assumed for Indian HDVs in 2030.

For electric powertrains, we assume that battery weight decreases due to advancements in technology such as better tires, aerodynamic improvement, and high energy density battery development. For fuel cell powertrains, we maintain a 60% efficient fuel cell and do not assume any further improvement in efficiency and storage.

For diesel- and natural gas-fueled vehicles, we assume an increase in biofuel consumption over the course of the period studied, as discussed in more detail in the fuel cycle section; we do not factor in any changes to efficiency or performance attributable to these biofuel blends.

Table 4
Fuel and energy consumption figures used.

	Powertrain	2023	2030	Unit	Sources
12 t truck	Diesel + biofuels	15.6	15	L/100 km	Simulation based on Yadav et al. (2023)
	CNG + biogas	14.3	13.5	kg/100 km	Estimated using simulation based on Yadav et al. (2023) & 12t NG-Diesel adjustment factor
	BEV	44	40	kWh/100 km	Simulation based on Yadav et al. (2023)
	FCEV	3.52	3.2	kg/100 km	Simulated based on methodology mentioned in Mao et al. (2021)
55 t tractor-trailer	Diesel + biofuels	47.2	45.3	L/100 km	Simulation based on Yadav et al. (2023)
	LNG + biogas	40.6	38.2	kg/100 km	Estimated using above & 40t NG-Diesel adjustment factor
	BEV	134	121	kWh/100 km	Simulation based on Yadav et al. (2023)
	FCEV	9.7	9.2	kg/100 km	Simulated based on methodology mentioned in Mao et al. (2021)
Urban bus	Diesel + biofuels	39.7	38.1	L/100 km	Simulation based on Yadav et al. (2023)
	CNG + biogas	35.6	34.1	kg/100 km	
	BEV	133	130	kWh/100 km	
	FCEV	8.6	8.1	kg/100 km	Simulated based on methodology mentioned in Mao et al. (2021)

We assume a lifetime age of 15 years for rigid trucks and tractor trailers, based on a scrappage policy in India that makes it more expensive to operate commercial vehicles after 15 years (PIB Delhi, 2021). While vehicle scrappage under the current regime is voluntary, we expect it to become mandatory in coming years. For buses, we assume an average lifespan of 12 years based on a recent study that estimated the life-cycle cost of urban buses in India (Krelling & Badami, 2020).

To estimate upstream manufacturing emissions for each vehicle in terms of tonnes CO_2e/t, we use an emission factor specific to HDV manufacturing derived from Scania (2021). This value is scaled upwards by 6% for CNG and LNG vehicles based on the ratio of upstream manufacturing emissions for these trucks compared to diesel trucks in Ricardo (2020). For fuel cell manufacturing, we apply a per-tank emission factor derived from GREET (2021) and scale according to the tank size of each vehicle. As noted above, LFP batteries, the standard in China, are the main battery type in India; battery manufacturing emissions are estimated on a per-kWh basis based on Bieker (2021) and scaled according to the battery size of each vehicle. For batteries and fuel cells, we assume a 20% decline in upstream manufacturing emissions in the 2030 scenario to reflect the ongoing shift to lower-GHG energy sources over time. Table 5 summarizes the emission factors associated with manufacturing HDVs, including batteries and fuel cell systems.

Table 5
Overview of GHG emissions assumptions for vehicle upstream manufacturing.

Parameter	2023	2030	Data source	Notes
HDV glider and powertrain manufacturing emissions	6.6 t CO_2e/t	5.6 t CO_2e/t	Scania (2021)	Extrapolated from a total truck CO_2 figure of 27.5 tonnes (increased by 6% for natural gas versions).
Battery manufacturing emissions	68 kgCO_2e/kWh	55 kgCO_2e/kWh	Derived from Bieker (2021) and Argonne National Laboratory (2020)	Represents the carbon per kWh of battery based on a weighted market mix of batteries made in China for 2021 and 2030.
Fuel cell and H2 storage tank manufacturing emissions	4.2 t CO_2e per 5 kg gaseous storage tank and fuel cell	3.4 t CO_2e per 5 kg gaseous storage tank and fuel cell	Derived from Bieker (2021) and Argonne National Laboratory (2020)	Emissions are scaled based on the system size relative to a 5 kg tank.

Battery capacities considered for BEVs in 2023 are mentioned in Table 4. With the expected decrease in battery costs and likely increases in battery densities, the capacities of BEV batteries are assumed to be lower in 2030 to keep the same range, for better comparison. Battery recycling is likely to substantially reduce the GHG emissions impact of batteries. Due to uncertainty regarding future recycling processes, however, GHG emission credits corresponding to material recycling are not included in this assessment.

GHG emissions from the production of hydrogen tanks and fuel cells in FCEVs mostly arise from the energy-intensive production of carbon fiber-reinforced plastic for hydrogen tanks, and vary based on tank capacity. In this study, the hydrogen storage system is assumed to be a series of smaller 5 kg tanks linked to provide necessary storage. The GHG emissions associated with their production are, therefore, scaled based on the upstream emissions associated with manufacturing a single tank currently produced for lighter duty vehicles (IEA, 2020; Hyundai, 2022). We assume the hydrogen systems are produced with 20% lower GHG emissions in 2030, to reflect the lower GHG intensity of the future electricity grid. As materials from carbon fiber-reinforced plastic are currently incinerated or disposed as landfill, the recycling of hydrogen tanks is not considered in this analysis.

FUEL CYCLE

For this analysis, we include the GHG emissions from fuel consumption during vehicle use as well as the upstream emissions associated with fuel or electricity production. Together, these comprise the full well-to-wheel (WtW) emissions from fuel. Table 6 illustrates the scope of our fuel cycle emissions accounting. Due to data gaps on the upstream emissions of manufacturing different fuels in India, we use default emission factors for fossil fuels and biofuels produced in the EU estimated by Prussi et al. (2020). Because of the relatively higher share of coal in India's electricity grid mix (roughly 70%, compared to less than 15% for the EU), emission factors for fuel production in the EU may understate the emissions attributable to producing fossil fuels and biofuels.

Table 6

Scope of GHG emissions considered in fuel cycle.

Fossil fuels	• Crude oil/natural gas extraction (including flaring), processing and transport, and fuel refining and distribution; all including methane leakage • CO_2, CH_4, and N_2O emissions during fuel consumption
Biofuels	• Plant cultivation/waste collection, processing and transport, and fuel production and distribution • CH_4 and N_2O emissions of fuel consumption
Electricity	• GHG emissions of electricity generation, including new power plant infrastructure for renewable energy, transmission, distribution, and charging losses
Hydrogen	• For electrolysis-based hydrogen: GHG emissions of electricity, adjusted by energy losses during electrolysis and hydrogen compression or liquefaction • For natural gas-based hydrogen: natural gas extraction, processing, and transport; steam reforming and hydrogen compression; all including methane leakage • *Not included: Long-distance international hydrogen transport*

Table 7 provides an overview of the emission factors for fuels and the assumed blends used in this analysis. Each emission factor is weighted based on the assumed blend of fuel over the lifetime of a vehicle produced in 2023 or 2030. For BEVs, this study assesses the GHG emissions of both the grid-average upstream GHG emissions of electricity sourced from the average grid mix in India, as well as the life-cycle emissions attributable to renewable electricity sources. Projections of the generation mix in India through 2050 ware adapted from IEA's Stated Policies Scenario (STEPS) (IEA, 2022), while the life-cycle carbon intensity for the different types of electricity are derived from emission factors developed by the Intergovernmental Panel on Climate Change (Moomaw et al., 2011). The grid-average electricity mix and associated emissions change every year as the share of renewables increases, reducing the GHG intensity of electricity consumed by BEVs over time. The grid average emissions from the vehicles also vary based on each vehicle's life and kilometers travelled per year.

To estimate the emissions for the dedicated renewable electricity supplied to BEVs, we assume the electricity is fully additional and, therefore, attribute the emissions associated with installing new renewable electricity capacity to this fuel pathway. Based on current electricity supply in India, we assume a 2:1 ratio of solar to wind power. Even after accounting for upstream infrastructure emissions, renewable electricity emissions are substantially lower than those of fossil fuels or the current grid average. To calculate the per-kWh emissions for electricity, we factor in the loss rate associated with electricity transmission and distribution (T&D) in India, which, at 19%, is among the world's highest (EIA, 2015). Because renewable electricity is deployed and the grid is modernized over time, we assume this T&D loss rate declines linearly to 10%, closer to the global average, by 2030.

Table 7

Carbon intensity of electricity and fuels over time.

Vehicle year	12 t truck		55 t truck		Urban bus		Unit
	2023	2030	2023	2030	2023	2030	
Grid-average electricity (STEPS scenario)	725	521	725	521	749	543	gCO_2e/kWh
Grid-average electricity (SDS scenario)	524	260	524	260	560	287	gCO_2e/kWh
Renewable electricity	35	35	35	35	35	35	gCO_2e/kWh
Diesel	92.6	91.0	92.7	91.0	92.7	91.0	gCO_2e/MJ
Biofuel share (%)	0.1	5	0.1	5	0.1	5	—
CNG	68.6	67.6	n/a	n/a	68.6	67.6	gCO_2e/MJ
RNG share (%)	0	5[1]	0	5	0	5	—
LNG	n/a	n/a	77.2	74.8	n/a	n/a	gCO_2e/MJ
RNG share (%)	0	5	0	5	0	5	gCO_2e/MJ
Hydrogen (grey)	115.2	115.2	115.2	115.2	115.2	115.2	gCO_2e/MJ
Hydrogen (green)	16.3	16.3	16.3	16.3	16.3	16.3	gCO_2e/MJ

As with the electricity grid, this analysis includes a projection of changing biofuel blends over time based on stated policies. For the diesel fuel pool, we begin with a blend rate of 0.1% based on 2021 blend levels, increasing linearly to a 5% blend level based on current stated policy (PIB, 2022a). For the natural gas fuel pool, we assume that biomethane starts at 0% of the mix by volume in 2023, but increases to 5% by 2030 and 10% by 2040. The Indian government has proposed a national biomethane in transport strategy (called the Sustainable Alternative Towards Affordable Transportation), which aims to increase biomethane production to 15 million tonnes by 2030 (MoPNG, 2022). We assume this biogas will be generated from a 50/50 mix of manure and sewage sludge.

We assess the emissions from conventional natural gas-derived hydrogen based on an emission factor derived from the GREET model, using the average grid electricity mix for India to estimate emissions associated with hydrogen compression and distribution (Wang et al., 2021). We use the energy conversion loss rates for hydrogen production derived by Prussi et al. (2020), in conjunction with the infrastructure emissions used to estimate the GHG intensity of new, additional renewable electricity production, to derive an emission factor for green hydrogen made from dedicated renewable electricity. Though India has an ambitious national hydrogen mission with a goal of producing 5 million tonnes of green hydrogen in 2030, the exact mix of hydrogen produced in 2030 and its use across different sectors remain unclear(PIB, 2023). Therefore, we do not assume a shift in the hydrogen mix during the time horizon assessed in this study, and instead illustrate the results for green hydrogen and grey hydrogen separately.

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[1] We assume that the blend of CNG and LNG increases beyond 5% to reach 10% by 2040, which is reflected in the weighted emission factors.

RESULTS

For each vehicle-fuel combination described above, we estimate the life-cycle GHG emissions in gCO_2e/km for a model year 2023 scenario and a model year 2030 scenario. For each scenario, the results depict the vehicle's lifetime life-cycle emissions normalized on a per-km basis. Figure 2 through Figure 7 illustrate the results of our analysis. Different components of the overall emissions for a given powertrain are distinguished by color. Dark blue sections represent the combustion emissions of the fuel; lighter blue sections illustrate the emissions associated with upstream fuel or electricity production. Grey denotes emissions associated with manufacturing vehicles, while yellow and red indicate emissions associated with producing batteries or fuel cells, respectively, where applicable. The shaded sections indicate the change in total life-cycle emissions for each vehicle-fuel combination when a 20-year GWP is used instead of a 100-year GWP for methane, which increases the relative emissions attributable to vehicles using natural gas-derived fuels. The implications of the choice of GWP are examined in more detail in the discussion section.

Our results indicate that emissions from fuel production and use typically make up the largest part of total emissions for each pathway, except when high amounts of renewable energy are used to power the vehicle. Though maintenance emissions are included, they make up a small contribution of the overall emissions for each fuel and vehicle combination.

2023 SCENARIO

Figure 2 through Figure 4 illustrate the life-cycle emissions of vehicles produced in India in 2023 across a variety of fuel and vehicle technology combinations. The biofuel content in both the diesel fuel and natural gas fuel pool had only a minor impact on emissions. Even with an increase to 5% biodiesel and renewable diesel from waste sources by 2030, up from less than 1% biomass-based diesel in 2023, we estimate that these fuels only reduced the use-phase emissions of diesel HDVs produced in 2023 by approximately 2% over their life cycle. Likewise, the growth of biomethane blends from 0% in 2023 to 10% in 2040 had a small impact on the emissions of CNG HDVs, reducing their use-phase emissions by approximately 2% over a vehicle's lifetime. These reductions are influenced by the temporal aspect of the analysis, with a larger portion of lifetime kilometers traveled for each HDV occurring during the years in which the blend levels are low.

For vehicles produced in 2023, we estimate that BEVs offer the greatest reduction in lifetime GHG emissions compared to conventional, diesel-fueled HDVs. When using grid-average electricity, we estimate that based on vehicle type, BEVs have between 17% and 29% lower life-cycle emissions than their diesel ICE counterparts. These reductions increase substantially when using 100% renewable electricity to power those BEVs; on a per-km basis, BEV life-cycle emissions are 78%–83% lower than those of diesel ICE counterparts across the three vehicle categories. These estimates factor in the impact of one battery replacement in the vehicle's lifetime, which increases overall upstream battery manufacturing emissions by an additional 19 to 69 gCO_2e/km.

We estimate that the life-cycle emissions of FCEVs can vary substantially based on the source of hydrogen used to power the vehicle. When using natural gas-derived grey hydrogen, assuming a 100-year GWP, the life-cycle emissions from FCEVs entering the fleet in 2023 range between 12% and 14% lower than conventional, diesel-fueled ICE HDVs across the three vehicle categories. When using a 20-year GWP, meanwhile, we estimate that a grey hydrogen-fueled FCEV generates approximately the same life-cycle emissions as conventional, diesel-fueled HDVs across the three segments studied. However, when 100% green hydrogen made from additional, renewable electricity is used, we find that the life-cycle emissions from these vehicles match those of BEVs, with per-km life-cycle emissions approximately 81%–82% lower than diesel ICE counterparts.

Natural gas HDVs exhibited mixed results across the vehicle categories. For the 55-tonne tractor-trailer, a natural gas-fueled truck produced in 2023 generated approximately 1% lower life-cycle GHG emissions relative to diesel counterparts. In contrast, the 12-tonne natural gas truck and natural gas-powered urban bus manufactured in 2023 generated roughly 12% and 11% lower life-cycle GHG emissions per km, respectively. When using a 20-year GWP for methane, however, we estimate that natural gas-fueled vehicles generated approximately 9%–23% greater life-cycle emissions than their diesel vehicles across the three segments.

Figure 2

Life-cycle emissions for a 12-tonne truck driven in India, 2023–2037.

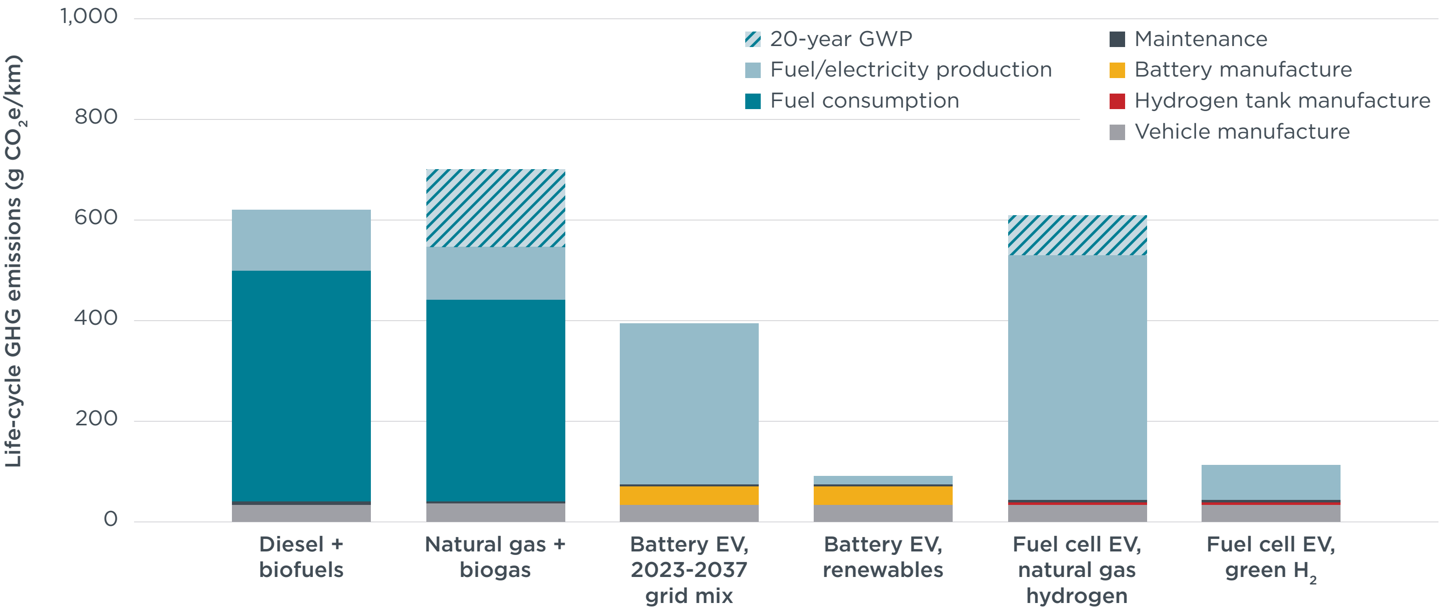

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Figure 3

Life-cycle emissions for a 55-tonne tractor trailer driven in India, 2023–2037.

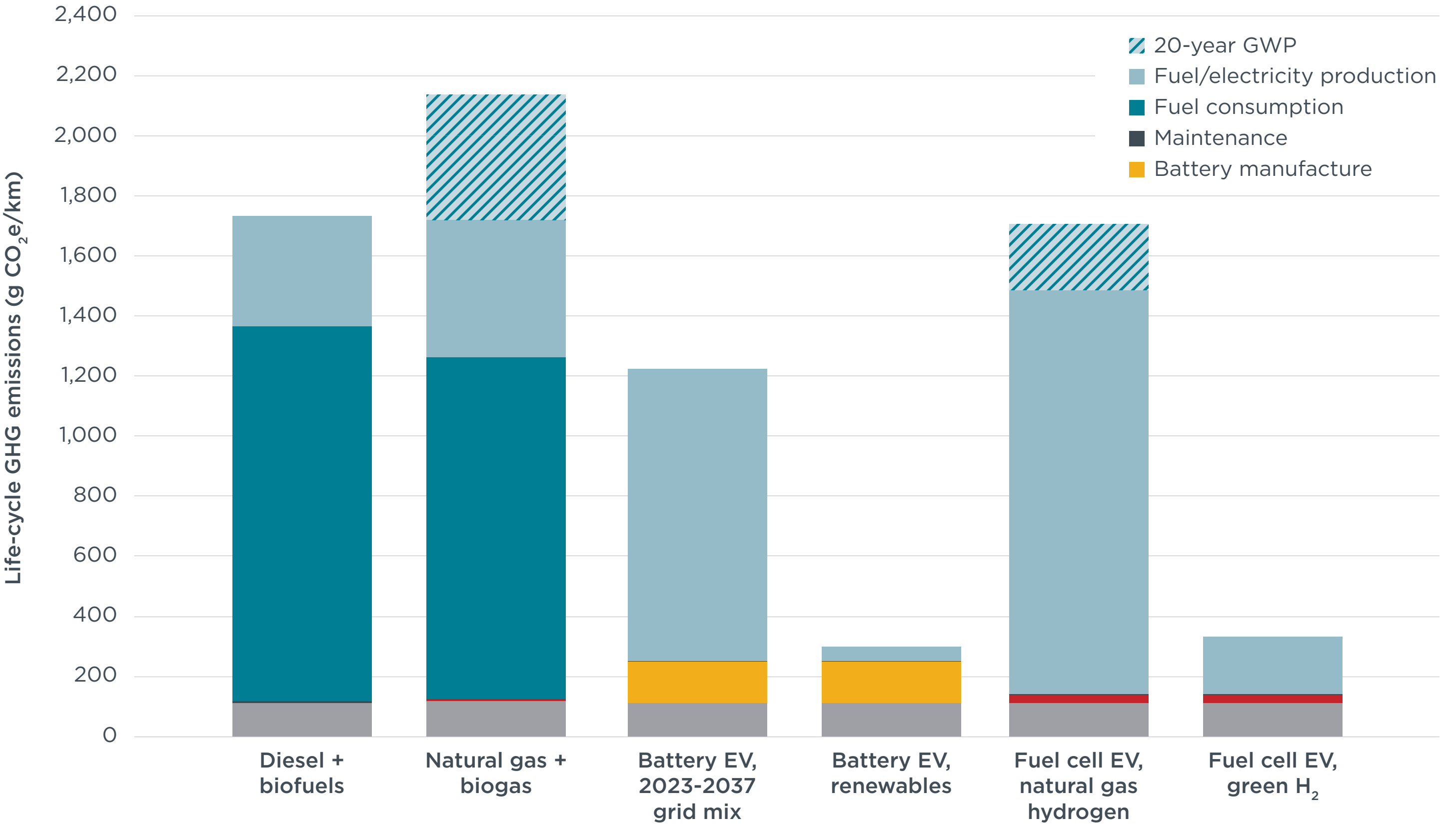

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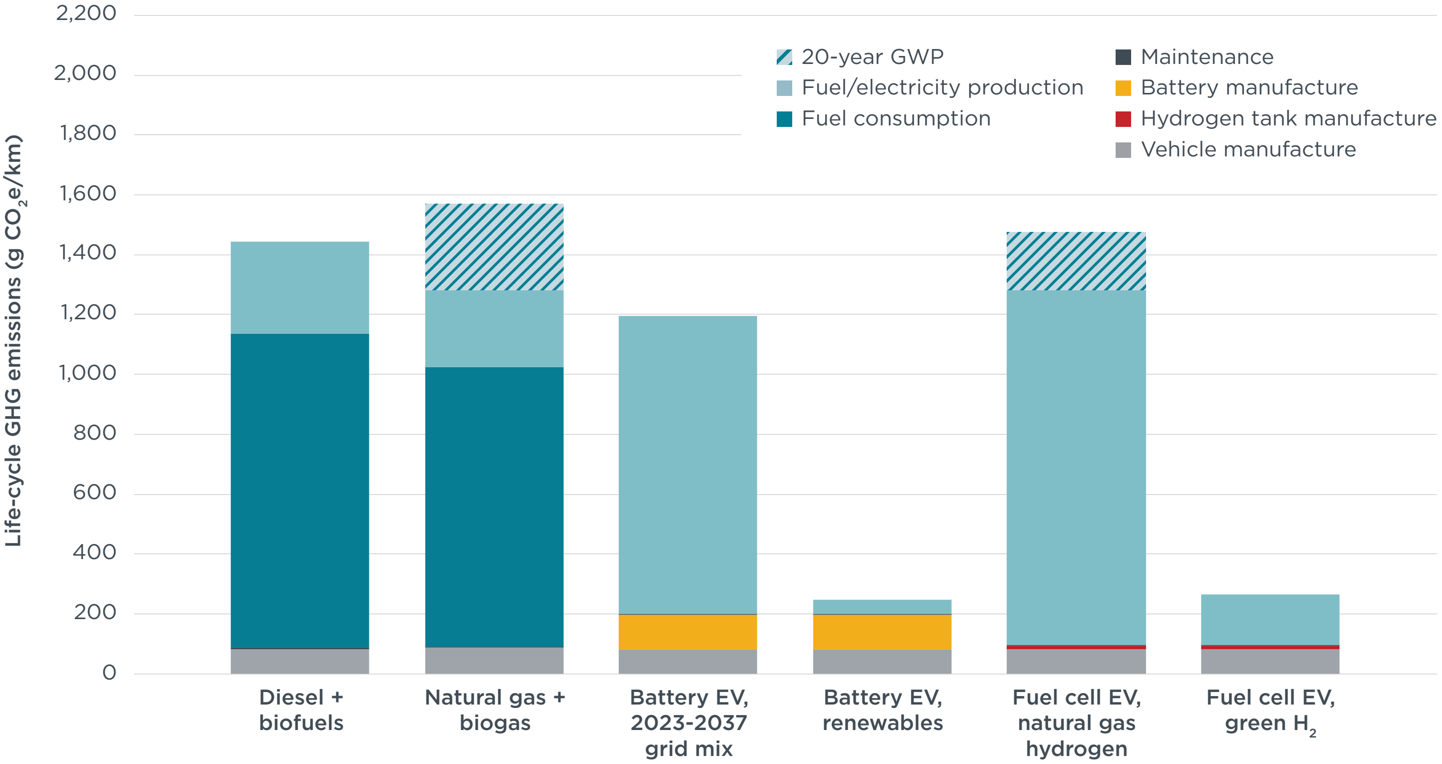
Figure 4

Life-cycle emissions for an urban bus driven in India, 2023–2034.



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2030 SCENARIO

Figure 5, Figure 6, and Figure 7 illustrate the life-cycle emissions of vehicles produced in India in 2030 across a variety of fuel and vehicle technology combinations. Across the different vehicle technologies, we estimate that per-km life-cycle emissions for the different HDVs decreased compared to the 2023 scenario, largely due to vehicle efficiency improvements. For some vehicle and fuel combinations, there was an additional decrease attributable to a reduction in GHG emissions reflecting changes to the fuel mix that drive down emissions from 2030 onward. In this scenario, diesel ICE HDVs generate approximately 5% lower GHG emissions on a per-km, life-cycle basis than their 2023 counterparts.

By 2030, improvements to the electricity grid have a sizeable impact on the life-cycle emissions of BEV HDVs. Specifically, we estimate that BEV HDVs entering service in 2030 generate approximately 30-32% lower life-cycle GHG emissions than the same models entering service in 2023, largely due to reduced upstream electricity grid emissions over their lifetime. Moreover, BEV HDVs generate approximately 38%–49% lower life-cycle GHG emissions than their 2030 diesel counterparts. When fully renewable electricity is used, BEV HDVs exhibit 80%–87% lower GHG emissions than 2030 diesel ICE HDVs, with the bulk of their emissions coming from upstream vehicle chassis and battery manufacture.

For FCEV HDVs produced in 2030, similar to the 2023 scenario, life-cycle emissions depend greatly on the source of hydrogen and GWP considered. For FCEVs produced in 2030 that use natural gas-derived hydrogen, we again find only a modest reduction in emissions, between 11%–18% lower than comparable 2030 diesel ICE models. When using a 20-year GWP, meanwhile, we estimate that a grey hydrogen-fueled urban bus generates approximately 3% lower life-cycle GHG emissions than a comparable diesel bus; in contrast, the 12-tonne truck and 55-tonne tractor trailer generate 6% and 2% greater life-cycle GHG emissions respectively than their diesel counterparts. When fueled by 100% renewable electricity-derived green hydrogen, however, the life-cycle emissions from FCEV HDVs produced in 2030 are comparable to those of BEV HDVs, with estimated per-km GHG emissions between 81%–83% lower than diesel ICE vehicles.

We estimate that natural gas-fueled HDVs produced in 2030 have life-cycle emissions comparable to conventional, diesel-fueled ICE HDVs. Across the three vehicle categories, we estimate that the emissions from natural gas-fueled HDVs range from 3%–13% lower than their diesel ICE HDV counterparts. When using a 20-year GWP for methane, however, they generated approximately 10%–20% greater life-cycle emissions than diesel counterparts.

We also find that biofuel content in both the diesel fuel pool and natural gas fuel pool had little impact on emissions from HDVs produced in 2030. Though the projected 2030 fuel mix assumes a large increase in advanced fuel volumes compared to 2023, the absolute quantities of these fuels remain relatively low; biodiesel reaches 5% of volumes by 2030 (compared to less than 0.1% in 2023) and biomethane reaches 5% of supplied natural gas in 2030 (compared to less than 2% 2023). Though these fuels generate lower life-cycle GHG emissions than fossil fuels, their overall impact on reducing emissions from the fuel cycle remains limited by their quantity.

Figure 5

Life-cycle emissions for a 12-tonne truck driven in India, 2030–2044.

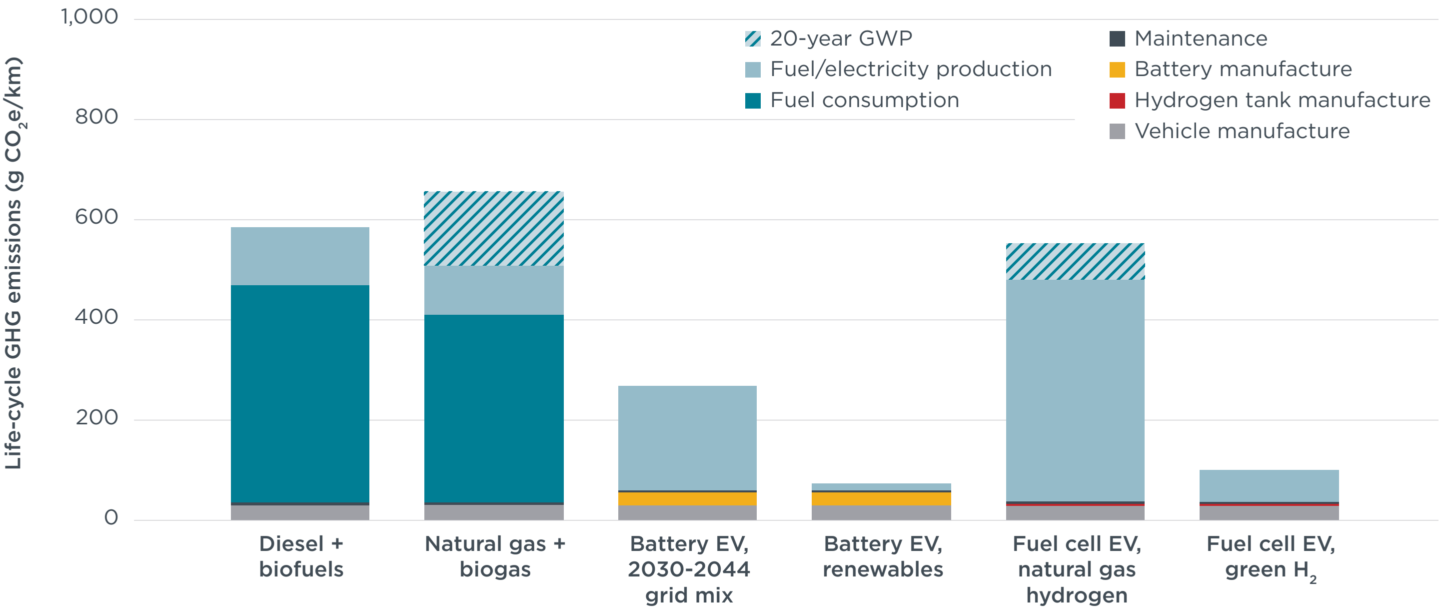

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Figure 6

Life-cycle emissions for a 55-tonne tractor trailer driven in India, 2030–2044.

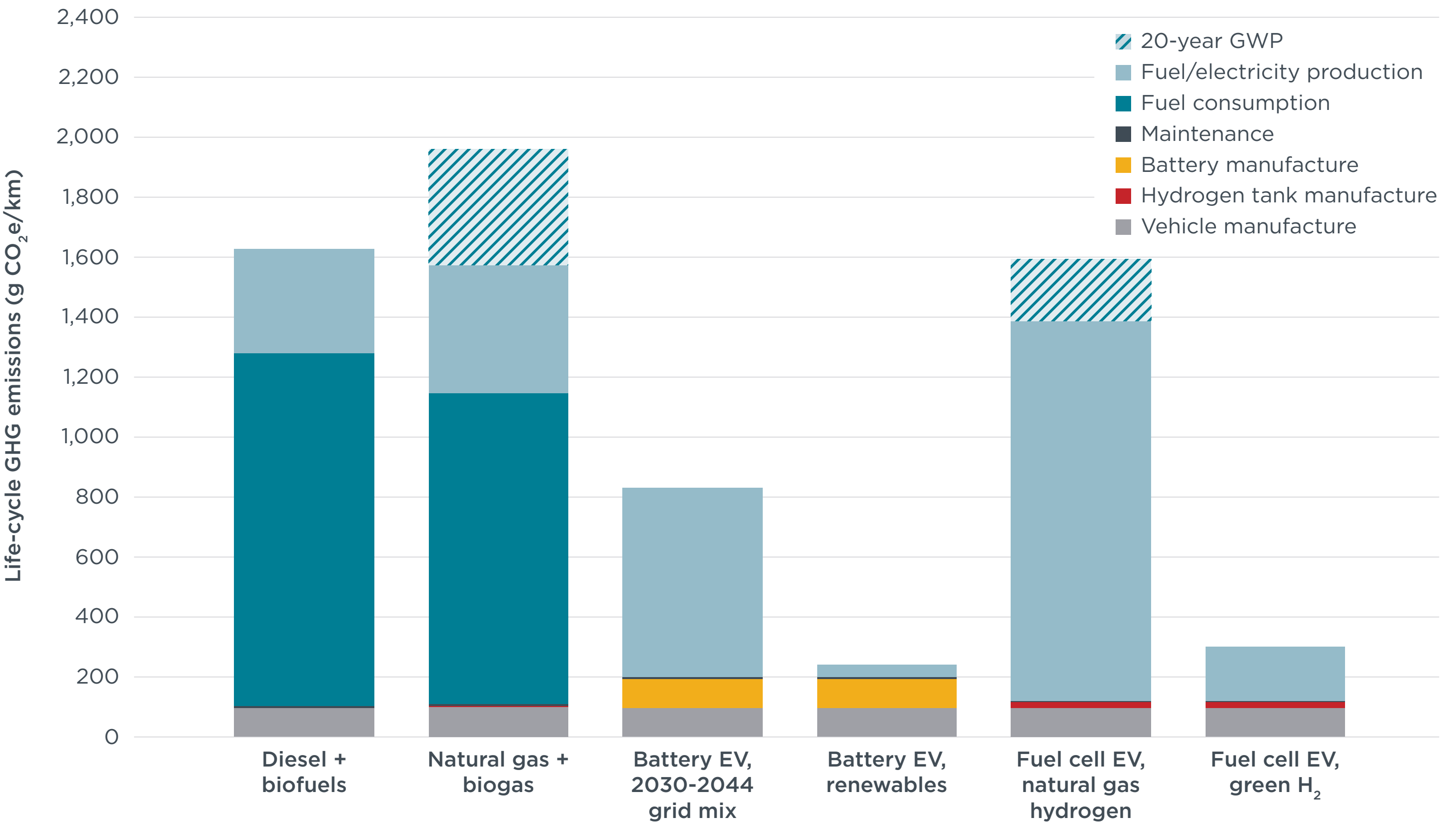

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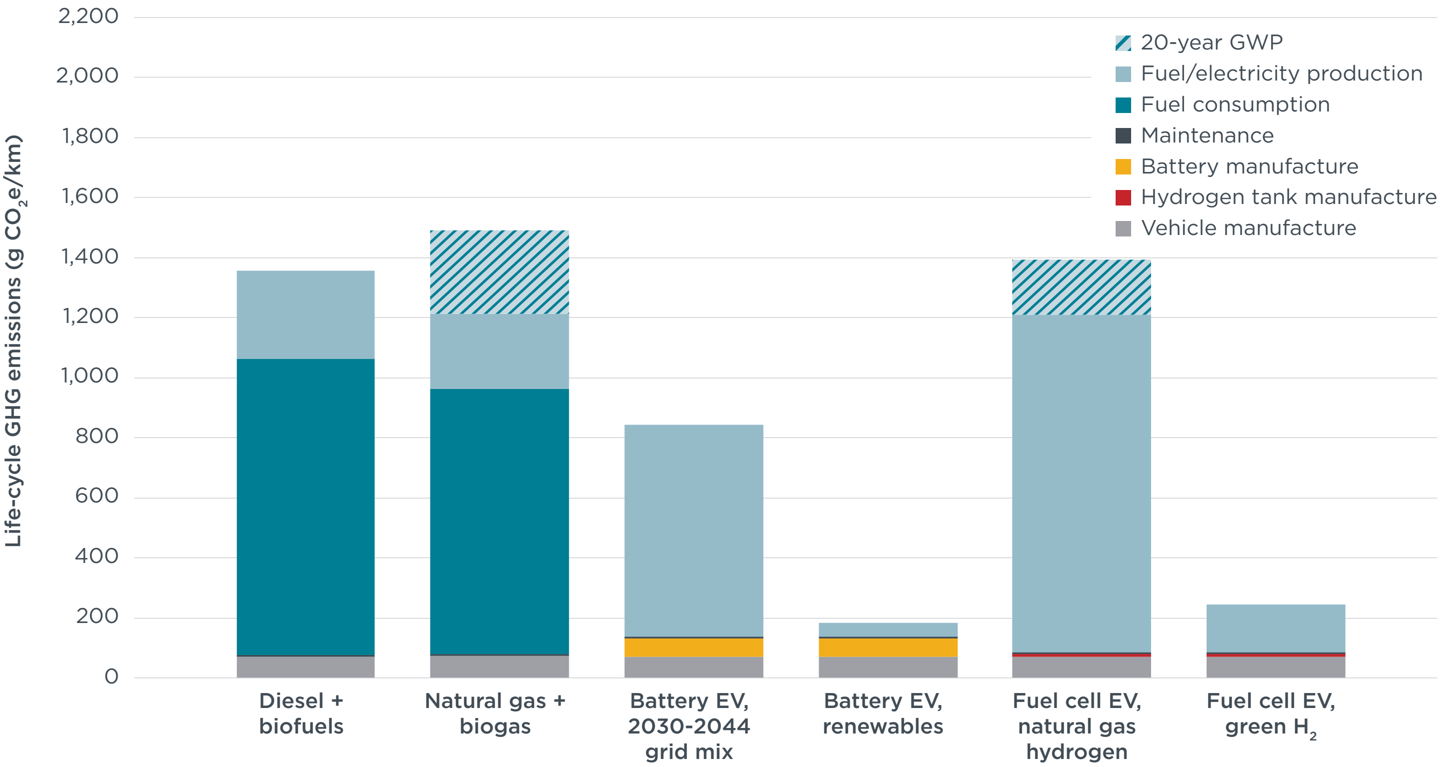
Figure 7

Life-cycle emissions for an urban bus driven in India, 2030–2041.



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DISCUSSION

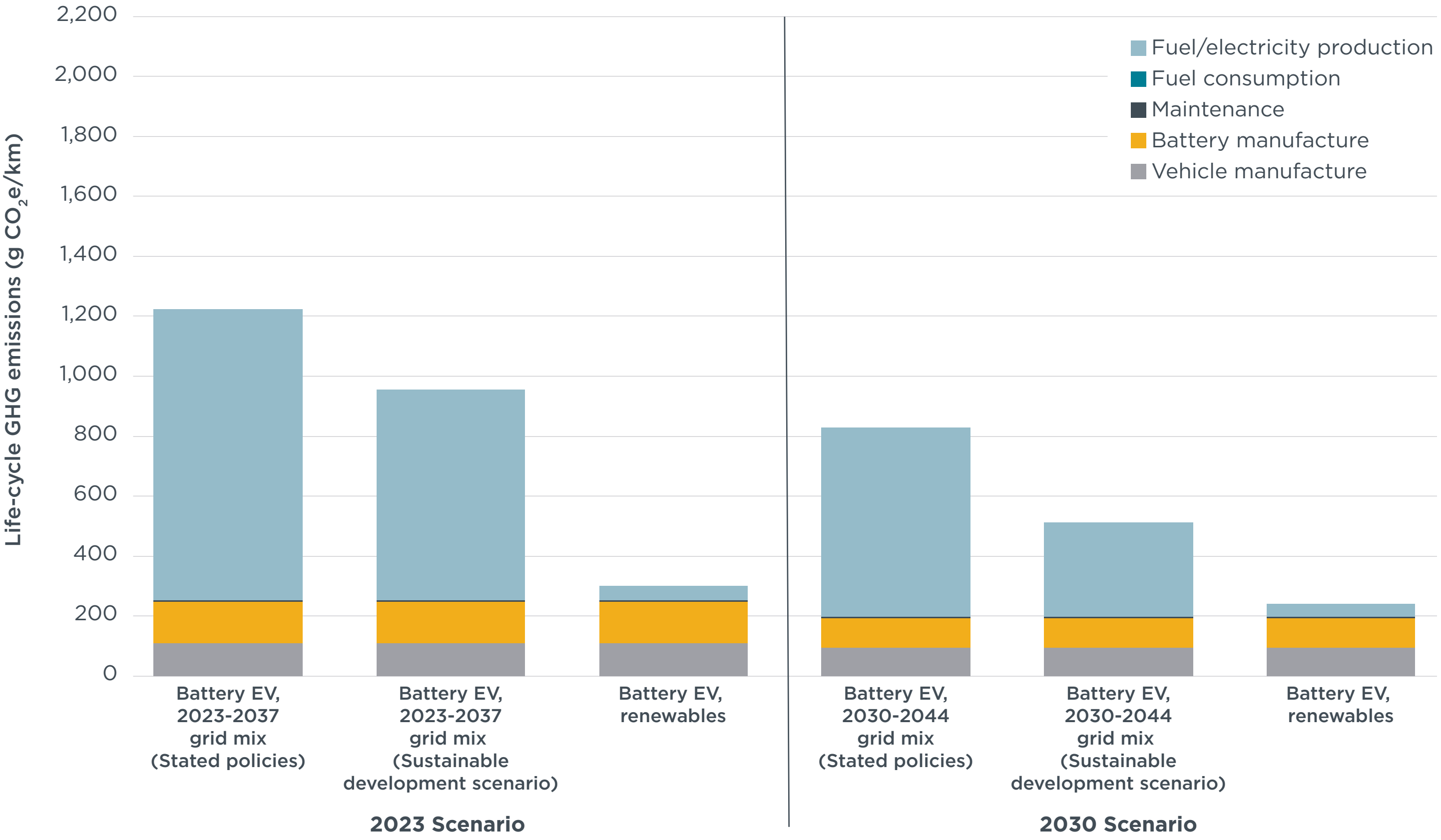
Life-cycle GHG emissions from the fuel cycle can greatly impact the relative life-cycle emissions of different powertrain options. Specifically, BEV HDVs offer the greatest immediate GHG reductions, with those entering service in 2023 generating between 17%–29% lower life-cycle GHG emissions than comparable diesel HDVs. Moreover, the relative benefits of BEV HDVs increase over time as the electricity grid decarbonizes; those entering the fleet in 2030 generated 38%–49% lower life-cycle GHG emissions than their counterparts in other vehicle categories.

These estimates factor in the contribution of India's existing, coal-intensive electricity grid; depending on the speed and scale at which the underlying electricity grid deploys renewables, the relative benefits of BEV HDVs could increase. The share of coal electricity in India's electricity grid was approximately 70% in 2021, and the baseline electricity grid assumptions used in this analysis assume it will remain high, with a projected coal electricity share of 55% in 2030 (IEA, 2022). However, by adjusting the projected change in the electricity grid from the IEA's STEPS model to the more ambitious Sustainable Development Scenario (SDS)—which projects a decline of coal in the grid to 30% by 2030 and 5% by 2040—the estimated GHG benefits of BEV HDVs would increase in turn.

Figure 8 illustrates the differences in emissions between these scenarios for vehicles entering the fleet in 2023 and 2030, compared to a BEV HDV that uses only renewable electricity. In the SDS scenario, BEV HDVs that enter the fleet in 2023 have between 35%–45% lower emissions than diesel ICE counterparts, which increases to between 62%–69% for 2030 BEV HDVs. This suggests that ongoing efforts to decarbonize the Indian electricity grid and reduce coal use may have complementary benefits in the road sector and could accelerate the climate benefits of electrification.

Figure 8

Comparison of life-cycle GHG emissions of a 55-tonne tractor-trailer entering the fleet in India in 2023 vs. 2030, across different scenarios of electricity grid composition.



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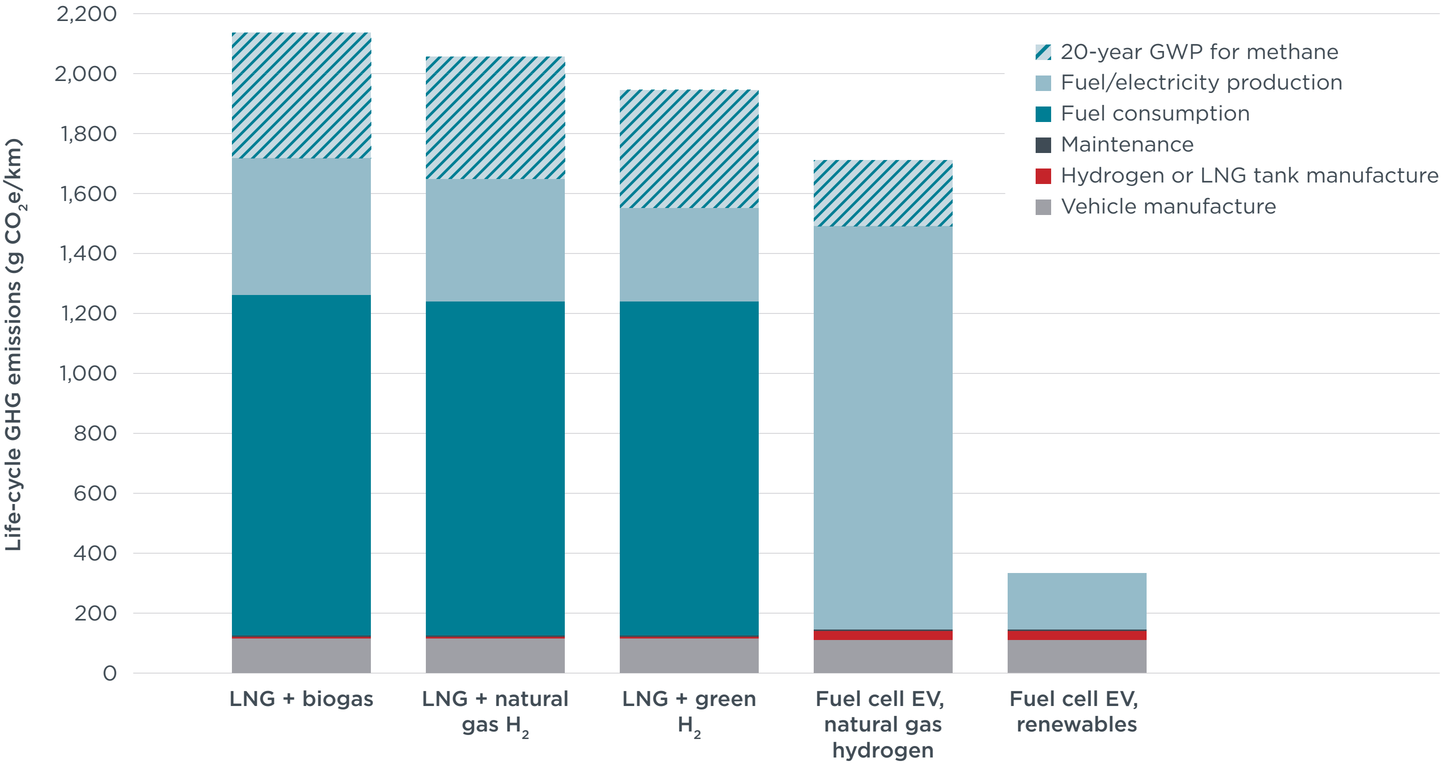
For FCEV HDVs, life-cycle GHG emissions greatly depend on the source of hydrogen. As noted, the life-cycle benefits of using grey hydrogen are modest, ranging from 12%–14% for 2023 FCEV HDVs and 11%–18% for those produced in 2030, relative to diesel ICE counterparts. On the other hand, with green hydrogen produced from additional, renewable electricity, FCEV HDVs achieve GHG reductions similar to those of BEV HDVs using green electricity. However, when factoring in the electricity conversion losses of approximately 30% associated with producing green hydrogen, in conjunction with the relatively lower efficiency of FCEVs compared to BEVs, we estimate that FCEVs require approximately 2.5–3.5 times more electricity per kilometer than a comparable BEV.

Across vehicle categories, life-cycle GHG emission reductions from natural gas HDVs are limited compared to BEVs and FCEVs due to their relatively constrained fuel efficiency in contrast to diesel HDVs, among other factors. Moreover, life-cycle emissions from these vehicles are substantially higher when using a 20-year GWP, as methane leakage throughout the supply chain has considerable near-term warming impacts. Specifically, when assuming a 20-year GWP, we estimate that emissions from natural gas-fueled HDVs produced in 2023 range between 9%–23% higher than their diesel counterparts. Using a 20-year GWP can also help to assess the near-term warming impacts of natural gas-derived hydrogen. In this case, we find that FCEVs produced in 2021 using grey hydrogen made from natural gas generate similar emissions to their diesel counterparts, ranging from 1% lower to 2% higher emissions.

To assess the potential GHG impacts of India's interest in blending hydrogen in the natural gas system (i.e., "hythane" blends), we also evaluated a scenario in which a hydrogen-natural gas blend is used in a CNG powertrain. We evaluated the per-km life-cycle emissions of a 55-tonne LNG tractor-trailer fueled with a blend of 18% hydrogen by volume that enters the fleet in 2023.[2] Figure 9 compares the life-cycle emissions for that vehicle fueled either with a mix of LNG and biogas, with grey hydrogen, or with green hydrogen. We also present the life-cycle emissions of a comparable 55-tonne FCEV tractor-trailer fueled by grey and green hydrogen. We find that, relative to a conventional natural gas mix, a hythane blend produced using grey hydrogen reduces the life-cycle GHG emissions of the 55-tonne tractor trailer by approximately 5%, while a hythane blend using green hydrogen reduces emissions by roughly 10%. In both cases, we estimate that using a dedicated fuel cell powertrain generates fewer emissions than a hythane blend.

Figure 9

Comparison of life-cycle GHG emissions of a 55-tonne tractor-trailer produced in 2023 using grid mix LNG vs. natural gas hydrogen hythane blend (18%), green hydrogen hythane blend (18%), and fuel cell EV trucks.



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Overall, this analysis finds that both BEVs and FCEVs can generate deep reductions in emissions from India's HDV fleet. Specifically, BEV HDVs can generate moderate GHG reductions compared to their diesel counterparts for vehicles entering the fleet in 2023, and we project that these reductions would increase as the share of renewable electricity in the grid grows. In contrast, FCEVs require large-scale transitions for the vehicle and fuel source to generate deeper GHG reductions, as the benefits of using natural gas-derived grey hydrogen are modest and decline towards 2030.

Looking at energy demand more broadly, due to conversion losses, green hydrogen production for use in FCEVs would require more renewable electricity for vehicles to travel the same distance than if the energy was used directly in BEV HDVs. Meeting

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[2] Due to the volumetric energy density difference between hydrogen and natural gas, this comprises approximately 6% by energy density.

India's Hydrogen Mission target of 5 million tonnes of green hydrogen production in 2030 would require approximately 120 GW of renewable electricity capacity, consuming approximately one quarter of the government's planned 2030 renewable electricity deployment (IEA, 2021).

Moreover, the costs of green hydrogen can be higher per unit of delivered energy than a comparable unit of electricity. Kelly and Zhou (2022) project that green hydrogen production in India would cost approximately 325–400 rupees per kg in 2030 (in 2019 rupees), which increases to approximately 650 rupees per kg when considering the cost of distribution and fueling infrastructure. Thus, aligning the costs of hydrogen-fueled trucks with conventional alternatives may require subsidies for both vehicles and fuels.

The results of this analysis broadly align with those of the analysis by O'Connell et al. (2023), which used a similar approach to evaluate the life-cycle emissions of HDVs produced in the EU. The primary differences in the results are attributable to differences in the underlying electricity grid, as India's electricity grid is much more coal-intensive. Whereas a BEV produced in the EU in 2023 can use grid-average electricity with an average of approximately 200 gCO_2e/kWh in IEA's STEPS scenario, a comparable BEV produced in India in 2023 would instead draw upon electricity with an upstream GHG intensity of over 700 gCO_2e/kWh, resulting in much higher life-cycle emissions. Even after accounting for these relative differences, however, we find as a broader trend that BEVs still offer the highest GHG savings of the technologies assessed, and that the results for BEVs produced in India in 2030 grow closer to those in the EU as the Indian electricity grid is projected to decarbonize. We also note that in the EU analysis, the assumed efficiency of diesel ICE HDVs improves at a greater pace by 2030 than in this analysis, resulting in a baseline that declines by more than 20% from 2021 to 2030. In contrast, in this study, the emissions from diesel HDVs decline by approximately 5% from 2023 to 2030. Thus, there may be greater opportunity to reduce the emissions of diesel ICE HDVs through efficiency improvements as well as through transitioning to zero-emission vehicles.

CONCLUSIONS

Though India has implemented standards to improve the efficiency of its trucking fleet, the heavy-duty sector remains one of the country's largest sources of GHG emissions and users of imported petroleum. This analysis used a life-cycle approach to evaluate a series of alternative vehicle powertrain and fuel combinations to consistently compare GHG emissions to the conventional diesel fleet. We assessed the lifetime emissions for a vehicle produced in 2023 and a similar vehicle produced in 2030, allowing us to examine the impacts of expected efficiency improvements and changes in fuel and electricity grids over each vehicles' lifetime. This analysis generated five key findings:

1. **Battery electric HDVs produced in India today can provide the greatest GHG emission reductions of present-day vehicle technologies, but their impact can be increased by a faster phaseout of coal in India's electricity grid.** We estimate that, across vehicle categories, the life-cycle GHG emissions for BEV HDVs produced in India in 2023 range from approximately 17%–29% lower than diesel ICE HDV counterparts when fueled by grid-average electricity over their lifetimes. We also find that life-cycle emissions from BEV HDVs are higher than in other markets due to the relatively large share of coal in India's electricity grid; when using exclusively renewable energy, GHG savings increase to a potential 78–83% life-cycle reduction relative to diesel vehicles. Therefore, deploying BEVs in the road sector should be accompanied by renewable deployment in the power sector to maximize their benefits.
2. **Biofuel blending will have a limited impact on HDV emissions in India.** Even with a rapid increase in second-generation and waste-derived diesel substitutes with low life-cycle emissions, we find that the overall impact of biofuels will be constrained by limited availability and low blend rates. Projecting a rapid increase from 2023 blend levels of less than 1% biomass-based diesel to a 2030 target of 5% proposed by the government of India, we estimate these fuels only reduce the use-phase emissions of diesel HDVs produced in 2023 by approximately 1% over their life-cycle. An increase in biomethane blending to 10% by 2040 had a similar effect, only reducing emissions for natural gas-fueled HDVs by approximately 1%. Together, this suggests that there are much greater emissions benefits from transitioning to zero-emission vehicles, even with the present-day electricity grid.
3. **At best, natural gas-fueled HDVs provide modest GHG savings compared to their diesel counterparts; at worst, they have higher GHG emissions.** Even assuming growing biomethane deployment into the natural gas grid, natural gas-fueled HDVs only provide a marginal benefit in the best circumstances. Specifically, using a 100-year GWP, we estimate that a natural gas-fueled 12-tonne truck or urban bus produced in 2023 generates approximately 11%–12% lower life-cycle GHG emissions than their diesel ICE counterparts, whereas a 55-tonne LNG-fueled tractor-trailer generates approximately the same emissions as its diesel equivalent. When evaluating these impacts with a 20-year GWP for methane, these natural gas fueled HDVs have higher emissions than diesel counterparts, with vehicles entering the fleet in 2023 generating 9%–23% higher life-cycle GHG emissions than diesel HDVs.
4. **Blending hydrogen into the natural gas grid will have a modest impact on the emissions of LNG trucks**. Moreover, the GHG impact of hydrogen blending is highly conditional on the efficiency of the vehicle and the source of hydrogen. For an 18% hythane blend using green hydrogen, for instance, we estimate a 10% decrease in emissions for a 55-tonne tractor trailer compared to a standard LNG mix. Even with the use of green hydrogen, hythane blends have limited impact on the life-cycle GHG emissions of HDVs, and likely would not justify the expense of producing and distributing green hydrogen. For all hythane blends evaluated, the life-cycle GHG emissions were significantly higher than either BEV HDVs or FCEV HDVs.

5. **The overall life-cycle impact of fuel cell HDVs varies considerably based on the source of hydrogen used**. Though FCEV HDVs fueled with grey, natural gas-derived hydrogen entering the fleet in 2023 have moderately lower life-cycle emissions compared to diesel ICE HDVs, with GHG reductions ranging from 12%–14%, these benefits largely remain in the same range for FCEVs produced in 2030. To achieve deeper GHG reductions from FCEVs, vehicle deployment would need to be accompanied by the deployment of renewable electricity-derived green hydrogen. We find that green hydrogen-fueled FCEV HDVs generate life-cycle GHG emissions roughly comparable to green electricity-powered BEV HDVs—though due to conversion losses, these trucks consume a greater quantity of electricity over the course of their lifetime.

REFERENCES

Ashok Leyland. (2023). *Ashok Lyland 5525*. https://truckindia.co.in/brochure/m&hcv/tractor-trailer/55-ton/al5525.pdf

Basma, H., & Rodríguez, F. (2023). *The European heavy-duty vehicle market until 2040: Analysis of decarbonization pathways*. International Council on Clean Transportation. https://theicct.org/publication/hdv-europe-decarb-costs-jan23/

Bieker, G. (2021). *A Global Comparison of the Life-Cycle Greenhouse Gas Emissions of Combustion Engine and Electric Passenger Cars*. International Council on Clean Transportation. https://theicct.org/publication/a-global-comparison-of-the-life-cycle-greenhouse-gas-emissions-of-combustion-engine-and-electric-passenger-cars/

Clean Energy Ministerial. (2023). Clean Energy Ministerial.

https://www.cleanenergyministerial.org/who-we-are/

CRRI. (2008). *Pilot study on effect of overloading on road infrastructure*. http://kmvdgoacircular.com/upload/Overloading%20of%20Road-study%20report.pdf

Dallmann, T., & Bandivadekar, A. (2016). *India Bharat Stage VI emission standards*. International Council on Clean Transportation. https://theicct.org/publication/india-bharat-stage-vi-emission-standards/

Delgado, O., Miller, J., Sharpe, B., & Muncrief, R. (2016). *Estimating the fuel efficiency technology potential of heavy-duty trucks in major markets around the world*. Global Fuel Economy Initiative. https://theicct.org/publication/estimating-the-fuel-efficiency-technology-potential-of-heavy-duty-trucks-in-major-markets-around-the-world/

Hyundai. (2022). *XCIENT rigid fuel cell truck*. https://trucknbus.hyundai.com/global/en/products/truck/xcient-fuel-cell

IPCC. (2013). Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. https://doi.org/10.1017/CBO9781107415324

Jin, L., Delgado, O., Gadepalli, R., & Minjares, R. (2020). *Strategies for deploying zero-emission bus fleets: Development of real-world drive cycles to simulate zero-emission technologies along existing bus routes*. International Council on Clean Transportation. https://theicct.org/publication/strategies-for-deploying-zero-emission-bus-fleets-development-of-real-world-drive-cycles-to-simulate-zero-emission-technologies-along-existing-bus-routes/

Kelly, C., & Zhou, Y. (2022). *Hydrogen Fuel for Transport in India*. International Council on Clean Transportation. https://theicct.org/publication/india-fuel-hydrogen-cost-jan22/

Krelling, C., & Badami, M. G. (2020). CNG and diesel urban buses in India: A life-cycle cost comparison. *International Journal of Sustainable Transportation*, *14*(8), 591–605. https://doi.org/10.1080/15568318.2019.1594468

Malins, C. (2019). What does it mean to be a renewable electron? *International Council on Clean Transportation*. https://theicct.org/publication/what-does-it-mean-to-be-a-renewable-electron/

Mao, S., Basma, H., Ragon, P.-L., Zhou, Y., & Rodríguez, F. (2021). *Total Cost of Ownership for Heavy Trucks in China: Battery-Electric, Fuel Cell Electric, and Diesel Trucks* (p. 60). International Council on Clean Transportation. https://theicct.org/wp-content/uploads/2021/12/ze-hdvs-china-tco-EN-nov21.pdf

Ministry of Heavy Industries. (2021). *Gazette Notification of FAME India Scheme II Extension*. Ministry of Heavy Industries. https://fame2.heavyindustries.gov.in/

MoEFCC. (2021). *India: Third Biennial Update Report to the United Nations Framework Convention on Climate Change*.

Moomaw, W., Yamba, F., Kamimoto, M., Maurice, L., Nyboer, J., Urama, K., & Weir, T. (2011). Renewable energy and climate change. In O. Edenhofer et al., (Eds.), *Renewable Energy Sources and Climate Change Mitigation* (pp. 161–207). https://www.ipcc.ch/site/assets/uploads/2018/03/Chapter-1-Renewable-Energy-and-Climate-Change-1.pdf

MoRTH. (2022). *India HDV Fuel Consumption Standards Implementation Notification*. https://static.pib.gov.in/WriteReadData/specificdocs/documents/2022/jul/doc20227669301.pdf

MoRTH. (2023). *Vahan Dashboard*. https://vahan.parivahan.gov.in/vahan4dashboard/

NITI Aayog, RMI India, & RMI. (2021). *Fast tracking freight in India: A roadmap for clean and cost-effective goods transport*. RMI India. https://www.niti.gov.in/sites/default/files/2021-06/FreightReportNationalLevel.pdf

NREL. (2021). *SunLine Transit Agency Fuel Cell Electric Bus Progress Report Data Period* Focus: Jan. 2020 through Jul. 2020. 50.

O'Connell, A., Pavlenko, N., Bieker, G., & Searle, S. (2023). *A Comparison of the Life-Cycle Greenhouse Gas Emissions of European Heavy-Duty Vehicles and Fuels*. International Council on Clean Transportation. https://theicct.org/publication/lca-ghg-emissions-hdv-fuels-europe-feb23/

PIB. (2020). *Petroleum Minister lays foundation stone for the first 50 LNG fueling stations, says 1000 LNG stations will be set up in next three years*. https://pib.gov.in/PressReleseDetailm.aspx?PRID=1673998

PIB. (2022a). *Amendments to the National Policy on Biofuels -2018*. https://pib.gov.in/PressReleasePage.aspx?PRID=1826265

PIB. (2022b). *India's Stand at COP-26*. https://pib.gov.in/pib.gov.in/Pressreleaseshare.aspx?PRID=1795071

PIB. (2022c). *The Government has set a target to raise the share of natural gas in energy mix to 15% in 2030 from about 6.3% now*. https://pib.gov.in/PressReleasePage.aspx?PRID=1844630

PIB. (2023). *National Green Hydrogen Mission*. https://pib.gov.in/PressReleasePage.aspx?PRID=1888547

PIB Delhi. (2021). *Vehicle Scrapping Policy India*. https://pib.gov.in/PressReleaseIframePage.aspx?PRID=1705811

Prussi, M., Yugo, M., De Prada, L., Padella, M., Edwards, R. & Lonza, L. (2020). *JEC Well-to-Wheels report v5: Well-to-Wheels analysis of future automotive fuels and powertrains in the European context*. https://doi:10.2760/959137

Sathiamoorthy, B., Narla, A., & Bandivadekar, A. (2021). *Market analysis of heavy-duty vehicles in India for fiscal years 2019–20 and 2020–21*. International Council on Clean Transportation. https://theicct.org/publication/market-analysis-of-heavy-duty-vehicles-in-india-for-fiscal-years-2019-20-and-2020-21/

Scania. (2021). *Life cycle assessment of distribution vehicles. Battery electric vs diesel driven*. https://www.scania.com/group/en/home/newsroom/press-releases/press-release-detail-page.html/3999115-scania-publishes-life-cycle-assessment-of-battery-electric-vehicles

Simcenter Amesim. (2022). *Simcenter Amesim | Siemens Software* [Computer software]. https://www.plm.automation.siemens.com/global/en/products/simcenter/simcenter-amesim.html

Singh, N, & Yadav, A. (2024). *Assessing the scale of zero-emission truck deployment required for meeting India's net-zero goal*. International Council on Clean Transportation. https://theicct.org/publication/assessing-the-scale-of-zet-deployment-required-for-meeting-indias-net-zero-goal-apr24/

Stocker, B. D., Roth, R., Joos, F., Spani, R., Steinacher, M., Zaehle, S., Bouwman, L., Xu-Ri., & Prentice, I. C. (2013). Multiple greenhouse-gas feedbacks from the land biosphere under future climate change scenarios. *Nature Climate Change*, *3*, 666-672. https://doi.org/10.1038/nclimate1864

Tata. (2023a). *Tata 1212 LPT Product Details*. https://light-trucks.tatamotors.com/pdf/1212%20LPT.pdf

Tata. (2023b). *Tata LPO 1618 Product Details*. https://5.imimg.com/data5/GF/HS/JK/GLADMIN-3061/tata-magna-lpo-1618-diesel-ac-intercity-bus.pdf

TCI & IIMC. (2015). *Operational efficiency of freight transportation by road in India*. Transport Corporation of India. http://cdn.tcil.in/website/tcil/Study_Report/TCI-IIM%20Report.pdf

Yadav, A., Narla, A., & Delgado, O. (2023). *Heavy-duty trucks in India: Technology potential and cost-effectiveness of fuel-efficiency technologies in the 2025–2030 time frame*. International Council on Clean Transportation. https://theicct.org/publication/heavy-duty-trucks-india-fuel-efficiency-jun23/

Wang, H., Zhao, X., Zhang, K., & Wang, W. (2022). Economic assessment of a renewable energy-electricity-hydrogen system considering environmental benefits. *Sustainable Production and Consumption, 33*, 903–920. https://doi.org/10.1016/j.spc.2022.08.010

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