WORKING PAPER 2021-12

APRIL 2021

Understanding the emissions impacts of large-scale vehicle electrification in India

Authors: Arijit Sen, Josh Miller, Anup Bandivadekar, Mukesh Sharma,[1] Dhirendra Singh,[2] and Jennifer Callahan

Keywords: vehicle tailpipe emissions, India, air pollution, electric vehicles, electricity grid

Introduction

High concentrations of hazardous pollutants such as fine particulate matter ($PM_{2.5}$) and ground-level ozone contribute substantially to premature deaths and disease, and India has some of the highest population-weighted exposures to ambient $PM_{2.5}$ and ozone in the world.[3] Among the chief contributors to poor air quality in India are emissions from the power and transportation sectors.[4] To reduce air pollution and also carbon dioxide (CO_2) emissions, India has adopted policies promoting the adoption of electric vehicles (EVs) and the decarbonization of the power sector.[5]

In this paper we estimate the emissions impacts of large-scale vehicle electrification in India through 2040 under various scenarios representing plausible evolutions of India's electricity grid. We find that ambitious vehicle electrification could reduce tailpipe emissions between 18% and 50% in 2040, depending on the pollutant. Considering the combined effects on road transport and power sector emissions, EVs could lead to net emission reductions of nitrogen oxides (NO_x) and CO_2 and only marginal increases in $PM_{2.5}$ and sulfur dioxide (SO_2), even under a pessimistic scenario in which the electricity for EVs is generated by coal and gas power plants. Improving power plant emission controls and/or reducing the share of coal electricity generation could lead to substantial net emission reductions for all pollutants.

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communications@theicct.org

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1 Department of Civil Engineering, Indian Institute of Technology, Kanpur

2 Airshed Planning Professionals Private Limited, Indian Institute of Technology, Kanpur

3 Kalpana Balakrishnan et al., "The Impact of Air Pollution on Deaths, Disease Burden, and Life Expectancy Across the States of India: The Global Burden of Disease Study 2017," *The Lancet Planetary Health 3*, no. 1 (2019): e26–e39. https://doi.org/10.1016/S2542-5196(18)30261-4

4 Chandra Venkataraman et al., "Source Influence on Emission Pathways and Ambient PM 2.5 Pollution Over India (2015–2050)," *Atmospheric Chemistry and Physics 18*, no. 11 (2018): 8017–8039. https://doi.org/10.5194/acp-18-8017-2018

5 Shikha Juyal et al., "Zero Emission Vehicles (ZEVs): Towards a Policy Framework," *NITI Aayog* (2018): 1–20. https://smartnet.niua.org/sites/default/files/resources/ev_report.pdf

Methodology

Grid scenario assumptions

We developed five scenarios for the energy mix of the electricity grid and coal power plant emission controls for 2020, 2030, and 2040, and analyzed the resultant emissions of $PM_{2.5}$, NO_x, SO_2, and CO_2 from electricity generation. These scenarios are Baseline, Reference (REF), Improved Emission Controls (IEC), Coal Phaseout (CP), and Combined (COM), and they are detailed in Table 1. The Baseline scenario is comprised of 2020 capacity and generation data from the Central Electricity Authority (CEA) and projections of likely capacity and generation in 2030 from CEA, extrapolated to 2040. We assumed implementation of already adopted decarbonization and emission control policies and plans, but no adoption of new policies.[6] In the Baseline scenario in 2020, coal power plant emission controls for $PM_{2.5}$ are 96% efficient and emissions of SO_2 and NO_x are uncontrolled. For 2030, emission controls for SO_2 and NO_x are assumed to be added at 90% and 70% efficiency, respectively, for power plants constructed before 2017, and at 90% efficiency for both pollutants for power plants constructed in or after 2017. For 2040, SO_2 and NO_x controls are assumed to achieve 90% efficiency for all power plants, regardless of year of construction.

Table 1. Key scenarios and assumptions for the road transport and power sectors

Scenario	EV assumptions	Power sector assumptions – energy mix	Power sector assumptions – emission controls
Baseline	EV sales shares remain low, at approximately 1% of sales to 2040	**In 2020**, 1,373 terawatt-hours (TWh) generation, 76% from coal. Remains the same for other scenarios. **In 2030**, 2,517 TWh generation, 49.6 from coal **In 2040**, 4,548 TWh generation, 14.5 from coal	**In 2020**, $PM_{2.5}$ controls are 96% efficient. Remains the same for other scenarios. **In 2030**, additional SO_2 control at 90% efficiency. NO_x control at 70% efficiency for powerplants that started operating prior to 2017 and 90% efficient for power plants that started operating in 2017 and thereafter. **In 2040**, all power plants have SO_2 and NO_x controls at 90% efficiency in addition to the $PM_{2.5}$ controls.
Reference (REF)	Aggregate of pathways for EV market share across all vehicle types: • 1% of sales in 2020 • 67% of sales in 2030 • 95% of sales in 2040 • 98% of sales in 2050	**In 2030**, 2,539 TWh generation, 50% from coal **In 2040**, 4,594 TWh generation, 15.3 from coal	
Improved (IEC)		Same as REF	**In 2030**, SO_2 and NO_x controls tightened to 95% and 90%, respectively, for all power plants. **In 2040**, SO_2 and NO_x controls tightened to 98% and 97%, respectively, for all power plants.
Coal Phaseout (CP)		**In 2030**, 2,539 TWh generation, 42% from coal **In 2040**, 4,594 TWh generation, 10.8 from coal	Same as Baseline and REF
Combined (COM)		Same as CP	Same as IEC

The grid assumptions in the REF scenario are the same as in the Baseline scenario except for a 0.9% increase in generation for 2030 and 1% increase in generation for 2040 due to additional demand from EVs; the REF scenario conservatively allocates this additional generation to coal and gas power plants based on their relative proportions in the Baseline scenario. In 2020, the IEC, CP, and COM scenarios have the same generation and emission control characteristics as the REF scenario. For 2030, the IEC scenario assumes an upgrade of emission controls for SO_2 to 95% efficiency and for NO_x to 90% efficiency for all power plants. For 2040, these controls are upgraded to 98% and 97%

6 Central Electricity Authority, "All India Installed Capacity (in MW) of Power Stations (As on 31.12.2019)," https://cea.nic.in/wp-content/uploads/2020/02/installed_capacity-12.pdf (2020).
Central Electricity Authority, "Draft Report on Optimal Generation Capacity Mix for 2029-30," https://cea.nic.in/old/reports/others/planning/irp/Optimal_mix_report_2029-30_FINAL.pdf (2019).

efficiencies, respectively, assuming India adopts emission standards for coal power plants that are equivalent to the European Union and United States.[7]

The CP scenario assumes there is substantial retirement of existing coal power plant capacity in 2040 and less development of new coal power plant capacity in 2030 and 2040. This is illustrated in Figure 1 and results in a 15% reduction in active coal power plant capacity in 2030 and a 46% reduction in active coal power capacity in 2040 compared to the REF and IEC scenarios. This, in turn, brings about a 16% reduction in 2030 coal power plant generation and a 29% reduction in 2040 coal power plant generation compared to the REF and IEC scenarios. There is a difference in capacity reduction and generation reduction because older power plants with large capacity and lower utilization factors are being retired and being replaced by power plants with higher utilization factors. The COM scenario combines the stricter emission controls of the IEC scenario with the rapid phaseout of coal power plants from the CP scenario. As in the REF scenario, the IEC, CP, and COM scenarios conservatively allocate the additional generation needed for EVs to coal and gas power plants; however, in the CP and COM scenarios, the reduction in coal capacity leads to lower overall coal electricity generation than the Baseline scenario, even after accounting for the additional electricity needed for EVs.

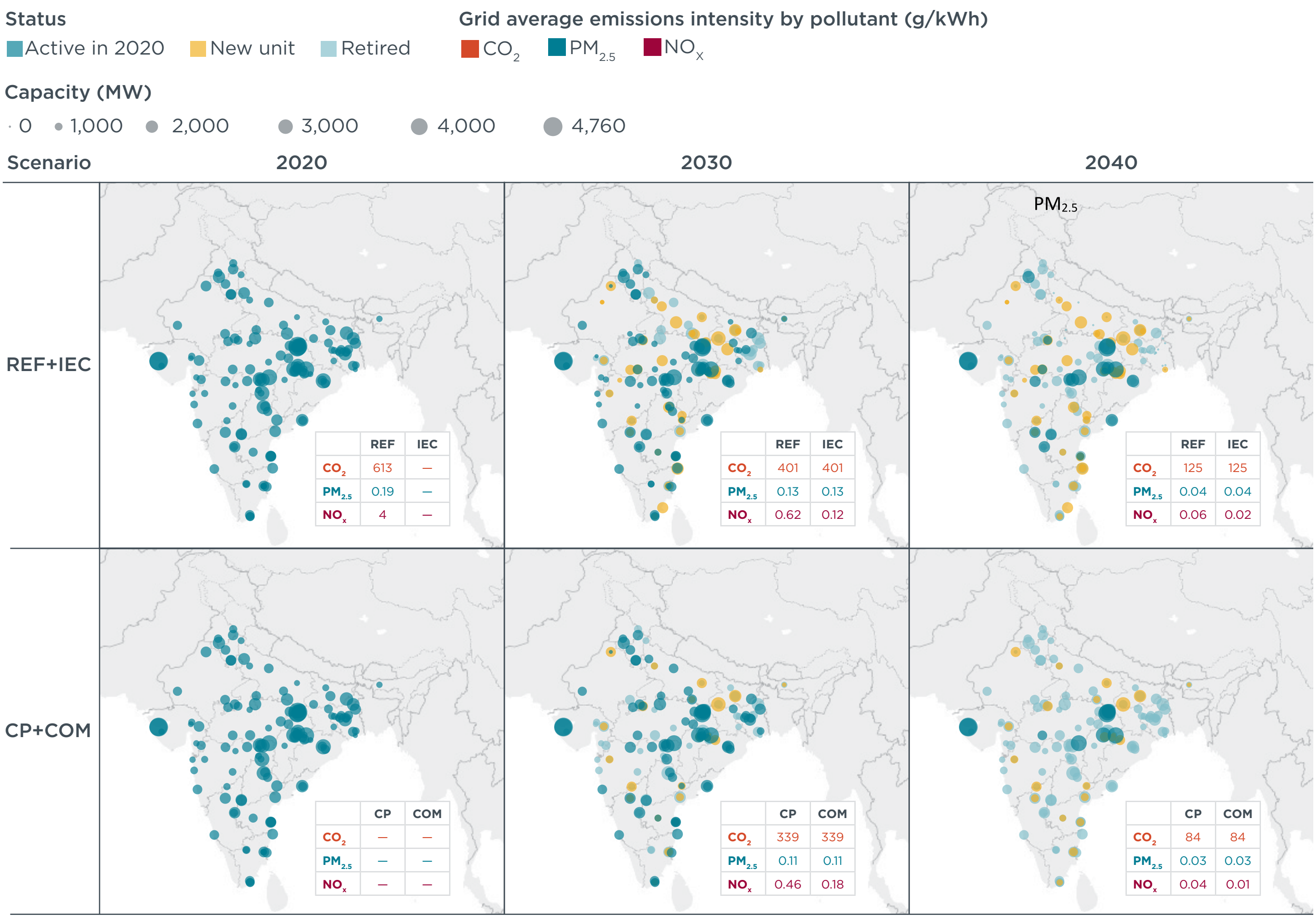

Figure 1. Coal power plant and grid average emissions evolution across applicable scenarios.

7 Xing Zhang, "Emission standards and control of PM2.5 from coal-fired power plant," *IEA Clean Coal Centre* (2016), https://www.iea-coal.org/report/emission-standards-and-control-of-pm2-5-from-coal-fired-power-plant-ccc-267.

Power plant retirements and tighter emission controls bring substantial changes to both the energy mix and the grid average emissions intensity in 2030 and 2040, as shown in Figures 2 and 3. In 2020, renewable energy, including hydropower, accounted for 17% of total electricity generation, whereas in 2030, it accounts for between 44% and 53% of the generation, depending on the scenario. The higher end of the range applies to the CP and COM scenarios. Additionally, in 2040, renewable energy accounts for between 82% and 86% of electricity generation. Between 2020 and 2040, the grid average emissions intensity of CO_2 drops by 80% in the Reference scenario and by 86% in the CP and COM scenarios. Likewise, the grid average emissions intensity of NO_x, SO_2, and $PM_{2.5}$ is reduced up to 99%, 99%, and 86%, respectively, in CP and COM in 2040 compared to 2020.

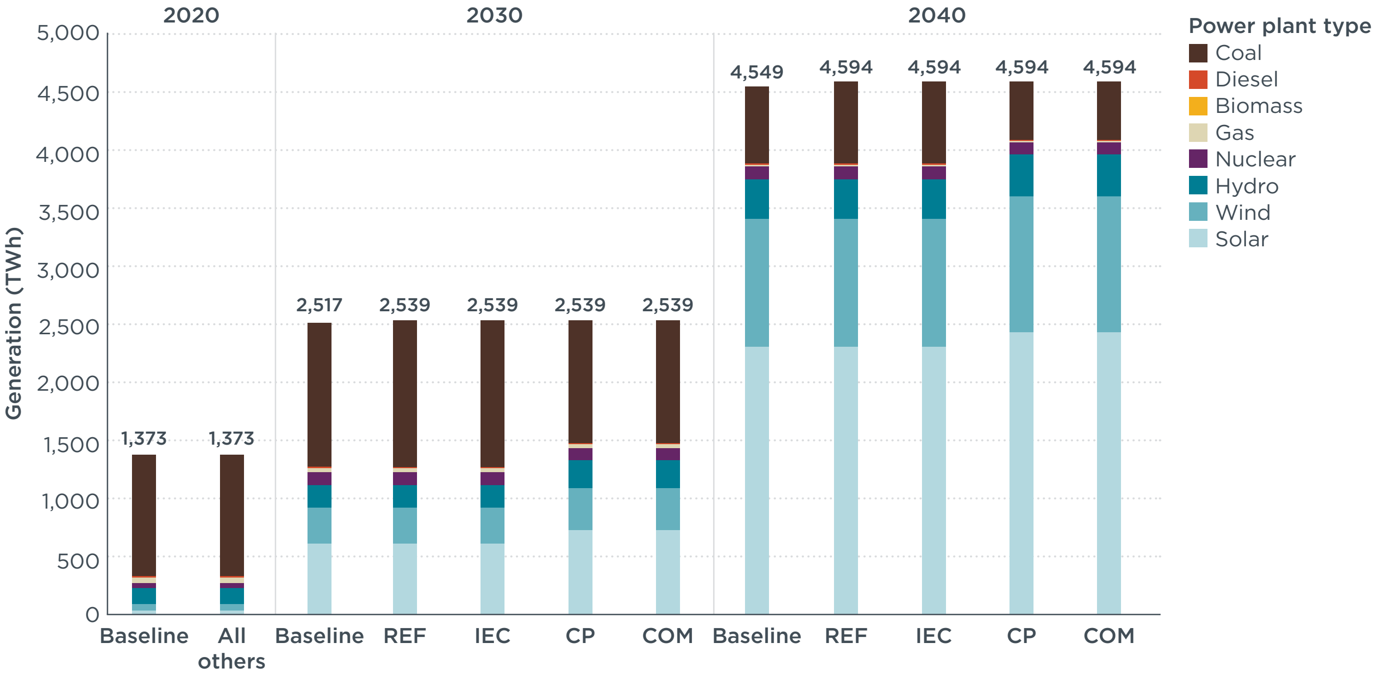

Figure 2. Generation (TWh) by technology for all periods and scenarios.

Figure 3. Grid average emission intensity for four pollutants. Data labels in 2030 and 2040 indicate percent changes compared to 2020, when the grid average emission intensity is the same for all scenarios.

EV sales assumptions

Two vehicle scenarios were modeled: a business-as-usual Baseline scenario and an Ambitious EV sales scenario. In the Baseline vehicle scenario, only about 1% of new sales are EVs in 2020, and we assumed no increase in the EV share of new sales by 2040. In the Ambitious EV sales scenario, from 1% of new sales in 2020, 67% of new sales across all vehicle types are assumed to be EVs by 2030 and 98% of total new vehicle sales and production are assumed to be EVs by 2050. The exceptions are medium and heavy trucks, which are assumed to reach 100% EV sales by 2060. This is illustrated in Figure 4. The curves were generated using an s-curve formula for which the key parameters are market saturation, the start year of fast growth, and the takeover time in years. We manually adjusted the sales share assumptions for several years at the start and end of each curve to account for actual and anticipated early market uptake, and model the effects of stringent vehicle CO_2 standards roughly in line with the European Union coupled with EV mandates and/or internal combustion engine (ICE) vehicle sales bans that fully electrify new vehicle sales by a specified year. These EV sales curves assume strong policy support at all levels of government in India and are informed by our expectations of potential model availability, technology readiness, cost-competitiveness, operational requirements, and business models.

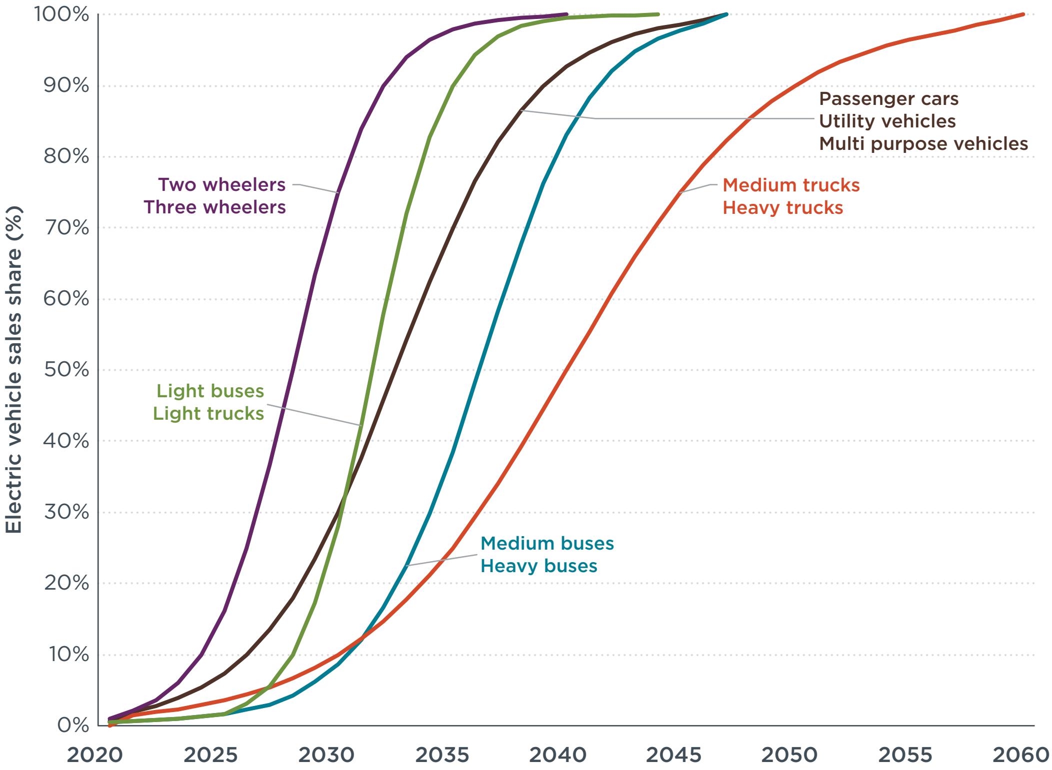

Figure 4. Ambitious EV sales assumptions

We assume the following additional key policy and technology parameters for specific vehicle types:

» *Two-wheelers and three-wheelers* – Strong fiscal support, declining battery costs, and widespread home charging.

» *Passenger cars, utility vehicles, and multi purpose vehicles* – Achieving the targets of the EV30@30 initiative, to which India is a signatory[8], rapid electrification of commercial fleets, and meeting the Society of Indian Automobile Manufacturers' long-term electrification goals.[9]

» *Light buses and trucks* – Faster uptake in urban areas and rapid uptake by 2028, assuming cost parity is achieved.

» *Medium- and heavy-duty buses and trucks* – Rapid deployment of electric buses due to ambitious local and state-level policies, declining battery costs, and accelerated fleet replacement of diesel buses with electric buses instead of compressed natural gas buses. Slower deployment of electric trucks due to infrastructure barriers and cost sensitivity, and urban vocational vehicles are the earliest fleet to electrify.

Methods of estimating emissions

As shown in Figure 5, emissions were estimated using several different models. ICCT's in-house India Emissions Model (IEM) was used to determine emissions from on-road vehicles in the transportation sector for both vehicle scenarios.[10] IEM is a stock turnover model that takes as its main inputs past and projected sales by vehicle category and powertrain, retirement rates, energy intensity, fuel parameters, and vehicle emission standards. Power sector emissions were estimated by IIT Kanpur using India-specific

8 International Energy Agency, "New CEM campaign aims for goal of 30% new electric vehicle sales by 2030," (2017), https://www.iea.org/news/new-cem-campaign-aims-for-goal-of-30-new-electric-vehicle-sales-by-2030

9 Society of Indian Automobile Manufacturers, *Adopting pure electric vehicles: Key policy enablers*, (December 2017), https://www.siam.in/uploads/filemanager/114SIAMWhitePaperonElectricVehicles.pdf

10 Gaurav Bansal and Anup Bandivadekar, *Overview of India's vehicle emissions control program*, (ICCT: Washington, D.C., 2013), https://theicct.org/sites/default/files/publications/ICCT_IndiaRetrospective_2013.pdf

emission factors and considering power plant locations and capacity, emission controls, and estimated total generation under each grid scenario.[11] We obtained emissions from all sectors other than road transport and power from the Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants (ECLIPSE) V5 Global Emission Fields model's current legislation scenario.[12]

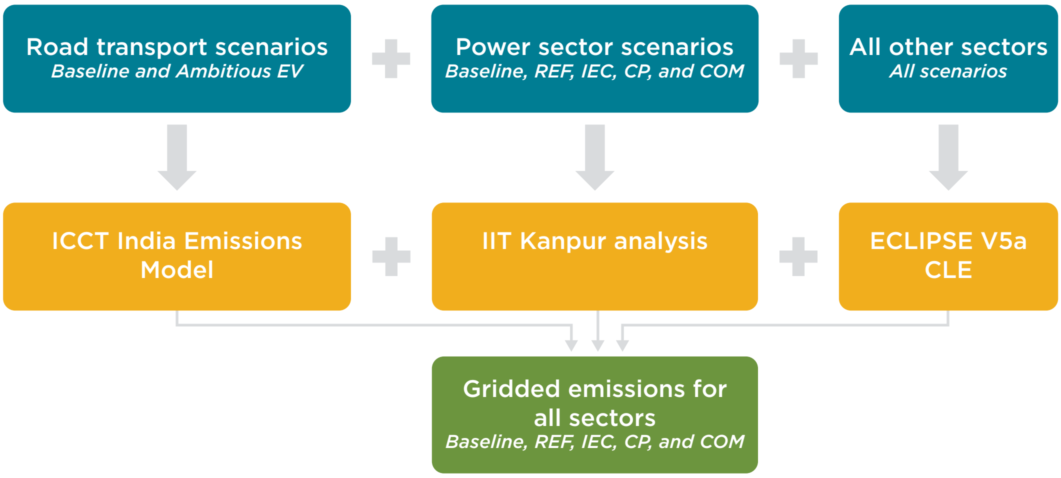

Figure 5. Flowchart of this study's methodology

Results

Compared to the Baseline vehicle scenario, the Ambitious EV sales scenario alters the fuel mix, energy consumption, and tailpipe emissions of the vehicle stock. It also influences power sector emissions because of the additional electricity needed to power EVs; however, as discussed in this section, we find that power sector decarbonization and emission control measures could offset this increase and lead to net power sector emission reductions even with substantial EV uptake. Analysis of gridded emissions shows that even in regions with significant coal power plant generation, vehicle electrification and reduction of grid average emissions could lead to an absolute reduction in pollutant emissions compared to the Baseline scenario.

Vehicle stock, energy consumption, and tailpipe emissions

Figure 6 shows the projected vehicle stock of two-wheelers and three-wheelers, light-duty vehicles (LDVs), and heavy-duty vehicles (HDVs) for the Baseline and Ambitious EV scenarios. In the Ambitious EV scenario, the stock of two-wheelers and three-wheelers electrifies fastest due to rapid EV sales growth and shorter average vehicle lifetimes. As a result, almost 100% of the stock for these vehicle types could be electrified by 2040. The LDV stock could be more than 50% electrified by 2040, in contrast to about 20% of the HDV stock.

11 Central Pollution Control Board. *Air quality monitoring, emission inventory and source appointment study for Indian cities*, (2011), https://cpcb.nic.in/displaypdf.php?id=RmluYWxOYXRpb25hbFN1bW1hcnkucGRm

12 Andreas Stohl et al., "Evaluating the Climate and Air Quality Impacts of Short-Lived Pollutants," *Atmospheric Chemistry and Physics* 15, no. 18, (2015), http://pure.iiasa.ac.at/id/eprint/11367/.

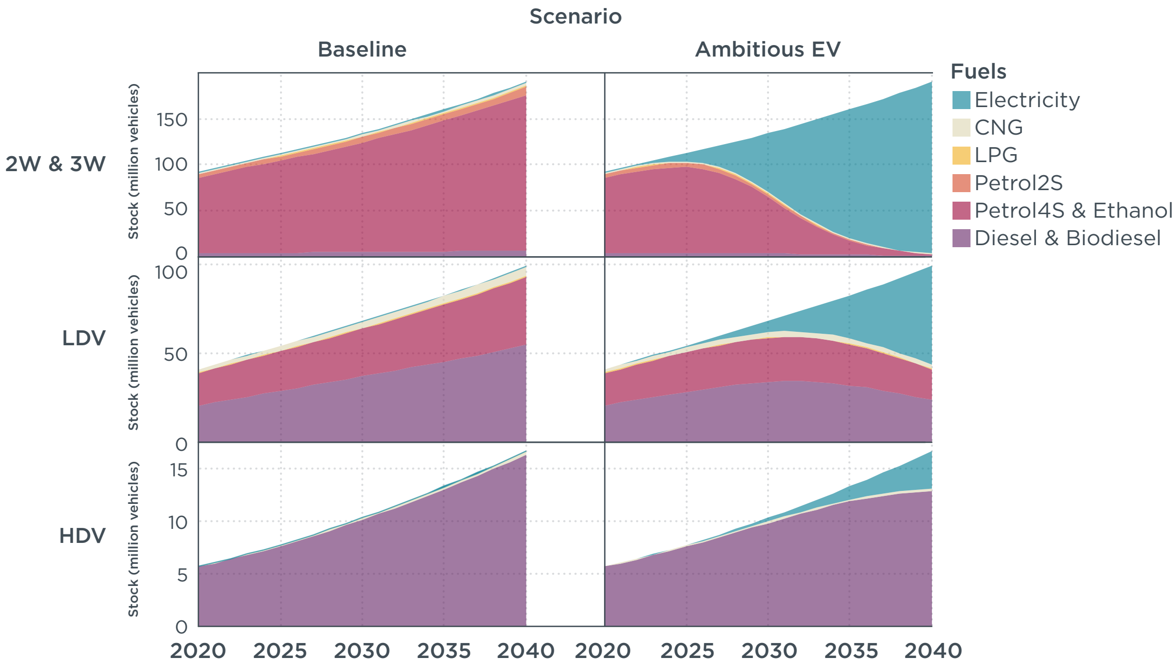

Figure 6. Vehicle stock by fuel type

Figure 7 shows the tailpipe emissions from different vehicle types in the two scenarios. In particular, it is seen that HDVs, which accounted for 35%–45% of the tailpipe emissions of the fleet in 2020, depending on the pollutant, account for 50%–60% of the fleet's total tailpipe emissions in 2040. This is a result of slower assumed EV uptake.

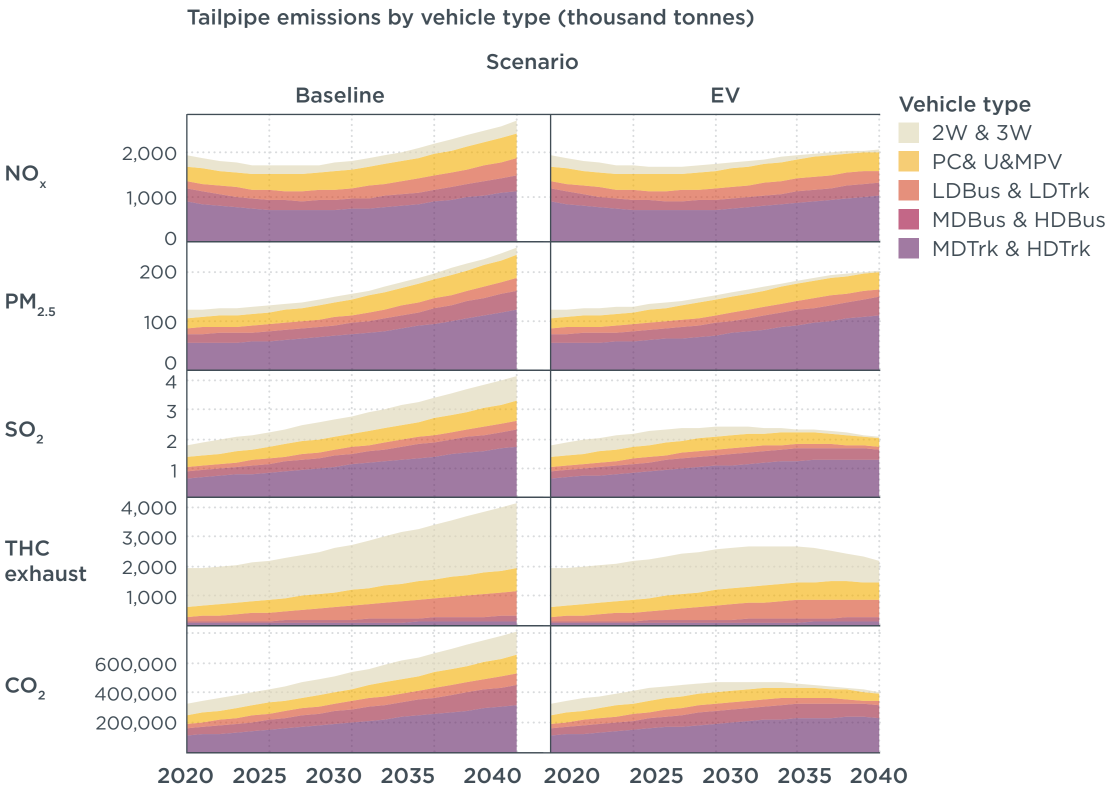

Figure 7. Tailpipe emissions by vehicle type

Figure 8 compares the energy consumption and NO_x emissions of India's on-road vehicle fleet by emission control vintage. In 2020, NO_x emissions were about evenly split between older Euro 3/III, Euro 4/IV, and pre-Euro 3/III vehicles, while Euro 3/III and Euro 4/IV vehicles dominated energy consumption. In both the Baseline and Ambitious EV scenarios, Euro 6/VI (equivalent to BS VI standards that applied to new vehicles sold from April 1, 2020 onward[13]) ICE vehicles dominate the fleet in 2030 and 2040, in terms of energy consumption and NO_x emissions. Compared to the Baseline, the Ambitious EV scenario decreases total vehicle energy consumption by around 11% in 2030 and by almost 41% in 2040, while NO_x emissions decline by 4% in 2030 and 24% in 2040. Euro 6/VI vehicles continue to contribute to most of the energy consumption and NO_x emissions in the fleet.

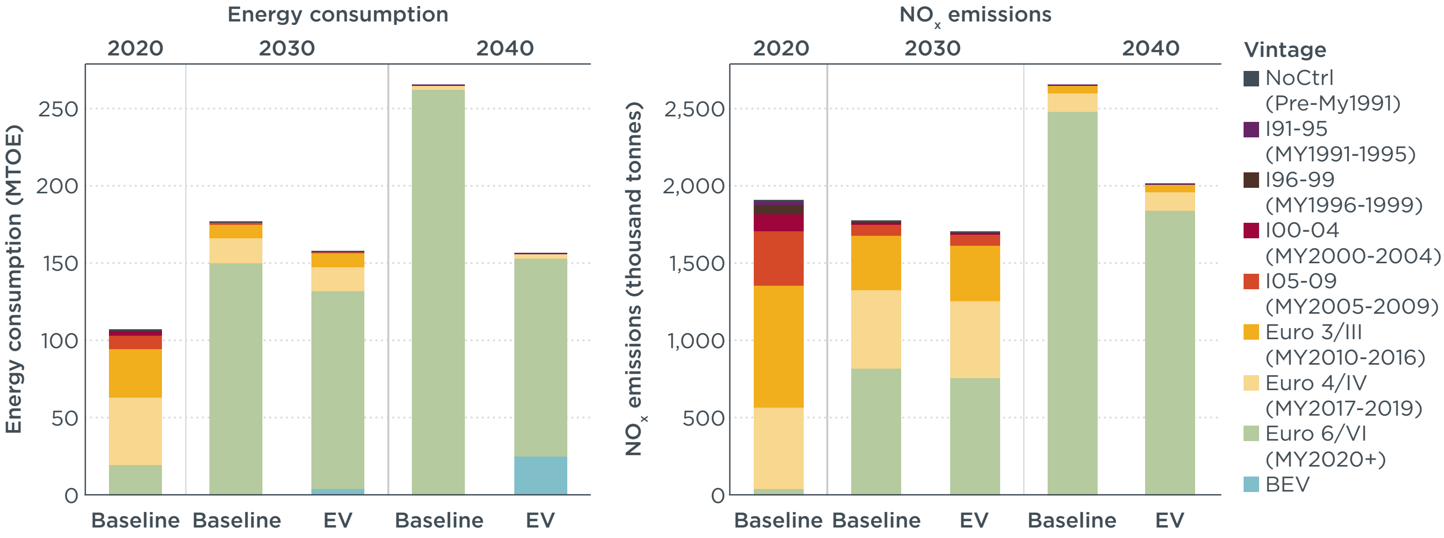

Figure 8. Vehicle energy consumption and NO_x emissions by vintage.

Aggregate road transport and power sector emissions

Estimates of aggregate road transport and power emissions of $PM_{2.5}$, SO_2, NO_x, and CO_2 for each scenario and evaluation period are shown in Figure 9. In 2020, the power sector accounted for 68% of $PM_{2.5}$, 74% of NO_x, nearly 100% of SO_2, and 72% of CO_2 from these two sectors. However, under the Baseline scenario, road transport emissions are projected to increase to 2030 and 2040, whereas power sector emissions are projected to increase to 2030 for $PM_{2.5}$ and CO_2 but decrease substantially by 2040. In 2040 for all pollutants, the road transport sector would surpass the power sector in annual $PM_{2.5}$, NO_x, and CO_2 emissions, with transport's share of these emissions at 61%, 91%, and 61%, respectively.

13 Tim Dallmann and Anup Bandivadekar, *India Bharat Stage VI emission standards*, (ICCT: Washington, D.C., 2016), https://theicct.org/publications/india-bharat-stage-vi-emission-standards

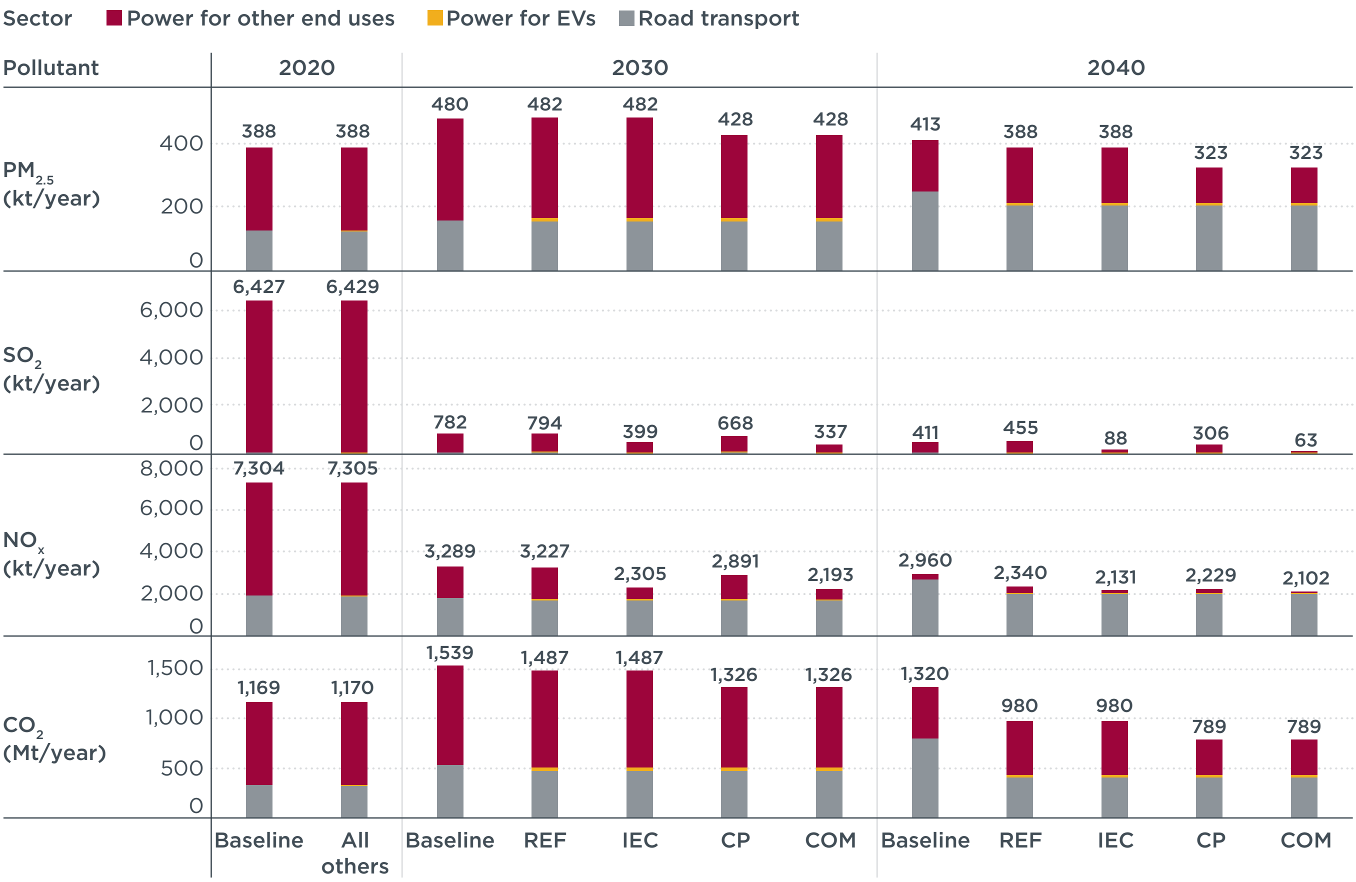

Figure 9. Aggregate emissions by sector and scenario.

The Ambitious EV scenario is projected to substantially reduce road transport emissions compared to the Baseline, by 18%, 24%, and 50% in 2040 for $PM_{2.5}$, NO_x, and CO_2, respectively. In the REF scenario, which conservatively allocates the additional generation for EVs to coal and gas power plants, EVs lead to a modest increase in SO_2 emissions in 2040; however, for all other pollutants, EVs lead to net emission reductions. In the IEC scenario, tighter power plant emission controls lead to substantial SO_2 and NO_x emission reductions, even with increased coal and gas generation to power EVs. Coal power plant retirement (CP) produces smaller SO_2 and NO_x reductions than the IEC scenario but leads to $PM_{2.5}$ and CO_2 emission reductions. The COM scenario represents the best of the IEC and CP scenarios, leading to substantial net emission reductions for all pollutants in 2030 and 2040.

Gridded road transport and power sector emissions

In the Baseline scenario, road transport emissions are assumed to be distributed based on population and road density. As shown in Figure 10, emissions hotspots include major population centers such as Delhi and highway networks across India. Between 2020 and 2040, the Baseline scenario shows increases in NO_x emissions in most parts of India driven by population and income growth and increased motorization.

The Ambitious EV scenario shows modest changes in 2030, with an average NO_x reduction of around 4% spread evenly across the country. However, in 2040, with large parts of the two-wheeler, three-wheeler, and light-duty fleets being electrified, the emission reductions are more substantial, representing a 24% average NO_x reduction compared to the Baseline in 2040.

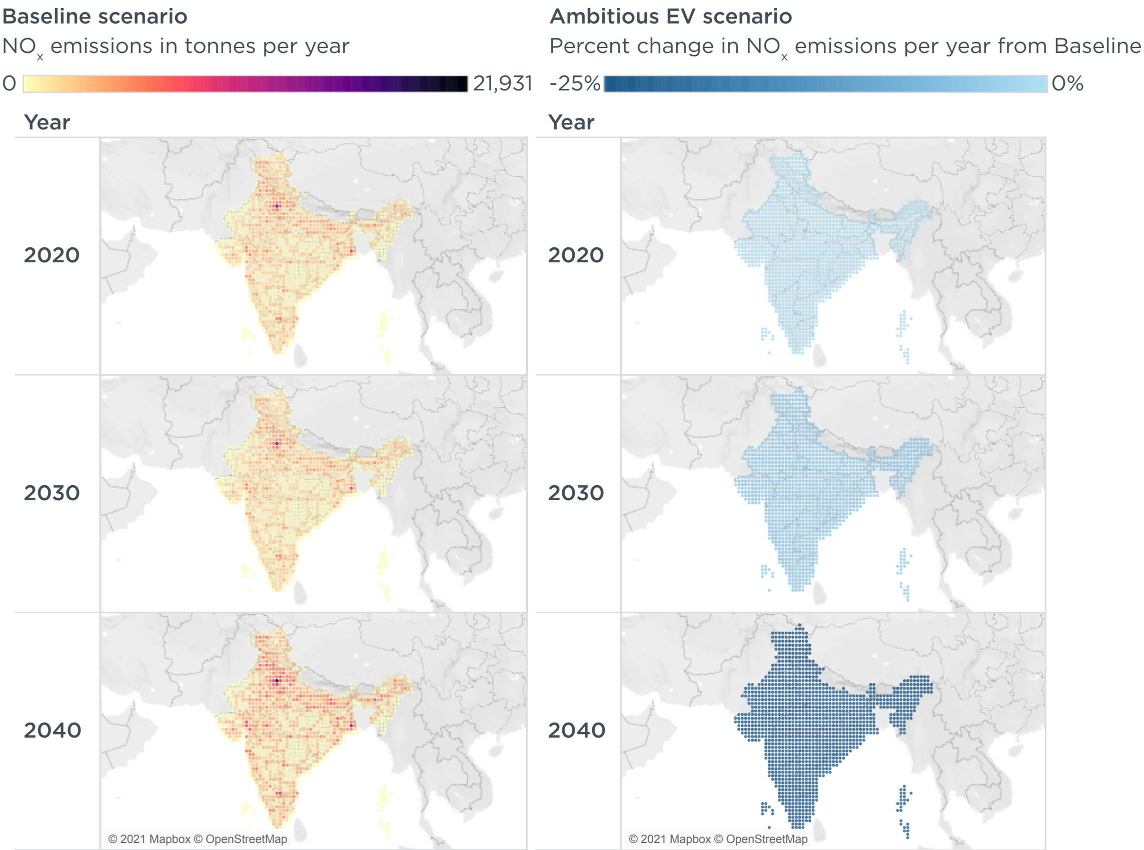

Figure 10. Gridded NO$_x$ emissions from road transport. Results for the Ambitious EV scenario are shown as percent changes in emissions from the Baseline scenario for the same year.

Unlike road transportation, power sector emissions tend to be concentrated around locations where there are significant thermal power capacities, such as the northern and eastern parts of the country (Figure 11). The northern part of India is a major demand center and the eastern part is the location of several large coal mines. In the REF scenario, increased power demand due to vehicle electrification could result in slightly higher NO$_x$ emissions (median 5%) from power plants across India compared to the Baseline under the conservative assumption that coal power plants are the main source of electricity for EVs. However, coal power plant retirements and/or tighter emissions controls in the IEC, CP, and COM scenarios could lead to substantial net reductions in power plant NO$_x$ emissions across the country, with only a handful of locations projected to see modest increases in power plant NO$_x$ emissions. In the COM scenario in 2040, all grid cells would see net reductions in combined power and road transport NO$_x$ emissions.

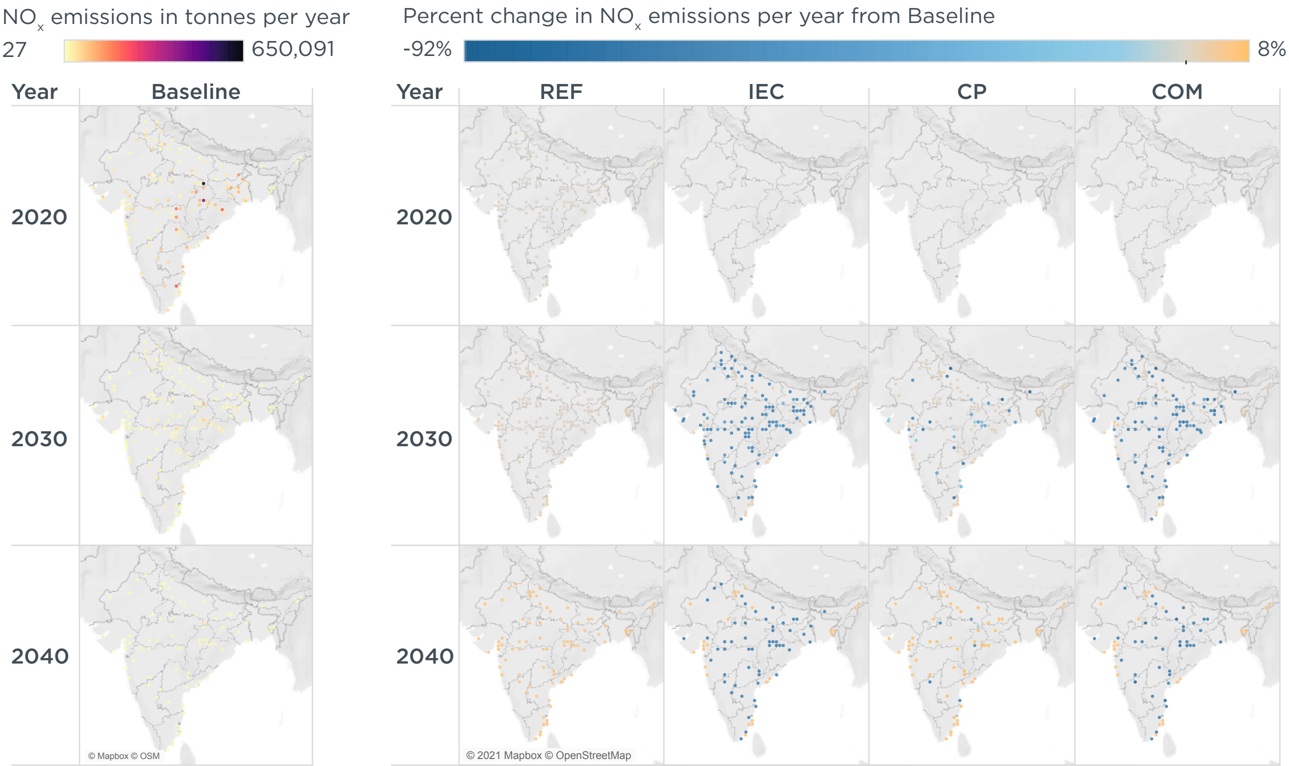

Figure 11. Gridded NO_x emissions from power plants. Results for the REF, IEC, CP, and COM scenarios are shown as percent changes in emissions from the Baseline scenario for the same year.

Conclusions

This analysis shows that vehicle electrification is an important contributor to reducing emissions in India's road transportation sector. Our Ambitious EV scenario shows an 18%–50% reduction in tailpipe emissions in 2040, depending on the pollutant, compared to the Baseline scenario in 2040. Considering current policies and plans for the power sector, the Ambitious EV scenario would lead to net emission reductions of NO_x and CO_2 and only marginal increases in $PM_{2.5}$ and SO_2, even under the pessimistic assumption that the electricity for EVs is generated by coal and gas power plants. Further, improving power plant emission controls and/or reducing the share of coal electricity generation could lead to substantial net emission reductions for all pollutants. Progressive coal plant retirement and emission control strategies could especially benefit the northern and eastern parts of the country, where major thermal power plants are located: these areas could see up to 92% reductions in power sector NO_x emissions compared to the baseline, even after accounting for the additional power generation needed for EVs.

Our findings underscore the benefits of improved power plant emission controls and progressive phaseout of coal power, which would substantially reduce power sector emissions regardless of EV uptake. The results also highlight how relying on a strategy of electrification that focuses only on light-duty vehicles is unlikely to halt growth in road transport emissions, which are projected to exceed power sector emissions in 2040. Hence, reversing the growth would require developing strategies to electrify vehicles faster, accelerate fleet renewal, increase vehicle efficiency, and improve upon existing Euro 6/VI emission standards. These strategies are particularly important for HDVs, as these are more difficult to electrify than LDVs and are projected to account for the bulk of tailpipe emissions in 2040 in our Ambitious EV scenario.

At the time of publication, ICCT is preparing a follow-up study that analyzes the impacts of these emissions scenarios on air quality in India using the WRF-Chem atmospheric chemistry model and then examines the health impacts of the air quality outcomes using our in-house model.