Should India move towards vehicle electrification? Assessing life-cycle greenhouse gas and criteria air pollutant emissions of alternative and conventional fuel vehicles in India.

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Abstract

India is the third largest contributor of greenhouse gases and its transportation emissions account for nearly one-fifth of all greenhouse gas (GHG) emissions. Furthermore, the transportation sector accounts a significant part of other air pollutant emissions that have damaging consequences to human health. Up until now, it was unclear what the greenhouse gas and air pollutant emissions consequences of electrifying vehicles in India would be, as replacing traditional vehicles with electrified ones reduces tailpipe emissions, but it will increase the emissions from the power sector when vehicles are charging. We mitigate that gap in the literature by performing a state specific life-cycle assessment of GHGs and criteria air pollutant emissions for representative passenger vehicles (four-wheelers, three-wheelers, two-wheelers and buses) driven in Indian states/union territories. We consider several vehicle technologies (internal combustion engine (ICE) vehicles, battery electric vehicles (BEVs), hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs)). We find that in most states, four-wheeler BEVs have higher greenhouse gases and criteria air pollutant emissions than other conventional or alternative vehicles and thus electrification of that vehicle class would not lead to emissions reductions. In contrast, in most states, electrified buses and three-wheelers are the best strategy to reduce greenhouse gases, but these are also the worst solution in terms of criteria air pollutant emissions. Electrified two-wheelers have lower criteria air pollutant emissions than gasoline only in five states. The striking conclusion is that unless the Indian grid becomes less polluting, the case for widespread electrification of vehicles for sustainability purposes is simply not there. Moving towards a sustainable, low carbon and low pollution electricity grid is a requirement to make a widespread transportation electrification case for India.

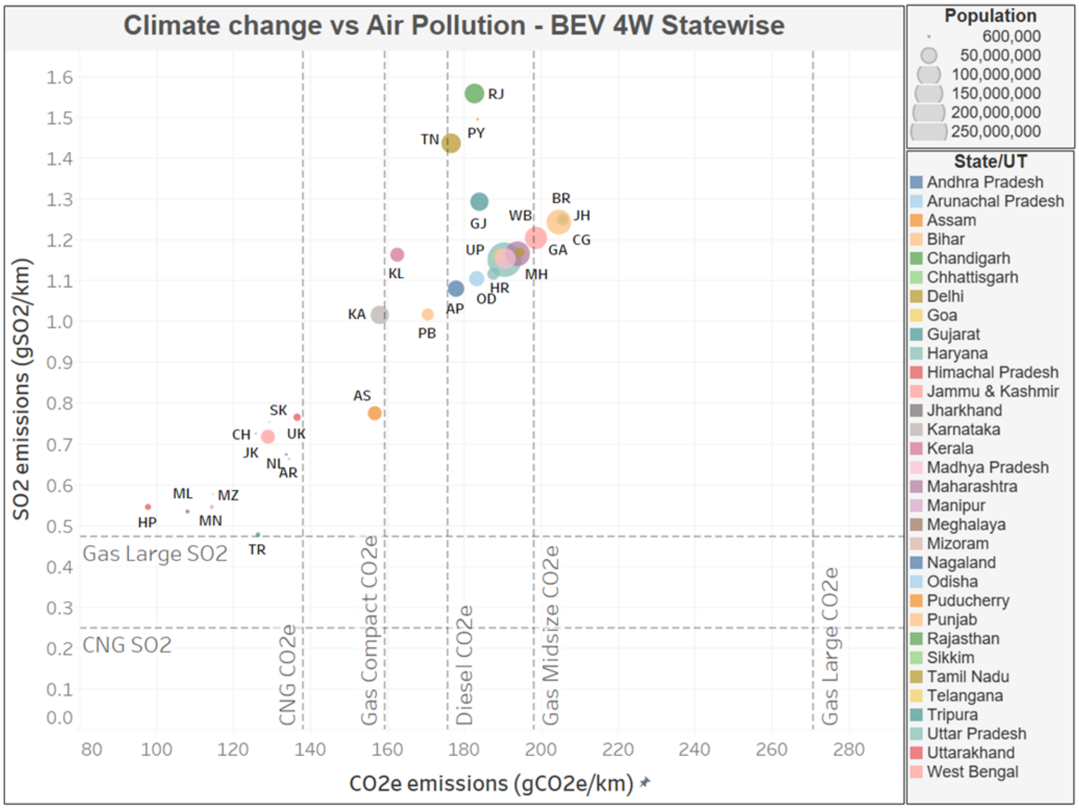
Keywords

India, life-cycle assessment, emissions, transportation, air pollution, climate change

Synopsis

India's road transportation sector is a large source of greenhouse gas (GHG) and criteria air pollutant (CAP) emissions. We compute the first state-specific GHG and CAP life-cycle assessment of conventional and alternative fuel vehicles (two-wheelers, three-wheelers, four-wheelers and buses).

Graphic for Table of Contents (TOC)/Abstract Art



Introduction

India is the third largest contributor of greenhouse gases (GHGs) in the world, and its transportation emissions account for nearly 1/5 of all greenhouse gas emissions in the country.[1] In addition to climate change impacts, transportation accounts for the emissions of criteria air pollutants (CAPs) that lead to health damages. Currently, 21 of the world’s 30 cities with the worst air pollution are in India.[2] Transportation related emissions account for a third of particulate matter ($PM_{2.5}$) pollution in Indian cities, and a somewhat higher proportion of nitrogen oxides, another set of compounds harmful to human health.[3] Due to low vehicle ownership, India has low per capita transportation emissions, but the fleet is growing rapidly: total vehicle sales increased from about 10 million in 2007 to over 21 million in 2016, and the total number of vehicles on the road is expected to nearly double to about 200 million by 2030.[4] With a current population of 1.38

billion[5] and an expected population of 1.64 billion[6] by 2050, bringing environmental sustainability to India's transportation system is a daunting challenge.

A move towards vehicle electrification can be perceived as sustainable, but the net effects on emissions of GHGs and CAPs will be determined by comparing the emissions profile from the electric grid and how those compare to the emissions from conventional vehicles. Furthermore, the health emissions consequences will differ across technologies, as tailpipe emissions may occur in densely populated centers, whereas the emissions associated with the charging of vehicle will be a result of dispersion and atmospheric chemistry from emissions out of a stack of an electricity generating unit.

India's current electricity generation relies heavily on coal[7] making the net effect of vehicle electrification unclear. Up until now, the greenhouse gas and air pollutant emissions consequences of electrifying vehicles in India was unknown. In this work, we perform state specific life-cycle assessment of these emissions for representative passenger vehicles (two-wheelers, three-wheelers, four-wheelers and buses) driven in Indian states/union territories. We consider several vehicle technologies (ICE, BEVs, HEVs and PHEVs).

Although multiple studies have been carried out to evaluate life cycle emissions for passenger vehicles for various countries such as the USA[8,9], Europe[10,11] , and China[12,13] , the literature specific to India is much sparser. For example, General Motors (GM) Corporation[8] assessed the life-cycle emissions of gasoline, diesel, E85, CNG (compressed natural gas), hydrogen, methanol, ethanol fuels, and for conventional, hybrid, and fuel cell powertrains for a pick-up truck using EPA Urban and Highway drive cycles. GM found that fuel cell vehicles can cut the equivalent-gasoline fuel consumption in more than half when compared to a conventional vehicle, and that hybrid gasoline vehicles could reduce fuel-consumption by 20%. GM's study did not consider battery or plug-in hybrid electric vehicles, and it did not assess emissions consequences. Other studies, such as Gupta et al.[14] and Patil et al.[15], performed tank-to-wheel (TTW) and well-to-wheel (WTW) studies for vehicles in India. Gupta et al.[14] studied 28 fuel and powertrain configurations and concluded that a split hybrid configuration would lead to a 20-40% reduction in CO_2 emissions over the Indian drive cycle for light duty four-wheelers. Patil et al.[15] showed that diesel-powered split hybrid electric vehicle was the most efficient among all configurations. Knobloch et al.[16] analyzed the net emissions reduction from electric cars in 59 regions of the world under different scenarios, including India. For the Indian case, the authors found that average electric vehicle was much more GHG intensive than most of the gasoline conventional four-wheelers. Another study, from the Council on Energy, Environment and Water[17] performed estimates of use phase emissions for electric vehicles and found them to be 122 gCO_2/km (compared to 130 gCO_2/km for a conventional gasoline ICE). Finally, the Global EV Outlook 2019[18], using a full life-cycle scope, found that vehicle specifications greatly impacted life-cycle emissions. A large ICE car (1900 kg) emitted 58% more GHG compared to a small car (1100 kg). Similarly, they found that a BEV with a battery size of 39 kWh had 17% more emissions compared to 36 kWh battery size BEV. Other related tools and analysis include GREET[19], a life cycle model developed by Argonne National Laboratory, but GREET is largely modeled on United States conditions.

CAP emissions, which cause health damages, have received less attention in the literature than the GHG life-cycle emissions. We identified only one study (Guttikunda et al.[20]) that estimated on-road emissions for different fuel/vehicle types in the Indian states and cities but does not consider life-cycle emissions.

Table S1 in the SI summarizes this literature. We find that there is no consistent and geographically detailed assessment of the greenhouse gas emissions and criteria air pollutants of vehicle electrification in India.

In Peshin et al.[21], we assessed life-cycle GHG emissions for four-wheelers. This study is novel in terms of calculating the life-cycle greenhouse gas and criteria air pollutant emissions associated with ICE vehicles, natural gas vehicles, BEVs and PHEVs operating in each Indian state/union territory and drawing policy implications for large scale electric vehicle implementation in these regions based on the current electricity mix in the different areas of the country. We do the analysis separately for each vehicle class: representative passenger vehicles (four-wheelers, three-wheelers, two-wheelers and buses).

The rest of the paper is organized as follows. First, we describe the scope, methods, and data for our analysis. We then discuss the results, detailed sensitivity analysis and policy implications.

Materials and Methods

We consider a life-cycle scope for the analysis that includes vehicle (and battery) manufacturing, fuel and/or electricity production, vehicle use, and disposal. We estimate life cycle emissions for greenhouse gas and criteria air pollutants for representative passenger vehicles (four-wheelers, three-wheelers, two-wheelers and buses) and for the following technology/fuel combinations: gasoline/diesel ICE vehicles, natural gas vehicles, BEVs and PHEVs. We perform a geographically specific analysis for each Indian state/union territory based on the current electricity mix in the different regions of the country.

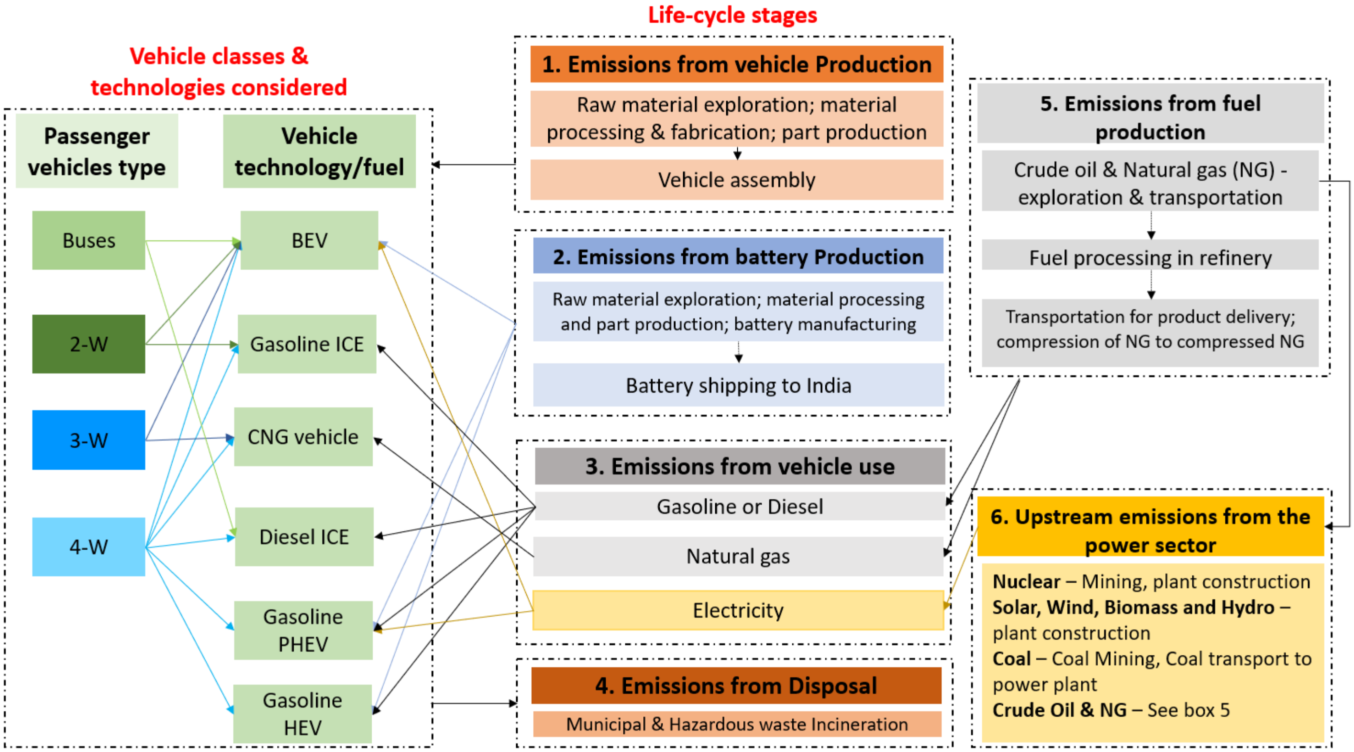


Figure 1. Study system boundary of life cycle greenhouse gas and criteria air pollutant emissions. Colored areas correspond to different life cycle stages. Gasoline and Diesel = internal combustion engine vehicle; HEV = hybrid electric vehicle; PHEV = plug-in hybrid electric vehicle; CNG = compressed natural gas; BEV = battery electric vehicle.

Emissions in the production step include raw-material extraction, processing and fabrication, parts production, vehicle assembly, painting and welding. For electric vehicles, production stage also includes battery-manufacturing and the associated need for mining of rare earth elements (such as lithium). We consider three lithium-ion batteries commonly used for BEV and PHEV: Lithium iron phosphate (LFP), Lithium manganese spinel (LMO) and Nickel Manganese cobalt oxide (NMC). For the HEV, Nickel metal hydride (NiMH) batteries are considered. We assume Li-ion batteries are produced in China and transported to India via airplanes.

The use of the vehicle is associated with emissions through the combustion of gasoline, diesel or natural gas (i.e., tailpipe emissions) or emissions from fossil fuel-based electricity production at power plants when the vehicle is being charged. Thus, we also include the fuel production steps for oil and natural gas, including fuel extraction, refining, and transportation. Regarding electricity generation, we consider the grid mix associated with the electricity consumption in different states/union territories (UTs) (from Sengupta et al., 2021)[22].

In hydrocarbon-based vehicles, emissions are dependent on the quality of the hydrocarbon used as fuel. Three major types of hydrocarbon-based fuels used in Indian vehicles are diesel, gasoline and compressed natural gas (CNG) which have been used. Mechanical parts of a hydrocarbon vehicle and an electrical vehicle cause equal recycling residues and emissions at end-of-life, mainly through municipal and hazardous waste incineration. We assume end-of-life disposal of conventional and electric vehicle have the same emissions intensity in pollutant per kerb weight (i.e., same assumption as in GREET). Today, a very small percentage of the lithium can be recycled and hence, is out of scope of this study.

Selection of representative vehicles: Vehicle sales in India have increased in the past decade with two-wheelers and passenger vehicles capturing majority of the market share. Table 1 shows the domestic automobile sales trends for the previous six financial years (from April 1st to March 31st of the following year).

Table 1. Automobile Domestic sales trends in India (in million vehicles)[23]

Category	**2013-14**	**2014-15**	**2015-16**	**2016-17**	**2017-18**	**2018-19**
Passenger Vehicles	2.5	2.6	2.8	3.0	3.3	3.4
Commercial Vehicles	0.63	0.61	0.69	0.71	0.86	1.0
Three Wheelers	0.48	0.53	0.54	0.51	0.64	0.70
Two Wheelers	14.8	16.0	16.5	17.6	20.2	21.2
Grand Total	**18.4**	**19.7**	**20.5**	**21.9**	**25.0**	**26.3**

We used the information from the Society of Indian Automobile Manufacturers (SIAM) Database[24] to determine the representative vehicles in different fuel categories based on their efficiency standards in India. Table 2 shows the representative vehicles chosen for the study.

The representative vehicles chosen for the analysis based on Original Equipment Manufacturer (OEMs) with the highest sales numbers in India, and within that we selected the vehicle models with highest fuel efficiency. The rationale for this selection is that if these vehicles are not emissions reducing, then the current fleet or new average vehicles sold are even less so.

Compact vehicles have been considered with kerb weight between 600-900 kg, midsize vehicles between 900-1200 kg and large vehicles 1200 kg and above. OEM Maruti Suzuki has continued to be the leading manufacturer in India in terms of units sold. In 2019, Maruti Suzuki sold 1.5 million vehicles across India.[25] This was ~3 times the sales of Hyundai which sold 0.5 million units being the second leading manufacturer in India. India currently does not have a plug-in hybrid vehicle model, but Toyota plans to launch Toyota Prius-Prime in the near future. We thus consider it as the representative PHEV. Two OEMs– Mahindra electric and Tata Motors have heavily invested in the EV Industry in India. In FY 2018-2019, 759,600 units of EVs were sold with electric four-wheelers only accounting for 3,600 of those.[26] Mahindra e20-plus-P2 has been chosen as the representative BEV as it represents the specifications of majority of BEV-4Ws sold in India currently.

For two-wheelers, we have chosen two vehicles from the two largest OEMs– Hero MotoCorp and Honda Motorcycles and Scooters (36% and 26% market share).[27] Photon developed by Hero MotoCorp group is a BEV-2W using lithium iron phosphate (LFP) batteries which has been compared with Activa 5G by Honda in the gasoline category. For three-wheelers, the conventional vehicle is chosen from the largest 3W OEM– Bajaj Auto having a market share of ~64%.[28] Similar to BEV-4W manufacturing, Mahindra electric has invested heavily in BEV-3W manufacturing and hence Treo is taken as the representative BEV. Tata Motors with the majority bus sales in India (31%)[29] is chosen as the representative conventional and alternative buses for the study.

Table 2. Representative vehicles considered in this study.

Manufacturer	Vehicle type	Vehicle model / variant	Kerb weight (kg)	Engine cc/ bhp	Emission stage	Fuel and type	Fuel efficiency (km per l/km full charge)	Battery specs (kWh)	Battery size (kg)
Maruti Suzuki	4W	Alto 800 STD	695	796	BSIV	Gasoline compact	24.7		
Maruti Suzuki	4W	Swift	965	1197	BSIV	Gasoline midsize	20.4		
Skoda Auto	4W	Octavia	1391	1798	BSIV	Gasoline large	15.1		
Maruti Suzuki	4W	Dzire	985	1248	BSIV	Diesel	28.4		
Toyota Kirloskar Motor	4W	Prius Hybrid	1400	1798	BSIV	Gasoline HEV	27.3	1.3	42
Toyota	4W	Prius Prime[30]	1526	1800	-	Gasoline PHEV	23.2	8.8	120
Tata Motors	4W	Magic Iris	805	611	BSIV	CNG	34.7		
Mahindra	4W	e20 plus P2[31]	937	25.4	-	BEV	110	15	112
Honda	2W	Activa 5G[32,33]	109	109.19	BSIV	Gasoline	60		
Hero	2W	Photon[34]	87	2	-	BEV	80	1.8	10.3
Bajaj	3W	Auto RE 4S[35]	388	198.88	BSIV	CNG	35		
Mahindra	3W	Treo[36,37]	340	2	BSIV	BEV	130	7.37	50.8
Tata Motors	Bus	Starbus 40+D AC LP 912/52[38,39]	7476	3783	BSVI	Diesel	4.55		
Tata Motors	Bus	Starbus Ultra 9/9m Electric[40]	8125	-	-	BEV	150	124	735

Data sources and assumptions for different life-cycle stages: Below, we provide data sources and assumptions used for the GHG and CAP emissions for each life-cycle stage. We assume passenger cars traveled about 150,000 kms over the lifecycle based on distance travelled of 12,600 kms/year and average life of 12 years[41] whereas two-wheelers travelled 6,300 kms/year and an average life of 8 years.[41] Three-wheelers are assumed to travel ~35,000 kms/year over a 10-year lifecycle.[41] For buses, since more than 100,000 km are driven in a year we assume that vehicle kilometers travelled per vehicle decreases exponentially with vehicle age as shown in the below equation.[42,43]

$$VKT_{age} = VKT_{1styear} * e^{(\alpha * age)} \quad where$$

$VKT_{age} =$ annual vehicle km travelled at age

$VKT_{1styear} =$ first year vehicle km travelled of the vehicle taken as 114,425 kms

$age =$ first year VKT of the vehicle as 12 years

$\alpha =$ decline parameter controls how fast vehicle km travelled declines over time taken as 0.07

We further assume that lithium-ion batteries are manufactured in China, so average emissions factors of 869 $kgCO_2/MWh$[44], $2kgNO_x/MWh$[12], 1.5 $kgSO_2/MWh$[12], 0.3 $kgPM_{10}/MWh$[12], 0.12 kgCO/MWh[12] for battery manufacturing emissions are used. We make this assumption as the vast majority of the lithium-ion batteries used for electric vehicles in India are currently imported from China. Driving patterns such as local vs highway and rural vs urban are not considered and are out of the scope of this study, as there is no data to include these aspects as far as we are aware.

Vehicle manufacturing emissions. In Tables S2 and S3 in the SI we provide details on our vehicle manufacturing materials in manufacturing processes. We assume that the energy used in vehicle manufacturing comes from three main sources: electricity, natural gas and fuel oil[45] as shown in SI (Table S4). The emission factors used are obtained from Central Electricity Authority(CEA)[46] and GHG Platform India database[1]. Table S5 shows the emission factors used for vehicle manufacturing. We convert emissions of different GHGs into CO_2-equivalent emissions by multiplying the mass of emissions and their Global Warming Potential(GWP). Based on the IPCC fifth assessment report[47], we take the GWP values for 100-year time horizon for methane(CH_4) and nitrous oxide(N_2O) to be 28 and 265, respectively. In the SI, Table S6,we provide our estimates for manufacturing emissions for each representative vehicle. The Energy and Resources Institute[48] and GREET criteria air pollutant emission factor data to interpolate for the current year and determine the emissions associated with vehicle manufacturing (see SI, Table S7).

Battery manufacturing emissions. HEV Toyota Prius uses NiMH batteries while BEV and PHEV use lithium-ion batteries. Average of NiMH AB2 and AB5 batteries are used in the study. Sullivan et al.[49] provides the weight composition associated with both NiMH battery types. The material production and manufacturing energy data for the components is from GREET 2020.[19] In the SI, Table S8,we show our assumptions from battery manufacturing energy consumption.

Hao et al.[50] performed the GHG emissions associated with the production of Lithium-Ion batteries for electric vehicles in China. The battery considered by Hao et al. is 28 kWh specification and three types of commonly used Li-ion batteries, LFP, LMO and NMC. Romare et al.[51] performed a comparative review of available life cycle assessments on lithium-ion batteries for light-duty vehicles and the results from the review were used to draw conclusions on how the production stage impacts the GHG emissions. The mass fraction of each material/component of the three lithium-ion batteries is shown in Table S9. Among all of these, the anode active materials take up the biggest share, 24.4%, 28.2%, and 33.6% for LFP, NMC, and LMO batteries respectively. This is followed by wrought aluminum. Aluminum is also heavily used in the batteries, including the anode current collector, anode tab, aluminum plastic film of battery cell, battery package, and module shell. Plastics include PP, PT and PET, used in the membrane and aluminum plastic film. In Tables S9, S10, S11, in the SI we show the assumed Li-ion battery mass composition, and our resulting estimates of component emissions. The average of the three battery technologies is taken for the four-wheelers as the battery type used was not available. Anode active materials take up the greatest share of the contribution to GHG emissions made by all components of the battery, respectively 48.4%(LFP), 60.7%(NMC) and 51.1%(LMO); followed by wrought aluminum, at 26.2%, 19.7%, and 24.9% respectively. These two components together contribute about 75-80% of the total battery manufacturing emissions. Mahindra e20-plus-P2 has a battery life warranty of 60,000 km so we consider 3 batteries being used over the life cycle of the vehicle.[52] Toyota Prius and Prius prime are considered to have battery life lasting the vehicle life cycle. Two-wheeler hero photon uses LFP battery with an estimated battery life of 28,000 km and hence we consider 2 batteries required over its lifetime.[34] Three-wheeler BEV Mahindra Treo and BEV bus Tata Starbus electric use NMC batteries with an estimated battery life of 80,000 km[36] and ~300,000 km[53], respectively.

We assume transportation of batteries for vehicle applications is done via airplane from China.[54] The International Air Transport Association(IATA) sets the transportation safety requirements for international air transportation, and it requires that all lithium-ion batteries must pass UN 38.3 testing in order to be transported and exported to different categories. We assume a cargo aircraft is used for transporting batteries from China to India. We take an average flight distance of 3786 kms[55] from Beijing to Delhi which comes under the long-haul cargo flight category. IPCC report[56] on transportation gives a range of 375-950 gCO_2/tonne-km for long-haul cargo aircraft emissions. It is estimated that air transport contributes to air pollution only at low-altitude which includes landing and take-off cycle(LTO).[57] Low-altitude aircraft emissions includes nitrogen oxides(NO_x) (other air pollutant emissions are considered to be negligible from air transport) which have been included in the battery shipping emissions. OECD Report[57] estimates this to be 5.56 g/tonne-km.

Table S12 in the SI takes an average of the range and computes the battery shipping emissions associated with different vehicles.

Fuel production and transportation emissions. We use the Ministry of Petroleum and Natural Gas Economics and Statistics Division report on Indian Petroleum and Natural gas[58] for 2017-18. The report indicates the amount of crude oil and natural gas consumption and where oil production originates. In the SI, Tables S13-S15, we present these assumptions. India consumed 250 million metric ton crude oil, with only 35 million metric ton being produced domestically. We consider the emissions factors from Masnadi et al.[59] regarding the production and transportation emissions of oil depending on its location. The transportation emissions are dependent of oil producing countries global exports, and we use that as our values, rather than specific transportation emissions to India.

In India, the refining sector is divided into public, private and joint venture enterprises. Table S13 in SI shows the crude oil processed along with gasoline and diesel produced in all the refineries. Also, Table S14 shows the natural gas onshore and offshore production.

We use Mohan et al.[1] estimate of natural gas exploration and transportation(~10.6 $MtCO_2e$/year) and fugitive emissions(~114,259 tCO_2e) and combine it with natural gas production data (Table S14),estimating a natural gas upstream emission intensity of 11 gCO_2e/MJ. The fuel refining efficiencies for gasoline, diesel and natural gas are assumed to be 87.7%, 86.2% and 94.3% respectively.[15] Assumptions for fuel transportation are shown in SI, Table S16. For CNG vehicles, fuel transportation includes the compression of natural gas which happens after delivery to refueling stations. There are two types of compressors, electric and natural gas-fueled compressors, with the former being the mostly commonly used. We assume an electric compressor process emissions factor of 4.18 gCO_2e/MJ.[19] In the SI, Table S17, we show our estimates of CO_2e

emissions associated with fuel production and transportation phase which includes exploration and transportation to refinery, fuel refining and fuel transportation to pumps processes.

GREET[19] 2020 data is used to determine the CAP intensity associated with crude oil and natural gas, as shown in Table S18. Natural gas emission factors include processing, transportation to refueling station and compression to CNG data as well while crude oil refining emissions are computed separately as shown in the SI, Table S19 taking the average of emissions from two refineries in India as provided in Majumdar et al.[60] CAP emissions from gasoline and diesel transport to refueling stations are a small contributor to overall fuel upstream emissions. The emission factors for this are taken from GREET and the assumed values are shown in Table S20.

Fuel use emissions. Tailpipe emissions depend on the type of transport and fuel used. India GHG Program report[61] provides a method for determining India specific road transport emission factors based on engine capacity and fuel type used for different vehicle types: two-wheelers, three-wheelers, passenger cars, buses and freight vehicles. Ramachandra et al.[62] performed a state-wise synthesis analysis of road transport GHG and CAP emissions using region specific mass emission factors. Sindhwani et al.[63] provided an assessment of criteria air pollutant emissions and trends in Delhi for different vehicle and fuel types. Table 3 summarizes the emission factors from Central Pollution Control Board (CPCB) for vehicular exhaust[64,65] based on the emission stages used for the representative vehicles.

Table 3. Emission factors in g/km (unless otherwise mentioned) for fuel combustion associated with the use of different vehicles. PC: Passenger car. 2W-4S: Two-wheeler four stroke

	PC - Gasoline	**PC - Diesel**	**PC - CNG**	**2W - 4S**	**3W - CNG**	**Bus-Diesel**
CO_2 (g/L)	2271.93	2644.4	2692	2271.93	2692	2644.4
CH_4	0.17	0.17	2.28	0.18	1.3	0.09
CO	1	0.5	0.78	1.403	0.62	0.5
NO_x	0.08	0.25	0.064	0.39	0.07	0.08
PM	0.03	0.025	0.02	0.011	0.012	0.0045
SO_2	0.053	0.053	0	0.023	0	0.093

Electricity upstream emissions. We use electricity generation data by fuel type for 2018 (Table S21 in SI). 80% of the coal used in power plants is produced in India while the remaining 20% comes from Indonesia (12%), South Africa(4%), the United States(2%) and Australia(1%), with some other countries together contributing the last 1%.[66] Since four-fifths of the coal for electricity generation is produced in India, we take the Indian coal exploration and transportation from mines to power plant emissions to account as the average for the electricity upstream emissions. Non-coking coal and surface mining contribute 95% of the coal produced as shown in the SI, Table S22.

We compute the emissions associated with diesel, electricity consumption and fugitive emissions associated with mining and post mining using the data from Mallapragada et al.[67] and Singh et al.[68], as shown in the SI; Table S23.Coal transportation is assumed to be through rail, road, and other sources(belt, rope etc.) with rail/road transport contributing 97% of the coal transport and hence have been used.[67] Rail transport in turn is divided into diesel and electric with 75% and 25% contribution, respectively.[67] The average distance from a coal mine to plant is assumed to be 515 km (Table S24).

Crude oil and natural gas upstream emissions data is discussed in detail under fuel production and transportation emissions. Table S5 showed that about 20% of the electricity generation comes from renewable energy sources such as nuclear, solar, wind, hydro and biomass. Weisser et al.[69] provides a guide to life-cycle GHG emissions from electric supply technologies. The alternative energy upstream emissions provided by Weisser have been used. For alternative energy sources, we also account for plant construction because we assume that there will be an uptick in these new plants in the coming decade. Differences in the GHG emissions for nuclear energy chains, are attributed to the enrichment technology used, as well as the nuclear energy technology type. We include the upstream emissions associated with Light Water Reactors (LWR) which is the most widespread and commonly used reactor technology. The upstream emissions for nuclear are estimated to be between 1.5-20 gCO_2eq/kWh. For solar power, four systems are assessed including mono-crystalline, poly-crystalline, amorphous and Copper Indium Gallium Diselenide. Production and construction of the module along with supporting infrastructure is estimated to contribute 65% of the total life cycle emissions. Mono-crystalline upstream emissions are estimated to be between 27.95-40.3 gCO_2eq/kWh whereas the other three photovoltaic system it is estimated to be 32.5-47.5 gCO_2eq/kWh. For wind turbines, 72-90% of cumulative emissions are estimated to contribute to turbine production and plant construction. All the wind projects currently in India are onshore with a total installed capacity of ~37 GW. The upstream emissions for wind power are estimated to be between 6.7-25.2 gCO_2eq/kWh.

The GHG emissions associated with hydro power plants vary significantly based on the type of plant i.e., run-off or reservoir, its size and usage as well as the electricity mix for its operation. The upstream emissions for hydroelectric plants are estimated to lie between 2-9 gCO_2eq/kWh. 0.2 TWh of the electricity generated in 2018 is assumed to come from biomass. Biomass upstream emissions are estimated to be between 35-99 gCO_2eq/kWh. In the SI, Table S25 we show our estimates of upstream emission factors used which have been computed by taking the mean of the estimations detailed above.

We determine that upstream CAP emissions for coal using TERI Air pollution emissions scenario[48]. We assume that 1 tonne of coal is equivalent to approximately 8.14 MWh of electricity. Argonne National Laboratory GREET data[19] is used to determine crude oil and natural gas upstream CAP emission factors (see SI, Table S26). Upstream CAP emissions associated with alternative sources of electricity are considered to be negligible and ignored from the scope of the study.

Electricity use emissions. We use the average emissions factors (the average emissions intensity of electricity generation from all sources at a given time in kg/MWh) from Sengupta et al.[22] The authors have developed a reduce-order dispatch model for Indian power generation to simulate average emission factor for the Indian states for year 2017-18.The approach constructed a merit-order curve of non-renewable generators ordered by variable cost of generation for each hour of the day. The model used publicly available database of all non-renewable generators in India with capacity higher than 25 MW and computed production-weighted variable cost of coal power generators with Government of India's coal dispatch database[70] which reports grade-wise coal amounts sold to power stations and grade-wise fixed fuel prices from Coal India and state-wise coal transport costs.[71,72] For gas plants, a region-based approach with domestic and imported gas prices and applicable state taxes was used.[73,74] For intrastate generating plants, 100% of capacity was allocated to respective states; for interstate generation states, capacity allocations to multiple states came from the MERIT India database and CEA.[75,76]

Net demand is computed by estimating the total hourly demand at the state-level by decomposing total daily demand reported from Power System Operation Cooperation(POSOCO)[77] by state-level diurnal load profiles of demand disaggregated at the monthly-level from Energy Analytics Lab.[78] The daily demand reported by state represents the power injected into the state at the state boundary. The average monthly diurnal renewable generation profiles were estimated by first disaggregating nationwide renewable generation data for 2018-2019[79] to obtain diurnal profiles of renewable generation and then applying these profiles to actual monthly renewable generation for each state from September 2017 to August 2018.[80] Net demand for each hour of year for each state was obtained by subtracting average monthly diurnal renewable generation from estimated total hourly demand for a given hour.

CO_2 and SO_2 emissions factors are estimated as functions of unit heat rate for fossil plants. The authors assumed a domestic Indian production-weighted average coal composition[81] for all plants. Figure 2 shows the grid emission factors used in this study to determine the emissions from electricity use.

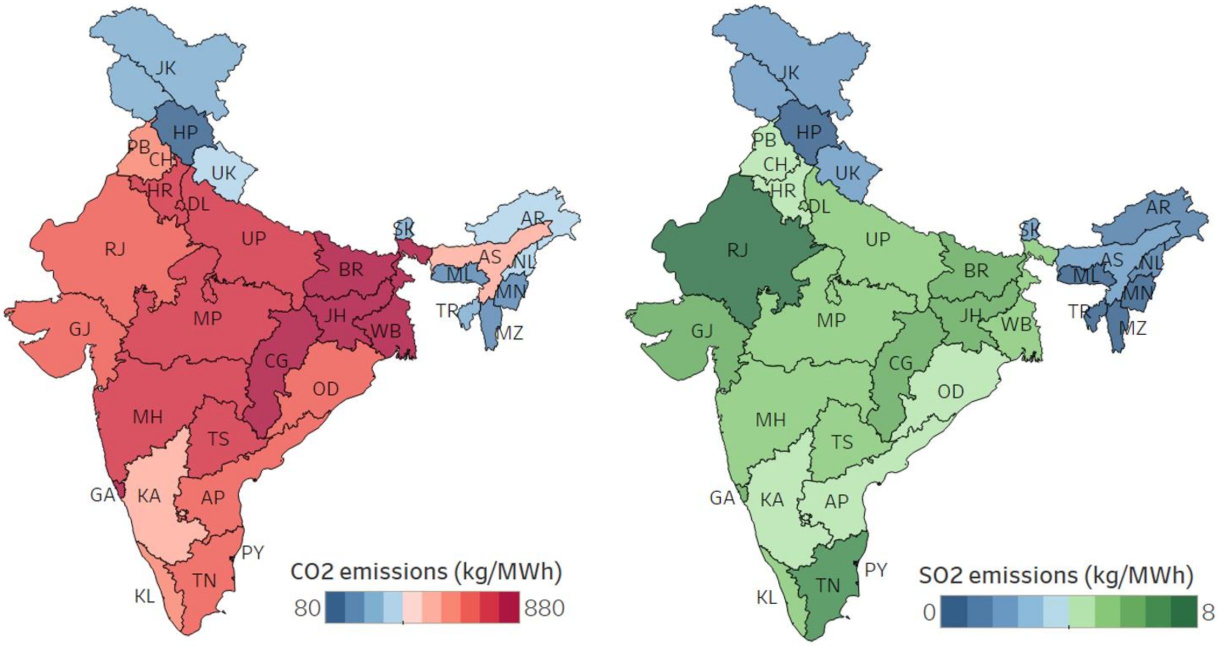


Figure 2. Average grid emission factors for Indian states in kg/MWh in year 2017-18.

The Energy and Resources Institute's air pollution emissions scenario report[48] provides power sector emission estimates of different pollutants from 2001–2051. This along with the electricity generation data in TWh[7] from the last decade is used to interpolate and determine the emission factor in kg/MWh for 2017-18. In the SI (Table S27 and S28), we show the power sector estimates from the report and our assumed criteria air pollutant emissions for 2011 and 2021 which are used to interpolate emission factors for 2017-18.

Vehicle disposal emissions. For vehicle disposal, we use GREET energy consumption data and multiply those by India specific emissions factors(see SI, Table S29). These emission factors multiplied with the kerb weight of the vehicle provides the GHG and CAP emissions associated with the representative vehicles.

Results and Discussion

Average national GHG and criteria air pollutant life cycle emissions of different vehicles. Figure 3 shows the life cycle emissions associated with each of our representative vehicle type when assuming a national average electricity emissions intensity of 767.3 kg/MWh[46] for CO_2, and 5.3 kg/MWh[48],0.04 kg/MWh[48],1.05 kg/MWh[48],0.47 kg/MWh[48], of SO_2, CO, NO_x, PM_{10}, respectively. We show the CO_2e emissions for all vehicle classes, but for sake of space we only show CAP emissions for 4W. The results for CAP emissions for the remaining vehicle types are shown in the SI **(**Figure S1,S2,S3**)**.

We find that electrifying 2W and 3W leads to lower emissions of CO_2 but increases the emissions of criteria air pollutants. For four-wheelers, we find that CNG vehicles have the lowest life-cycle emissions, and BEVs may increase CO_2 emissions when compared to some of the conventional vehicle alternatives. BEV buses have lower GHG emissions than comparable diesel vehicle, but the decrease in emissions is only about 7% compared to a conventional bus.

We find that using the national average emissions intensity, gasoline PHEV and BEV have higher emissions than conventional vehicles. This is due to the high emissions of criteria air pollutants from the coal-heavy electricity grid. CO emissions are much lower for PHEV and BEV compared to conventional gasoline vehicles. This is because the largest share of CO emissions is associated with fuel use stage.

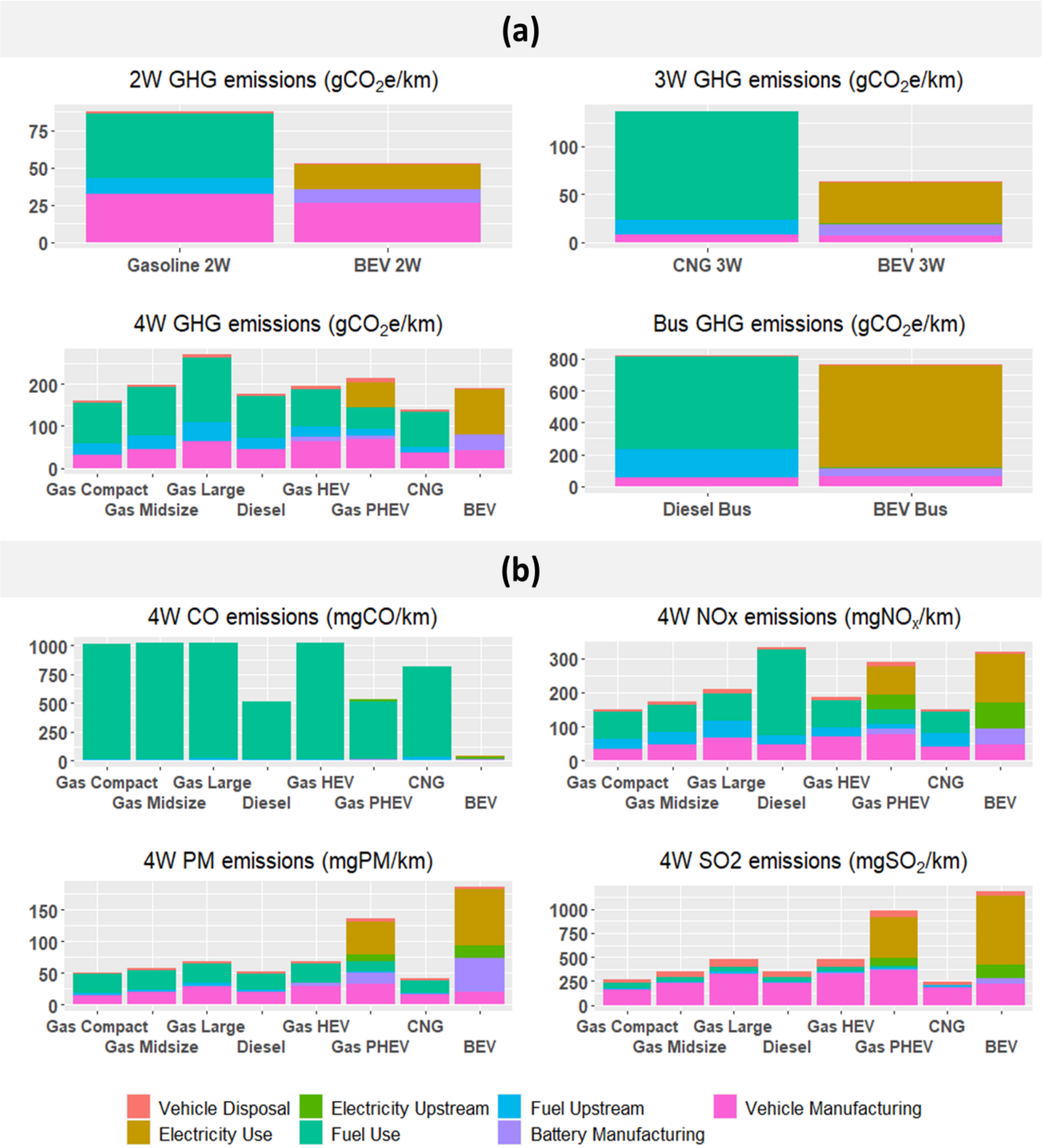


Figure 3. Average nationwide GHG (a) and CAP life cycle emissions (b) for different representative vehicles in India. Similar trend seen for other vehicle types shown in SI.

Regional variation matters: State-wise BEV climate change and air pollution comparison. In Figure 4, we show the CO_2 and SO_2 pair-wise emissions for 4-wheeler BEVs and compare those with the emissions of other 4W alternatives (depicted in vertical and horizontal dashed lines). Similar plots for other vehicle classes are shown in the SI. BEV-4Ws in Jharkhand, Chhattisgarh, Bihar and Goa have higher CO_2 emissions than all other alternatives (with the exception of a large gasoline vehicle) and emit more criteria air pollutants than all the other vehicle alternatives. There are 11 states/UTs for which electrifying vehicle would lead to lower GHG emissions than the alternatives, however even in those states electrifying 4W would lead to higher SO_2 emissions than using gasoline or diesel. Electrifying 4W in Rajasthan, Puducherry and Tamil Nadu leads to very high emissions intensity of SO_2, owing to the large share of coal in the electricity generation mix of those states.

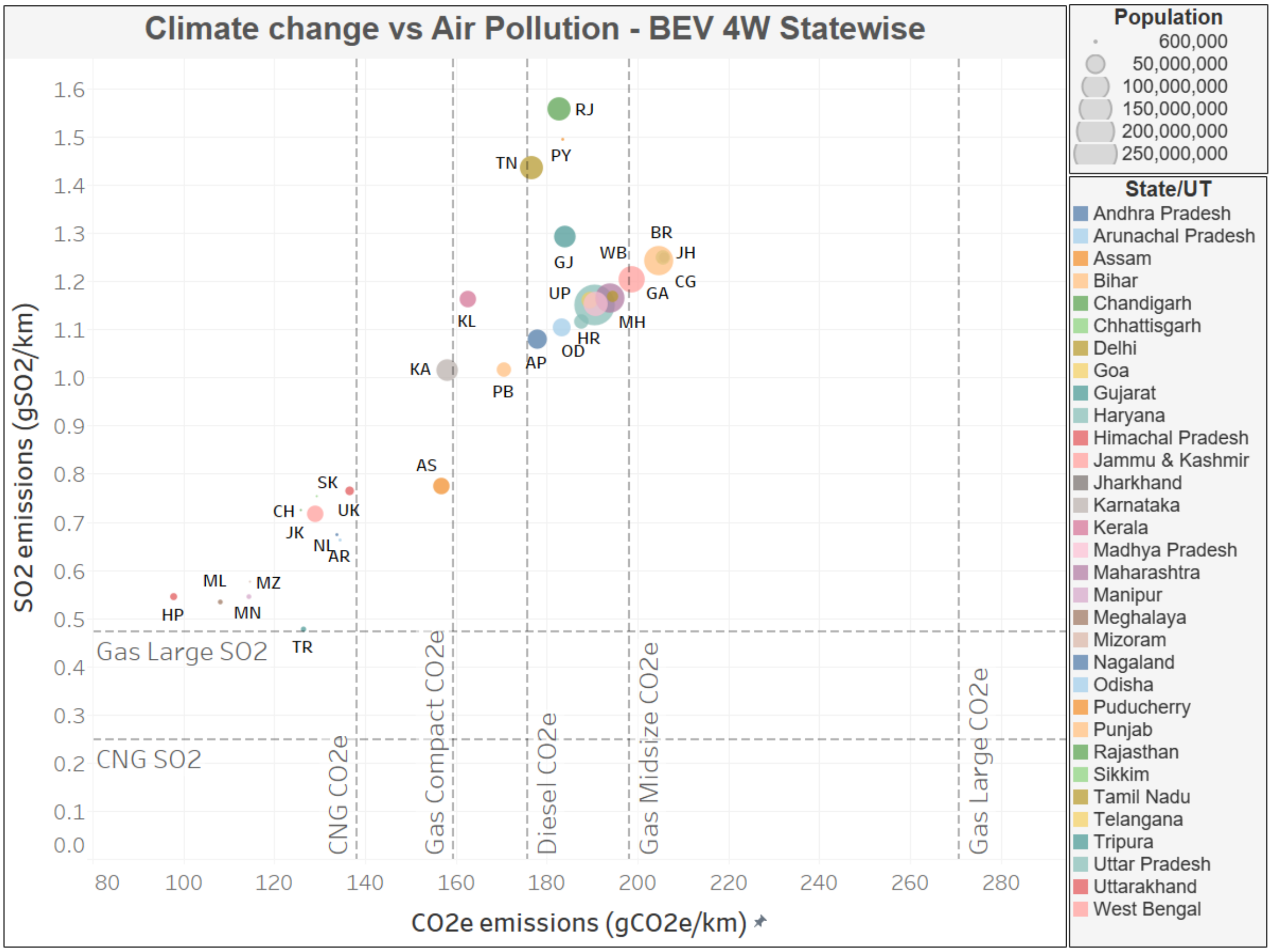


Figure 4. CO_2 and criteria air pollutant emissions per km driven for different 4-wheller representative vehicles in each India state/UT.

We find 2W gasoline vehicles have higher CO_2 emissions than BEVs for all Indian states/UTs (see Figure S4 in SI for details). Furthermore, 2W-BEV's SO_2 emissions are lower than gasoline vehicles in only 5 of the 32 states/UTs. 3W-BEVs have much lower CO_2 emissions in all states and union territories. However, SO_2 emissions for 3W-BEVs are higher in all regions compared to a representative CNG three-wheeler(see Figure S5). For the buses, we find that in Jharkhand, Chhattisgarh, Bihar and Goa BEVs have higher GHG emissions than a conventional diesel bus(Figure S6).

PHEV-4W GHG emissions are higher compared to BEV GHG emissions for all states. However, 24 of the 32 states/UTs have lower PHEV SO_2 emissions compared to BEVs (Figure S7). This is attributed to the higher fossil fuel use in power plants required for charging battery electric vehicles in turn resulting in higher SO_2 emissions. Figure S8 summarizes the vehicle types with the least GHG, and CAP emissions associated with Indian states.

Range of monetized damages from climate change and air pollution. While information on GHG and CAP emissions may be of interest, policy makers may likely require a way to compare the effects of these two types of emissions in comparable units to understand the sustainability implications of different vehicle strategies. In this section, we provide order of magnitude estimates of the monetized damages from air pollution and greenhouse gases of life-cycle emissions for different vehicles. In Figure 5, we show the range of damages, in cent of dollar per km, for different vehicles.

Regarding the damages from climate change, we multiply the GHG emissions by the social cost of carbon (SCC) in $\$/tonCO_2$. The SCC values have ranged widely in the literature with some estimated as low as \$10 to as high as \$150.[82] Ricke et al.[83] provide estimates of country specific SCC, and their median estimate for India in $USD\$_{2010}$ is $\$86/tCO_2$(ranging from \$49 to \$157 for 66% confidence intervals) emitted in 2020 under the shared socioeconomic pathway-2(SSP2) and representative concentration pathway-6(RCP6) for the short-run damage function and growth adjusted discount rate scenario. We use $\$_{2020}50/tCO_2$ as our baseline number and also provide results for $\$_{2020}35/tCO_2$ and $\$_{2020}150/tCO_2$. To put this in perspective, a SCC of $\$50/tonCO_2$

equates to ~1 ¢/km for a gasoline four-wheeler. An average citizen driving about 12,500 kms per year would then be inducing climate damages of $125. If this externality is fully taxed, these $125 correspond to ~6% of the average income (India's per capita income ~$2000/year[84]).

For the criteria air pollutant damages, we use the damage estimates for CO, NO_x and SO_2 from Shindell.[85] The values used are for the composition-health impacts at discount rates of 3% (baseline), 5% and 1.4% (lower and upper estimates respectively). These numbers are in $USD\$_{2007}$ and we adjust them to $\$_{2020}$ using the consumer price index.[86] PM_{10} damage estimates are taken from Victoria Transport Policy Institute study[87] and Wang et al.[88] and are also converted to $\$_{2020}$. These damages are only meant to provide order of magnitude implications, as the effects of air pollutions will be highly dependent on dispersion and exposure to the increased concentration of pollutants.

We find that, with the exception of BEV-2W, the negative externalities associated with BEVs across different vehicle types is currently much higher compared to conventional vehicles.

Figure 5. Estimates of climate change damages (in blue) and air pollution damages (in pink) for different vehicle segments and fuels in India (all in cent of $\$_{2020}$ per km). We assume a $\$_{2020}50/tCO_2$ for the social cost of carbon, and the low and high values shown as asterisks in the plot represent the SCCs of $\$_{2020}35/tCO_2$ and $\$_{2020}150/tCO_2$. Air pollutant damages comes from Shindell[85], the Victoria Transport Policy Institute study[87] and Wang et al.[88].

Sensitivity Analysis. We perform variety of sensitivity analyses, several of which are shown in the SI (Section 4)**.** We provide a detailed treatment of the effect of ambient temperature, effect of different marginal emissions factors, and other sensitivity factors such as kerb weight, fuel efficiency, battery rated capacity, vehicle kilometers travelled and grid emission factors. Our key findings from the sensitivity analyses are discussed below.

Ambient Temperature Effects. For 4W, we estimate the fuel economy decreases by about 14% for diesel vehicles and 13% for gasoline vehicles at 20˚F. The decrease in fuel economy at 95˚F is half that at 20˚F for both gasoline and diesel four-wheelers. The energy consumption increases by 89% at 20˚F and 33% at 95˚F for battery electric 4W. For 2W and 3W, we estimate the fuel economy decreases by ~24% for conventional vehicles at 20˚F. The decrease in fuel economy at 95˚F is 12%. For BEVs, we see a decrease of ~22% in equivalent fuel economy at 20˚F and 12% decrease at 95˚F. For buses, the decrease in fuel economy is estimated to be about 24% for diesel vehicles at 20˚F. The decrease in fuel economy at 95˚F is approximately half that at 20˚F (12%). The energy consumption increases by 41% at 20˚F and 17% at 80˚F for battery electric buses (BEBs). Figure S9-S12 in SI shows the ambient temperature effects on the emissions across different states.

Marginal Emission Factors. Figure S13-S16 in the SI show the computed life cycle emissions from the marginal emission factors in monsoon and non-monsoon months associated with the top 10 states based on population contributing to about 75% of the Indian population (~1 billion). The state-specific marginal emission factor data is obtained from Sengupta et al.[89] and explained in the SI. Afternoon charging shows overall decrease in both CO_2e and SO_2 emissions with the heavily populated states of Maharashtra and Tamil Nadu benefiting the most with afternoon charging in both monsoon and non-monsoon months.

Other sensitivity factors. We performed a monte-carlo simulation with distributions for uncertain inputs as defined in Table S31-S34 and refer the reader to that section for additional sensitivity analysis.

Given its size, India's transportation emissions pathways will play a key role in achieving decarbonization and sustainability of the global energy system. In this study, we estimate the life cycle GHG and CAP (CO, NO_x, PM, SO_2) emissions associated with conventional and alternative fuel vehicles. We find that in most states, four-wheeler BEVs have higher greenhouse gases and criteria air pollutant emissions than other conventional or alternative vehicles, and thus electrification of that vehicle class would not lead to emissions reductions. In contrast, in most states, electrified buses and three-wheelers are the best strategy to reduce greenhouse gases, but these are also the worst solution in terms of criteria air pollutant emissions. Electrified two-wheelers have lower criteria air pollutant emissions than gasoline only in five states.

A move to electric vehicles in Indian states and union territories makes sense only if it is accompanied by greening of the grid in order to address both climate change and air pollution issues associated with charging of these vehicles. The process of coal phaseout can take decades given the financial challenges and significant impacts on livelihoods of those associated with it. However, there are multiple steps government of India can take in ensuring the smooth transition to renewables. In December 2015, the Indian government came up with the policy requiring power plants to install pollution control equipment (flue gas desulfurization units) by the end of 2017, but the deadline has been extended twice already. It is anticipated that even then, 70% of the plants may fail to meet the set standards in 2022.[90] Given three-fourth of the coal power plants[91] in India are using inefficient sub-critical coal technology and are highly polluting, meeting the set standards and staying on the defined deadline could be a first step towards responding to the air pollution crisis affecting the country.

The battery manufacturing and shipping emissions can also be brought further down if they are manufactured in India instead of China in coordination with the transition to a greener grid. Afternoon charging (2 pm–6 pm) shows overall decrease in both CO_2e and SO_2 emissions for majority of the heavily populated states for all vehicle types. However, these reductions are still not low enough to be able to displace the conventional vehicles based on air pollutant emissions in the current grid mix. The electric mobility sector in India is still in a nascent stage. In spite of the government's policy signal and considerable financial support, EV market development is still on a bumpy road. One significant challenge with regards to scaling up EV adoption has been provision of EV charging infrastructure. The electric four-wheeler segment in particular is grappling with this barrier to EV adoption. As the widespread charging infrastructure is built and EVs adopted, improvements to fuel efficiency and CO_2 standards can help to further reduce the emissions of the last generation of combustion engine cars. India's infrastructural challenges are unique, and, hence, the best practices in electric mobility identified in advanced international markets may not be feasible or effectively address India's problems; the approach to tackling the challenges and developing solutions needs to be tailor-made for Indian states and union territories.

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