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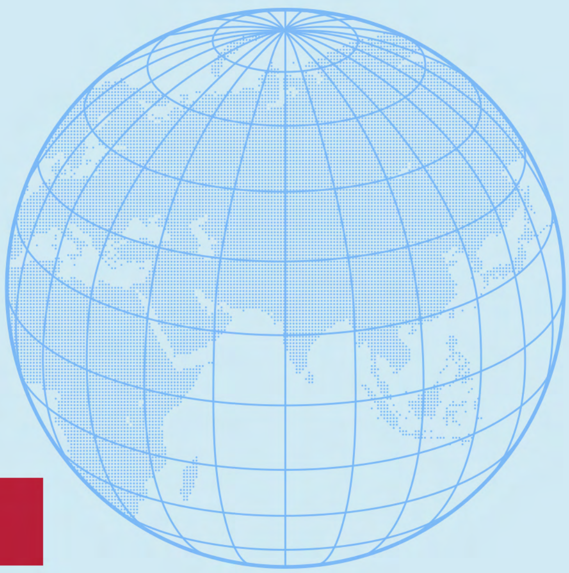
Demystifying The Climate Benefit of EV Transition in India

Opportunity to Decarbonise Through Vehicle Electrification is Complex

Shyamasis Das



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Demystifying The Climate Benefit of EV Transition in India

Opportunity to Decarbonise Through Vehicle Electrification is Complex

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Abbreviations and Acronyms

BESS	Battery Energy Storage System
CAFE	Corporate Average Fuel Economy
CDM	Clean Development Mechanism
CEA	Central Electricity Authority
CEM	Clean Energy Ministerial
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
E-rickshaw	Electric Rickshaw
ECA	European Court of Auditors
EV	Electric Vehicle
FY	Financial Year
gCO_2	Gram CO_2
gCO_2/km	Gram CO_2 per Kilometre
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GW	Giga Watt
ICE	Internal Combustion Engine
ICCT	International Council on Clean Transportation
IEA	International Energy Agency
INL	Idaho National Laboratory
IPCC	Intergovernmental Panel on Climate Change
ITF	International Transport Forum
Kg	Kilogram
kJ/km	Kilojoules per Kilometre
Km	Kilometre
Kmpl	Kilometre per litre
kWh	Kilo Watt-hour
LCA	Life-Cycle Assessment
MIDC	Modified Indian Driving Cycle
MoEFCC	Ministry of Environment, Forest and Climate Change
MoP	Ministry of Power
MW	Mega Watt
NDC	Nationally Determined Contribution
NEP	National Electricity Plan
PV	Photovoltaic
RE	Renewable Energy
RPO	Renewable Purchase Obligation
SERC	State Electricity Regulatory Commission
SUV	Sports Utility Vehicle
tCO_2	Tonnes of CO_2
ToD	Time-of-Day
TWh	Tera Watt-hour
UNFCCC	United Nations Framework Convention on Climate Change
Vkm	Vehicle Kilometre
VRE	Variable Renewable Energy
WLTP	Worldwide Harmonised Light Vehicles Test Procedure

Executive Summary

Battery-driven electric vehicles (EVs) hold promise for decarbonising India's rapidly growing road transport sector. However, achieving significant emission reductions through widespread EV uptake is not a given. It hinges on the energy performance of EVs and cross-sector linkages, especially to the power sector. This paper examines the complexities of the climate impact of the transition to electric drivetrains based on a data-driven analysis that best reflects the real-world use of EVs. It offers actionable insights that call for interventions spanning policy to implementation levels to maximise the climate benefits of India's EV revolution.

1. The Allure of Electric Mobility and the Imperative for a Reality Check

India's economic progress is intricately linked to the expansion of its road transport network. This sector, while vital, is a significant contributor to the nation's greenhouse gas (GHG) emissions and deteriorating air quality. EVs, heralded globally as a cornerstone of green transportation, offer a compelling solution to mitigate these environmental challenges. However, in a country where fossil fuels still dominate electricity generation, transitioning from petroleum to electrons in powering the vehicles does not automatically result in substantial emission reductions.

This paper provides an in-depth analysis of the factors influencing the actual climate benefits of EV adoption in India. It moves beyond simplistic comparison of individual vehicle models and assumption of constant electricity supply mix across the country to examine the broader EV and energy landscape, considering:

- The diversity of vehicle energy performance within and across segments.
- The dynamic nature of India's grid electricity supply, including the temporal variation in renewable energy (RE) share.
- The crucial role of EV charging pattern and its alignment with clean electricity availability.
- The geographical variation in electricity supply mix and its implication for regional EV strategies.

By dissecting these linkages, the paper aims to provide policymakers, implementing agencies, industry leaders, and investors with the insights needed to make informed decisions and unlock the full decarbonisation potential of electric mobility in India.

2. The Fallacy of Simplicity: Why a Real-World Approach is Essential for Evaluating EV Emissions

Numerous studies have attempted to quantify the emission reduction potential of EVs. However, many rely on simplified methodologies that can misrepresent the true climate impact. These approaches often fall short in several critical aspects:

- **Cherry-Picking Models for Comparison:** Focusing on comparisons between select EV and conventional vehicle models fails to capture the wide range of energy efficiencies that exist within vehicle segments. This can lead to misleading generalisations about the overall impact of EV adoption.
- **Overlooking the Dynamics of the Grid Electricity Supply:** Assuming a static national average grid electricity carbon dioxide (CO_2) emission factor disregards the fluctuating nature of India's electricity supply mix. The share of renewable energy (RE), particularly solar and wind, varies significantly throughout the day, influencing the emissions associated with EV charging at different times.
- **Ignoring Variable Charging Patterns:** EV charging is not a constant load. Factors like vehicle use-case, travel characteristics, and the availability of charging infrastructure influence when and where EVs are charged. Owing to the varying charging pattern, EVs may avoid GHG emissions significantly, deliver limited climate dividends, or even consume more carbon space depending on their charging alignment with periods of high RE availability.

3. A Deeper Analysis: Unveiling the Underlying Factors Shaping Emissions from EVs

Electric Drivetrains Outperform in Energy Efficiency, but Grid Electricity Dictates Emissions

Analysis of a comprehensive dataset of vehicle models available in the Indian market confirms the inherent efficiency advantage of electric drivetrain

across nine distinct vehicle segments, including two-wheeled and three-wheeled vehicles, passenger cars, and buses. On average, EVs consistently demonstrate end-use energy consumption levels at least three times lower than their conventional counterparts. Moreover, advancements in battery technology and power electronics promise further improvements in EV efficiency, widening the gap in the years to come.

When factoring in the annual average carbon emission factor of India's grid electricity at present, the emissions advantage of EVs diminishes. While still generally cleaner than internal combustion engine vehicles, their emissions are directly tied to the proportion of fossil fuels used for power generation. This highlights the critical need to accelerate the decarbonisation of the electricity grid to fully realise the emission reduction potential of EVs.

Time-of-Day Charging: A Critical Factor for EV-Related Emissions

This study underscores the profound impact of aligning EV charging with periods of high RE supply on the grid. Charging during evening or overnight hours, characterised by increased reliance on coal-fired power plants, leads to significantly higher emissions compared to charging during the daytime when sunshine brings down the carbon load of grid electricity.

The findings demonstrate that choosing the right time to charge can significantly alter the emissions profile of an EV. Charging during the day can avoid nearly 10% higher CO_2 emissions compared to charging during the evening. This translates to additional yearly emission reductions of 10 kg of CO_2 in the case of an electric scooter and 106 kg for an electric sedan.

The impact is even more profound for electric buses, where daytime charging is not just beneficial but essential to achieve meaningful emission reductions.

Geographical Variations: Tailoring EV Strategies to Regional Electricity Mixes

For different reasons, the majority of RE growth in India is in a handful of states. Recognising the diversity of electricity generation sources and associated emission intensities across India is paramount for an effective decarbonisation strategy. This paper analyses the power procurement mixes of nine major Indian cities, revealing substantial variations in the carbon footprint of their electricity supply. Consequently, the emissions from an EV can vary significantly depending on the city or state in which it is operated. This underscores the need for ramping up renewable electricity generation capacity at a sub-national level and regionally tailored approaches to EV deployment and charging.

4. A Clean Energy Future: Unlocking the True Potential of Electric Mobility

India's desired low-carbon electricity pathway, detailed in the National Electricity Plan (NEP), is crucial for unlocking the climate benefits of EV transition. The plan envisions a substantial increase in non-fossil fuel-based power generation, resulting in a projected decline in the grid emission factor by end of this decade.

This clean energy transition will be vital for EVs. As the grid becomes progressively decarbonised, the emissions gap between EVs and conventional vehicles will widen significantly. By FY 2031-2032, EVs across all segments are projected to achieve substantial emission reductions. However, this benefit is predicated on the alignment of EV charging with hours of high RE share on the grid and/or large-scale deployment of long-duration energy storage capacity.

5. Overcoming Barriers: Navigating the Challenges to a Sustainable EV Transition

While the path to a cleaner transportation future through electric mobility is promising, several key challenges need to be addressed:

- **Accelerating RE Capacity Addition:** Meeting ambitious targets for solar and wind power deployment will be essential to achieving the desired grid decarbonisation. The runway to realise the goals is getting shorter each passing day.
- **Managing the Intermittency of RE:** Optimal utilisation of the high shares of variable RE sources like solar and wind necessitates significant investments in energy storage capacities, including pumped hydro and battery energy storage systems.
- **Making Clean Electricity Available for EV Charging:** Increasing the share of variable RE will further skew the temporal distribution of clean electricity making it harder to decarbonise EV charging.

6. Conclusion: A Call to Action for a Sustainable Electric Mobility Future

This paper emphasises that transitioning to a cleaner and more sustainable transportation future through vehicle electrification requires a holistic and realistic approach. It calls for coordinated action from policymakers, industry stakeholders, and consumers, focusing on:

- **Aligning EV Charging with Greener Hours:** Encouraging daytime charging through time-of-day electricity tariffs tailored for regional contexts, providing public charging in sync with travel patterns, and leveraging the charging flexibility in case of battery swapping.
- **Promoting EVs with Higher Energy Efficiency:** Nudging production and marketing of more efficient EV models by mandating energy labelling of traction battery packs and systems and setting more stringent CO_2 emission targets under future Corporate Average Fuel Economy (CAFE) enforcement cycles with expanded scope.
- **Coupling EV Charging Infrastructure with Distributed RE Resources:** Facilitating cost-effective integration of charging facilities with RE at the local level through innovative renewable-energy-as-a-service mechanisms and application of end-of-mobility-life batteries for energy storage.

By embracing this multifaceted strategy, India can harness the full potential of EV transition to curb transportation emissions and drive its mobility to a sustainable future.

1. Introduction: The Promise to Decarbonise Road Transport

Road transport in India plays a major catalytic role in the country's economic growth. It accounts for about 87% of passenger traffic and 60% of freight traffic movement in the country, while the overall transport sector contributes about 10% to the GDP[1] (Ministry of Environment, Forest and Climate Change, 2022). On the flip side, road transport accounts for 12% of India's energy-related carbon dioxide (CO_2) emissions and is a major source of criteria air pollutants. The increasing demand for private mobility and the transport of goods are likely to drive up energy consumption, and consequently CO_2 emissions from road transport may double by mid-century (International Energy Agency, 2023). This calls for shifting to a fuel that could potentially drive the country's road mobility to a low-emission future.

Worldwide, electric vehicles (EVs) are considered a climate- and environment-friendly transport solution to tackle global warming and deteriorating urban air quality. In the absence of fuel combustion onboard the vehicle, there is no tailpipe emission from driving an EV. This is a significant advantage over an ICE vehicle (internal combustion engine vehicle) because tailpipe emissions are a cocktail of global warming gases, primarily CO_2, and smog-forming criteria pollutants, including particulate matter, nitrogen oxides, carbon monoxide, and hydrocarbons. Moreover, an EV is more energy-efficient than its conventional counterpart thanks to fewer moving parts in the former (Idaho National Laboratory, 2024). EVs are also equipped with regenerative braking systems that help recover some energy that would otherwise be lost during braking (Yang, et al., 2024).

Recognising the potential benefits of battery-driven vehicles, India regards electric mobility as a major lever for decarbonising its motorised road transport and cleaning urban air (Ministry of Environment, Forest and Climate Change, 2022). India is among the few countries that support the global EV30@30 campaign, which aims for at least 30% of new vehicle sales to be electric by 2030 (Clean Energy Ministerial, 2019). While the electric mobility sector in the country has jumpstarted on the back of a slew of financial supports from the government, whether switching from liquid fuels to electrons has resulted in the desired CO_2 emission cut poses an important question to reflect on. Although this paper does not study the impact on ambient air quality, it is worth mentioning here that the transition to EVs is considered an important intervention to address the serious issue of urban air pollution in the country.

The vast majority of EVs are charged with grid electricity supplied by the distribution utilities. This electricity is generated from a mix of energy sources. In the case of India, grid electricity is predominantly coal-based despite considerable growth in renewable energy in recent times. For instance, in FY 2022–2023,[2] about 75% of the electricity was generated from fossil-fuel-based thermal power plants (India's Climate and Energy Dashboard, 2024a). Therefore, when three-fourths of electricity consumption is catered by carbon-intensive sources, any form of consumption of grid electricity in India, including EV charging, has a substantial greenhouse gas (GHG) emission footprint. This predicates the need for an in-depth data-driven assessment that not only takes stock of the effectiveness of EV adoption as a lever to fight climate change but also sheds light on tapping the potential of EV transition to produce immediate substantial emissions cuts in the context of India. Waiting for a renewable energy-dominated future electricity supply to scale up EV adoption would possibly lead to consuming more carbon space and leaving an even shorter time window to mitigate global warming.

Regarding the structure of this paper, Section 2 sheds light on the modus operandi currently followed for evaluating the GHG emission benefit of EV adoption and the need for taking a nuanced approach to appropriately understand the real impact of EV transition. It also highlights the research questions that the study addresses. This is followed, in Section 3, by a one-of-a-kind comparison between electric and conventional vehicles across different segments in India on the basis of vehicle energy efficiency and corresponding GHG emissions. Section 4 analyses how operational GHG emissions of EVs differ subnationally. This aspect has never been quantitatively studied before in the Indian context. Section 5 sheds insights into the daily profile of GHG emission intensity of grid electricity in India and how this impacts the climate benefit of EV adoption. Although

[1] Gross Domestic Product.
[2] When latest yearly data is available at the time of synthesising this paper.

the issue of varying share of renewable energy in daily electricity supply-mix of the country is widely acknowledged, this is possibly the first significant effort to analyse and show its consequences on the CO_2 emission footprint of electricity end-use, including EV charging. Section 6 deals with how the GHG emission impact of EVs plays out considering the future of India's electricity supply. It also highlights the possible challenges on the road ahead. Section 7 concludes the paper with some key takeaways and policy recommendations. It also alludes to how the industry and EV users can potentially benefit from the insights.

2. Current Approach to Understanding the Climate Benefit of EVs in India

Considering the significance of the possible climate impact of vehicle electrification, there is an existing body of work that has studied GHG emissions from EVs relative to conventional vehicles and other fuel or technological options. These studies assess EVs' GHG emission impact encompassing different stages of vehicle lifecycle. The approaches are found to differ depending on the objectives and scopes of analyses. Following are some of the prominent studies on GHG emissions related to EV uptake in India.

In 2021, the International Council on Clean Transportation (ICCT) published two papers on the climate impact of EV transition. One is a comparison of the lifecycle GHG emissions of combustion engine and electric passenger cars across four markets: China, Europe, India, and the United States (Bieker, 2021). Additionally, this study evaluates how the lifecycle GHG emissions of cars expected to be registered in 2030 compare with vehicles registered at present.

Although for the other auto markets the analysis is based on average vehicle characteristics across the most representative market segments, in the case of India the study considers specific car models: the Tata Tigor (for the hatchback segment), the now-discontinued Mahindra e-Verito (representing the sedan segment), and the Tata Nexon (for the sports utility vehicle (SUV) segment). The carbon intensity of the electricity consumed for charging EVs is based on the Intergovernmental Panel on Climate Change published lifecycle GHG emissions of the different electricity generation technologies. For the future electricity mix, the study refers to the International Energy Agency's Stated Policy Scenario and the Sustainable Development Scenario.

The other paper by the ICCT estimated the emissions impacts of large-scale vehicle electrification in India through 2040 under various scenarios representing plausible evolutions of India's electricity grid using the ICCT's India Emissions Model. It considered five scenarios for the energy mix of the electricity grid and coal power plant emission controls for 2020, 2030, and 2040, and analysed the resultant emissions of PM2.5, NOx, SO_2, and CO_2 from electricity generation. Some of the CO_2 emissions-related assumptions considered here are common to the previous study.

Another major piece of research on EV-related emissions is carried out by the International Transport Forum (ITF) in collaboration with the World Bank. ITF's report, "Life-Cycle Assessment of Passenger Transport" adopted life-cycle assessment (LCA) approach using its in-house Transport Life-Cycle Assessment Tool for various transport modes, including private and shared options (International Transport Forum, The World Bank, 2023). The vehicle technologies considered for the study are internal combustion engines, battery electric vehicles, and fuel cell electric vehicles. The fuel types considered are diesel, petrol, compressed natural gas (CNG), blue hydrogen (CNG-based) and green hydrogen (100% renewable energy based). The study considers several modelling assumptions regarding vehicle characteristics, distance and modes, fuel/energy efficiency, energy mix, among others.

These studies have contributed significantly to the present-day understanding of GHG emission impact of vehicle electrification, mostly from the vehicle lifecycle point of view. All these papers are essentially outcomes of transport emission models in some way or the other. Although a well-to-wheel or lifecycle assessment gives a holistic view of the possible state of emissions at each stage of a product, such study largely relies on other literature or sources for emission values at the stages entailing vehicle and battery manufacturing and fuel extraction and production.

There is also a high level of uncertainty around these estimates, and these are difficult to validate because of the complexity in gathering or monitoring the required data. There are no certified emission values of new vehicle models at the time of their homologation in India. Moreover, the degree of control or oversight on emissions or energy consumption during extraction, manufacturing, or production is limited because of the inherent challenges to enforce. Other than industry energy efficiency-related regulations (for example, Perform, Achieve and Trade scheme in India),[3] there is hardly any direct policy intervention on greening vehicle manufacturing or fuel extraction whereas there are several policy instruments in effect or proposed to make vehicle use low-carbon or less emission intensive.

Without undermining the importance of reducing emissions during other stages of a vehicle's lifecycle, this study carries out an in-depth assessment of tank-to-wheel emissions (i.e., operational emissions of vehicles), which is a subset of well-to-wheel emissions.

2.1 Need for a Real-World Approach to Evaluate the True Carbon Footprint of Driving an EV

While a vehicle driven by an internal combustion engine emits GHGs through its tailpipe that can be estimated from its fuel economy (kilometre per litre (kmpl) in the case of liquid fuel, or per kilogram for gaseous fuel) and emission factor of the fuel (petrol, diesel, CNG, etc.),[4] an EV has indirect operational GHG emissions on account of electricity consumption, which is akin to Scope 2 emissions from an electricity end-use (US Environmental Protection Agency, 2024). The EV-emission calculations done by existing studies are based on country-level annual average CO_2 emission factor of grid electricity (expressed in grams CO_2 per kilowatt-hour[5] (gCO_2/kWh)) and energy economies (km/kWh) of select EV models. Although this method is simple and reasonable, it masks some key heterogeneities in the underlying factors. A GHG emission assessment for EVs would benefit from a grounded approach. How?

- **Basing Stock or Segment-Level Comparison on Select Vehicle Models Could be a Misrepresentation.** In reality, considering the fuel economy of a specific model as an average of a vehicle segment can be quite off the mark. At the least, it merits an assessment to see whether that is the case. For example, analysing a sample of 15 petrol models of popular sedans in India shows that the certified vehicle fuel economy varies from 12.6 kmpl to 23.2 kmpl (i.e., the difference is almost 2x) where 18.4 kmpl is found to be the mean.[6] This shows that choosing a specific vehicle model as a representative of a segment for understanding vehicle performance may lead to a high margin of error.

- **Applying Annual Average Emission Factor of Grid Electricity Disregards the Dynamics in Electricity Supply.** Country-level annual average emission factor of grid electricity is considered the de facto value for GHG emission intensity of supplied electricity and is applied to estimate grid electricity consumption related emissions. However, it does not take into account the variations in electricity supply mix and resulting change in GHG emission intensity over a year and across a day. This is especially important in the context wherein the share of renewable energy is rising rapidly but lack of deployment of utility-scale energy storage systems limits the uniform availability of this zero-carbon electricity. The national average emission factor value also ignores state- or distribution utility-level heterogeneity in electricity supply mix.

- **EV Charging is Not a Constant Load.** Using the annual average emission factor of grid electricity would have been logical if the concerned electricity end-use shows uniform daily load profile. EV charging does not fit into this load category at all. Daily mobility pattern in general is super dynamic and so is EV charging.[7] The latter exhibits skewed temporal pattern which in turn differs considerably depending on the EV use-case and corresponding duty-cycle, and preference or scope for charging. These factors are often intertwined.

This paper intends to bring forth the impact of the heterogeneities in many of the underlying factors, particularly related to EV charging and electricity supply, on the climate benefit of vehicle electrification.

[3] The scheme aims at reducing specific energy consumption—i.e., energy use per unit of production for designated consumers in energy intensive sectors—with an associated market mechanism to enhance the cost effectiveness through certification of excess energy saving, which can be traded.
[4] Calorific value of the fuel or its density may also need to be accounted for in the calculation.
[5] kilo Watt-hour (kWh) is the unit of electricity or electrical charge.
[6] The mean value is not a weighted average based on vehicle sales.
[7] There is limited seasonality in mobility and EV charging patterns.

The study addresses the following research questions in context of India:

- How do the average energy efficiency and operational GHG emissions of EVs play out vis-à-vis conventional vehicles across different segments considering the range of vehicle models sold in the market?
- How is the climate benefit of EV transition predicated on the energy transition in the electricity sector?
- How is the GHG mitigation potential of vehicle electrification stacked up considering the temporal patterns of electricity supply mix and EV charging?
- How does the GHG emission impact of EVs possibly differ sub-nationally?
- What are the possible interventions to effectively leverage EV transition in curbing transport-related GHG emissions?

Finding answers to these questions gives a real-world insight into the emission reduction benefit of EVs, which would potentially help carry out a proper stock-taking of the progress of decarbonisation of India's road transport and develop an effective strategy to fully leverage the promise of vehicle electrification. The findings are of great significance considering the scale of the impact that EV transition in the country—home to among the world's largest two- and three-wheeled vehicle markets and the fifth-largest car market (PwC India, 2024)—would potentially make.

A range of stakeholders would gain from the analysis. These include policymakers and implementing agencies, electricity regulators and distribution utilities, the auto industry, and EV fleet operators. Otherwise, limited understanding about the realisable climate benefit of EV adoption impairs their decision-making ability regarding transition to low-carbon alternatives in the transport sector. The study would also help shape public perception—especially among early EV-adopters[8]—towards owning EVs and making new energy vehicle adoption sustainable.

3. GHG Emissions of EVs vis-à-vis Conventional Vehicles

India has witnessed considerable traction in uptake of EVs in recent years. From close to just 8,000 sales in year[9] 2015, EV sales rose 200 times to reach more than 1.6 million in 2023 (JMK Research & Analytics, 2024). However, this high EV growth is not uniform across vehicle segments. Two-wheeled and three-wheeled EVs have cumulatively contributed about 94% of the total EV registrations till 2023. There are segments that have undergone very limited to almost no electrification. Commercial availability of EV models in the market is similarly skewed. While there are very few electric cargo minitruck models (with a payload capacity of 600 kg) currently available in the market, there are over 450 electric two-wheeled vehicle models up for purchase. Electrification has also led to the emergence of a new segment, the electric rickshaw (e-rickshaw), which does not have another motorised counterpart. It is important to note that sub-classes too matter significantly since vehicle performances, use-cases, and customer preferences differ considerably, as does EV penetration.

Considering the possible market heterogeneity and commercial prevalence of EV models, this study slices India's automobile market into 10 segments or sub-segments by vehicle form-factor to understand how the electric drivetrain fares compared to conventional or prevalent alternative vehicle technologies in terms of GHG emissions. These are: scooters,[10] bikes,[11] three-wheeled cargo vehicles, autos and e-rickshaws (three-wheeled passenger vehicles), four-wheeled cargo minitrucks (payload of 600 kg), Sports Utility Vehicles (SUVs),[12] sedans,[13] hatchback cars, and standard-size (12-metre) buses. Segments like light commercial vehicles with a payload of 1,200 kg, midi-size (nine-metre) buses, and heavy-duty trucks have not been considered for analysis due to sparse publicly available reliable data or lack of commercially available electric models.

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[8] Early EV-adopters are found to be more environment and climate conscious than the following EV-adopters.

[9] Unless explicitly stated otherwise, "year" refers to a calendar year.

[10] Scooters are also known as motorcycles. As per Central Motor Vehicles Rules, 1989, a motorcycle falls in Category L-1—i.e., a light two-wheeled powered vehicle with maximum speed not exceeding 70 km/h and engine capacity not exceeding 50 cc if fitted with a thermic engine, or motor power not exceeding 4 kW if fitted with an electric motor.

[11] Bikes are also called motorbikes. As per Central Motor Vehicles Rules, 1989, a motorbike comes under Category L-2—i.e., a light two-wheeled powered vehicle with maximum speed exceeding 70 km/h and engine capacity of more than 50 cc if fitted with a thermic engine, or motor power exceeding 4 kW if fitted with electric motor.

[12] Including compact SUVs.

[13] Including compact sedans.

3.1 Electric Drivetrain has an Energy Economy Advantage

It is well known that EVs are more energy efficient than Internal Combustion Engine (ICE)-vehicles. This technology advantage potentially enables EVs to have lower operational GHG emissions than conventional vehicles depending on the carbon load of the electricity consumed in EV charging. However, vehicle electrification making major impact in reducing emissions from motorised road transport effectively depends on how substantial the differential in energy efficiencies between electric and competing technologies is considering the current high share of fossil-fuel-based electricity generation in India and the emission intensity of EV manufacturing. Latter is reportedly more carbon intensive than that of conventional vehicles. According to a published whitepaper by ICCT, 68 kgCO_2e per kWh is the GHG emission intensity for battery manufacturing in India which adds about 10 gCO_2e to every kilometre run over the 15-year life of a hatchback car that increases to about 15 gCO_2e for a SUV[14] (Bieker, 2021).

To understand the efficiency benefit of the present EV deployment, the study finds it important to evaluate the vehicle energy performance landscape across different fuel types instead of limiting the comparison to one set of vehicle models. To this end, the investigation estimates, maps, and compares the energy economies of all or most of the popular electric and conventional vehicle models[15] and does not cherry-pick a specific model. This exercise has been carried out separately for the 10 vehicle segments.

The evaluation is done based on certified fuel economy values of vehicle models with internal combustion engines, and certified driving ranges of electric models, as available on the public domain, mostly on third-party portals. This study has not validated the accuracy of these values beyond reasonable checking. It is important to note here that there is a lack of publicly available official repositories of such vehicle model data in India despite these being mandatorily tested and certified at the time of vehicle homologation and are relevant to the public.

To make segment-level comparisons with electric vehicles, the study considers ICE vehicles running on mainstream fuels, which include petrol, diesel, and CNG wherever applicable. Where strong hybrid variants[16] are a common vehicle type, the study considers the energy economy performance of those strong hybrid models as well. For information about exclusion of certain vehicle technologies or fuels from the scope of this paper, refer to Appendix–A.

For the comparative analysis, the vehicle models, electric or ICE-based, that were commercially available in the Indian market as of September 2023 have been studied. In segments where there are many ICE or electric models, a sample approach has been adopted, as in the case of two-wheeled vehicles. The energy efficiencies of all vehicle types have been expressed in kilojoules per kilometre (kJ/km). Figure 1A and Figure 1B capture the landscape analysis by type of vehicle drivetrain for all vehicle segments except bus. Figure 2 shows the comparison for standard-size buses. To make it easier to compare technologies, the box and whisker diagrams point out the mean energy economy values for different variants in each vehicle segment.

Both graphs confirm that the efficiency of a vehicle technology in a segment varies over a range. This is especially pronounced in the case of the SUV and sedan segments across electric, ICE, and hybrid versions. This is primarily due to the existence of sub-classes (e.g., high-end cars and entry-level cars) in these segments based on vehicle features. This is also applicable to petrol bikes where engine capacities vary over a large range. In the analysis, bikes with engine capacities below 200 CC have been considered. Efficiency also ranges for standard-size ICE buses due to the differing fuel economies of CNG and diesel versions.

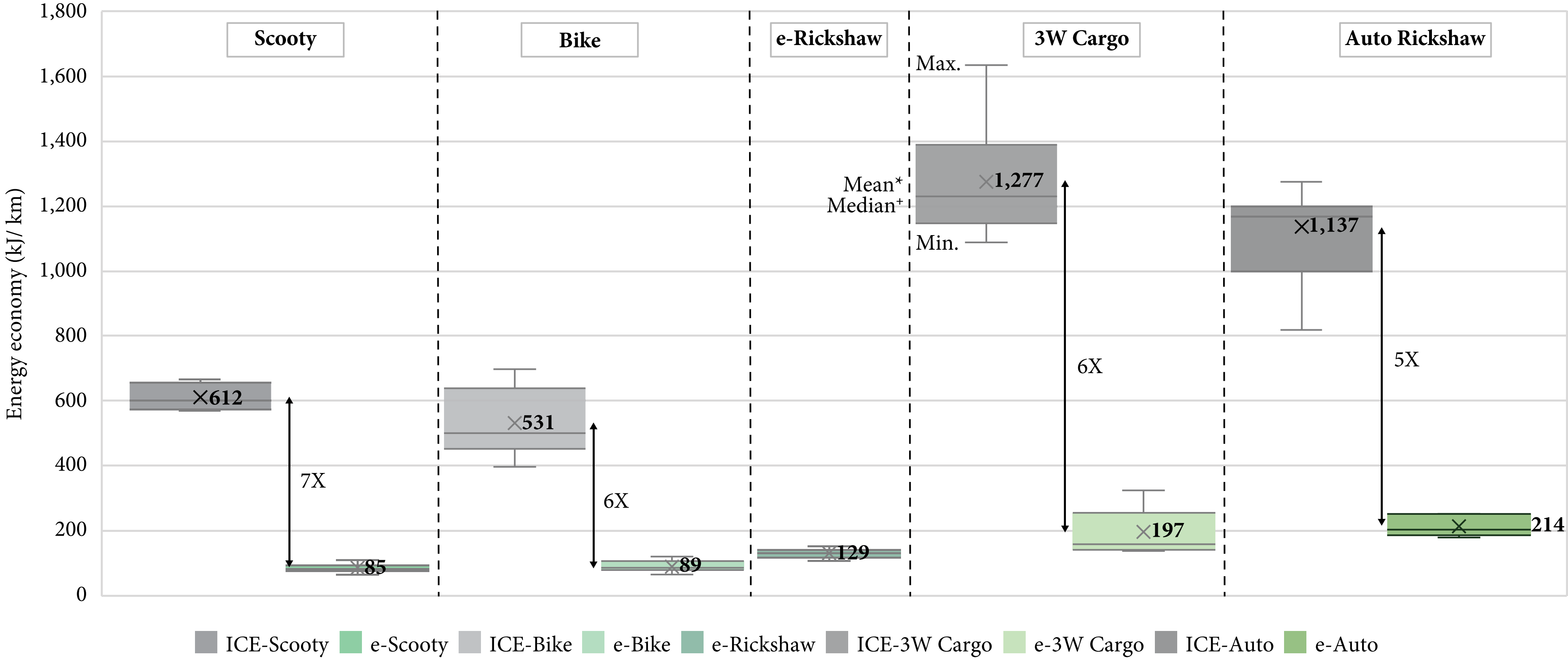
On the other extreme, the vehicle energy efficiencies of scooters and e-rickshaws hardly exhibit a range. This small spread in energy economy, despite the assessment of several models, indicates that the electric technology platform in these segments is mature and there are effectively no sub-classes.

14 The ICCT study assumes that a hatchback car and SUV is expected to run 165,000 km and 188,000 km respectively over its lifetime.

15 Provided required data of the models is publicly available.

16 Strong hybrid cars consist of a combustion engine and an electric motor that work together, as well as independently of each other. The electric motor can power the car in certain scenarios, like low-speed city driving, but when the driver demands more pace, the engine comes to life. The engine charges the batteries while driving, which thus does away with the need for the vehicle user to charge the battery. Like EVs, strong hybrids are often equipped with regenerative braking systems. Due to the battery, albeit of smaller capacity compared to that in an EV (for example, Grand Vitara strong hybrid model has a 0.76 kWh Li-ion battery, whereas Tata Nexon EV Max is powered by a 40.5 kWh Li-ion battery), and the regenerative braking system, a strong hybrid vehicle registers improved fuel economy than a pure ICE counterpart.

Figure 1A: Comparison of Energy Economies Between Electric and Conventional Vehicle Model Stocks in Two-Wheeled and Three-Wheeled Segments

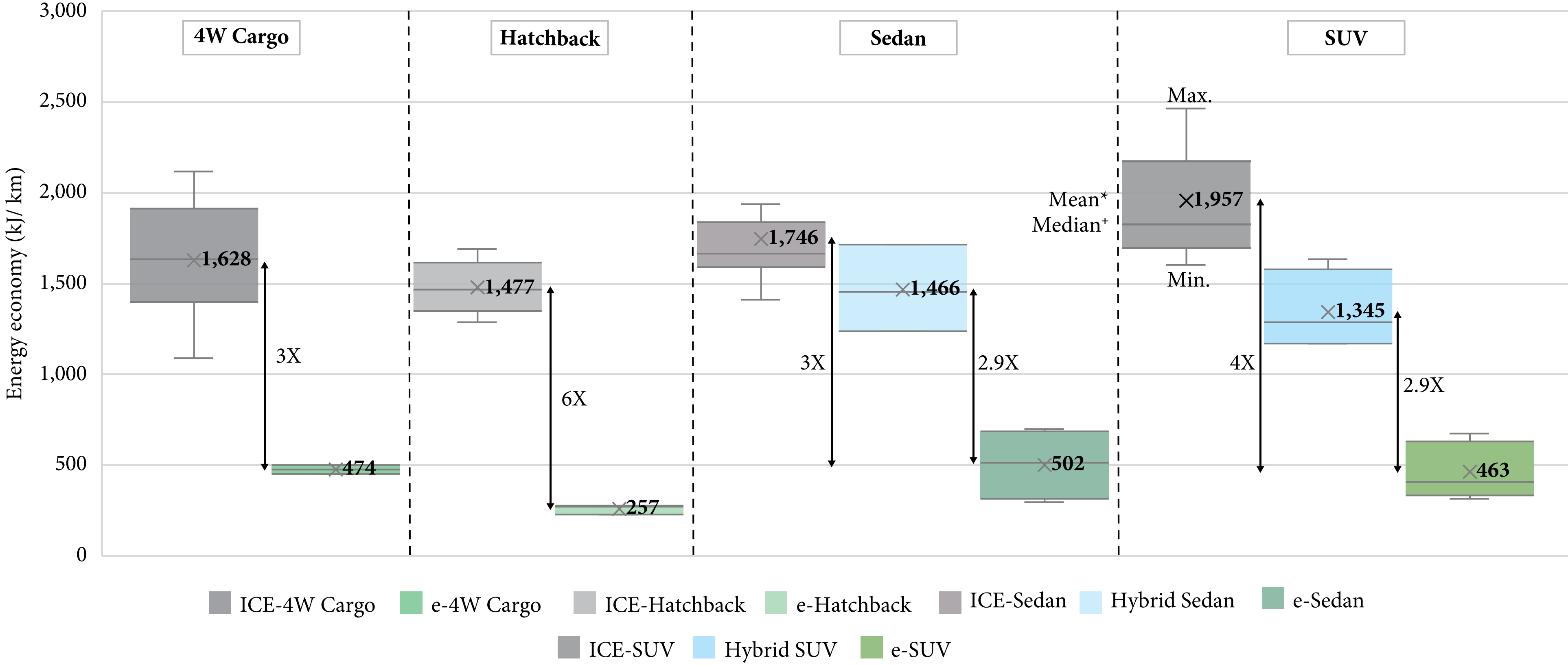


Mean refers to the average of the energy economy values of different models in a segment. It is not a weighted average based on vehicle sales.

+Median refers to the middle value of the given data when all the values are arranged in ascending order.

Source: Author's analysis.

Figure 1B: Comparison of Energy Economies Between Electric and Conventional Vehicle Model Stocks in Four-Wheeled Segments



**Mean refers to the average of the energy economy values of different models in a segment. It is not a weighted average based on vehicle sales.*

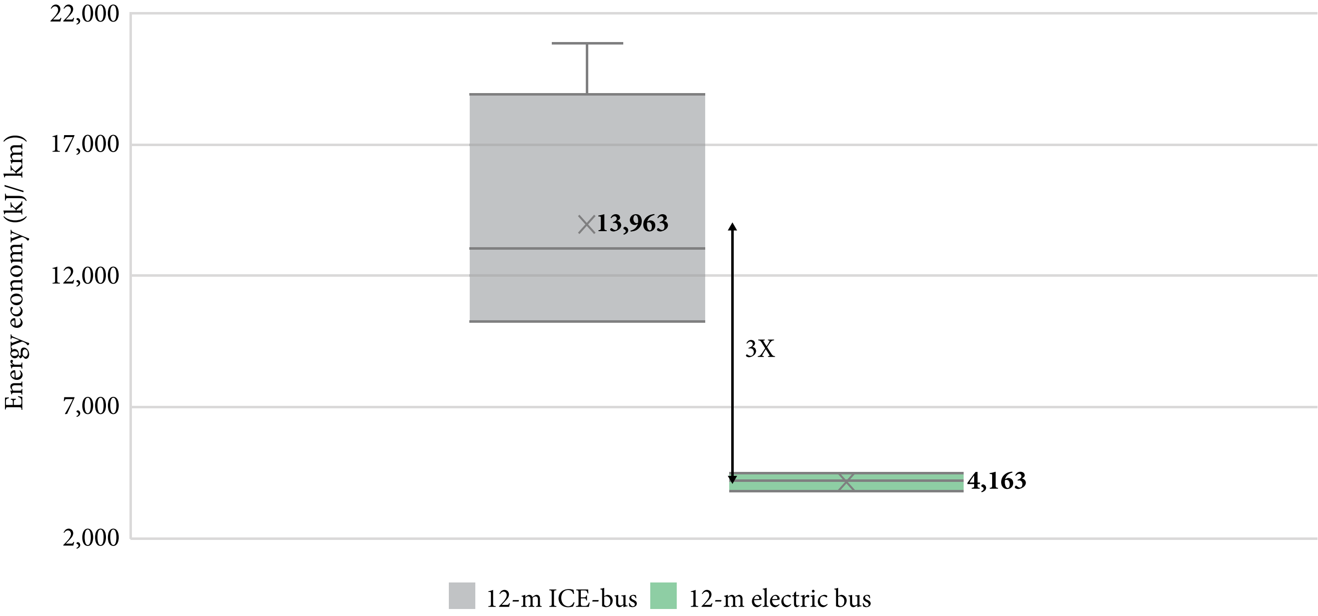
+Median refers to the middle value of the given data when all the values are arranged in ascending order.

Source: Author's analysis.

Note:

- *Model stock refers to the group of vehicle models of a particular technology (electric, pure ICE, or hybrid) in a vehicle segment.*
- *The vehicle segments are arranged in the order of increasing engine capacity or electric motor rating from left of the graph to the right.*
- *3W and 4W refer to three-wheeled and four-wheeled vehicles respectively.*
- *ICE vehicle models include petrol, diesel, or CNG fuel-type. Hybrid model stock comprises of only strong hybrid ones.*
- *The values on the box & whisker diagrams indicate the mean energy economies for the different variants in each vehicle segment.*
- *A line arrow indicates the estimated gap in average energy economy between electric and ICE or strong hybrid vehicle model stocks in a segment. The adjacent value shows the times the mean energy efficiency of ICE or strong hybrid model stock is lower than that of electric model stock in a vehicle segment.*
- *The vehicle models launched after September 2023 are not considered in the analysis.*

Figure 2: Comparison of Energy Economies Between Electric and ICE Buses (Standard-Size)



Source: Author's analysis.

Note:

- *ICE bus models include diesel or CNG fuel-type.*
- *Electric bus models are low floored which is passenger friendly but reduces the fuel economy of the buses.*

A comparison based on the mean energy efficiency values shows that current EVs are about three to seven times more efficient than their pure ICE counterparts, varying across different segments.

As expected, the efficiency edge of electric cars lessens when their performance is compared with strong hybrid models. While on average, current electric SUV and electric sedan models are over four times and three times, respectively, more efficient than pure ICE models, the gaps reduce to 2.9 times when compared to strong hybrid versions. It is worthwhile to note here that greater shares of premium models (with less energy economy) in electric sedan and electric SUV segments have a lowering effect on the mean energy economies of the stock of electric models in these segments.[17]

The differential in energy efficiency between electric and conventional vehicles is likely to increase in the future, as the energy densities of EV batteries are anticipated to improve, making upcoming EVs considerably lighter. The electric drivetrain may also become more energy efficient. One can find an indication of this from the improved energy economy of recent electric car models compared to the early generation of electric four-wheeled vehicles. For example, Mahindra e-Verito, a now-discontinued electric compact sedan model, reportedly had a certified energy economy of about 5 km/kWh, whereas presently the average energy economy of the entire electric sedan segment, which includes some of the feature-loaded, high-end electric car models (with less energy economy), is about 8 km/kWh.

Additionally, the recent trend in fuel economy values of ICE-cars in auto markets with stricter emission standards and testing protocols indicates limited scope for future improvement. Despite tightened testing standards since the 2010s, the European Court of Auditors found that real-world emissions from conventional cars have not decreased materially in 12 years (European Court of Auditors, 2024).

On-road energy economies of the vehicles, both ICE and electric versions, are likely to be lower than the reported efficiencies, depending on the driving conditions like road congestion and condition, driving style, etc. Also, the use of air-conditioning increases the auxiliary energy consumption in a vehicle that consequently reduces its effective energy economy. EVs are expected to offer slightly better efficiency in

[17] According to the auto industry executives, a greater number of luxury electric sedan and SUV models are expected to be introduced in India in view of the growing customer preference for high-end models (ET Auto, 2024).

city driving conditions owing to their regenerative braking systems. A real-world driving test of Nexon EV Max electric car has reportedly shown about 3% improvement in its driving range when the vehicle is driven in a city (Autocar India, 2024).

While comparing the energy efficiencies of EVs with ICE and strong hybrid versions, it is difficult to consider that these vehicle technologies offer comparable performance on all metrics. One should be mindful that the electric drivetrain is fundamentally a different technology platform. The study also finds it infeasible to carry out a like-for-like comparison as currently there is no vehicle model that has all three technology variants—pure ICE, strong hybrid, and electric.

With the given coal-dominated power generation in India, it would be interesting to find out whether the current technological superiority of electric drivetrains allow vehicle electrification to be a major lever for GHG abatement in motorised road transport.

3.2 How do EVs Fare in GHG Emissions When Electricity Emission Factor is Considered?

With the fuel switch from petroleum products to electricity, the tank-to-wheel GHG emissions associated with EVs depend on the carbon load of the electricity that is used in charging the batteries of these vehicles.[18] In line with the present-day common approach for calculating indirect operational emissions of an electricity end-use including EVs, the study first estimates the carbon footprint of driving an EV based on the weighted average emission factor of India's grid electricity as published by the Central Electricity Authority (CEA) for FY 2021–2022, the latest year for which information is available at the time of this evaluation.[19] The emission factor is reportedly 715 grams CO_2 per kWh (Central Electricity Authority, 2022).[20] Considering there is energy loss during transmission and distribution of electricity, 9% loss[21] is accounted for while applying the above emission factor value (International Transport Forum, The World Bank, 2023).

To make the comparison between EVs and conventional vehicles in a segment, the study considers specific CO_2 emissions of a vehicle type (expressed in grams CO_2 per kilometre (gCO_2/km)) as the yardstick. It is derived based on the emission factor (gCO_2 per unit of fuel consumption) of the concerned fuel and the average certified energy economy (fuel consumption per km) that is deduced for each vehicle-type from the landscape analysis presented before. Figure 3A and Figure 3B show the specific CO_2 emissions of vehicle model stocks by type of drivetrain for all vehicle segments except for buses. Figure 4 displays the comparison for standard-size buses.

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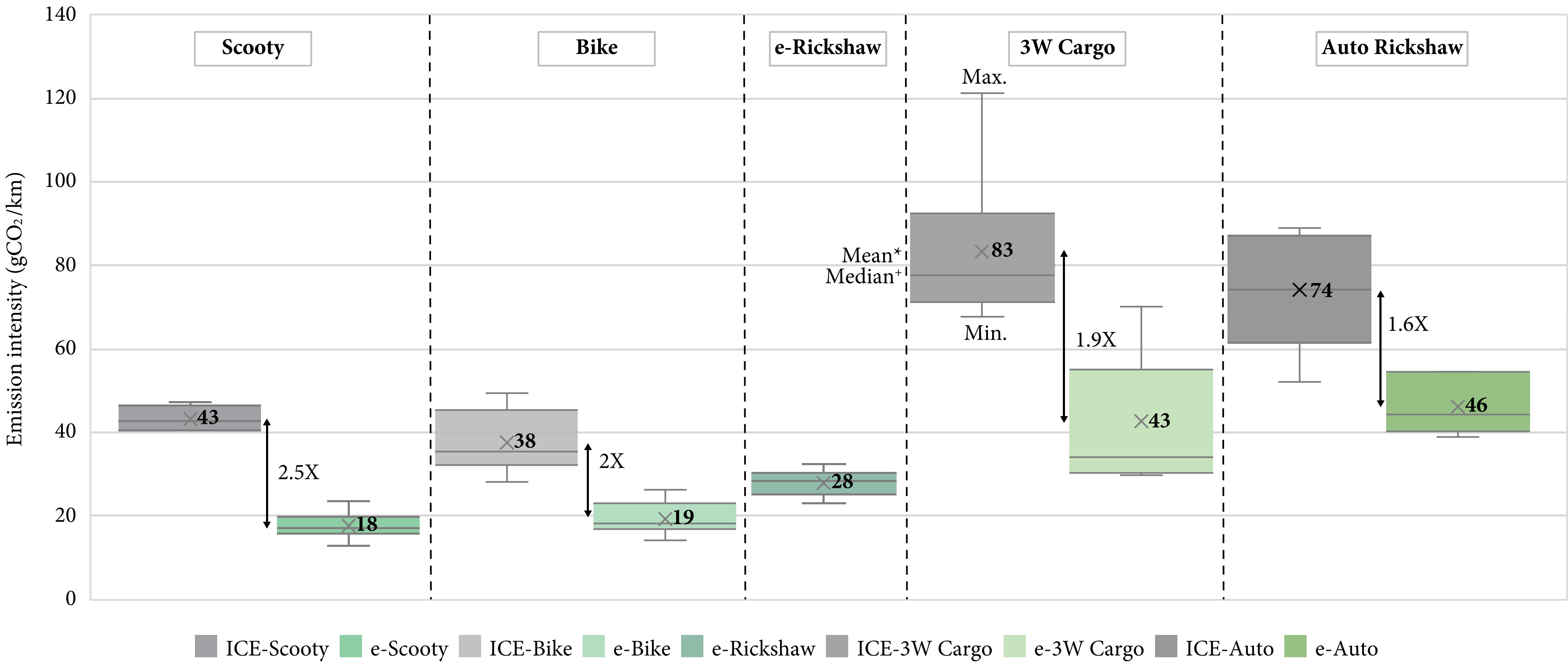
[18] In case of an EV, the source of electricity consumed in EV charging is regarded as the "tank".

[19] Central Electricity Authority (CEA) annually publishes India's yearly average emission factor of grid electricity based on the CDM methodology ACM0002, Version 20.0. The emission factor is based on the average emissions of all power generation stations connected to the grid, weighted by their net electricity generations.

[20] Excluding cross-country electricity transfers and including renewable energy supply. This derived emission factor is considered the representative value for CO_2 emission intensity of India's grid electricity and is used in emissions calculations related to grid electricity consumption.

[21] This includes only technical line loss and excludes power theft and commercial losses.

Figure 3A: Comparison of CO_2 Emission Intensities (gCO_2/ km) Between Electric and Conventional Vehicle Model Stocks in Two-Wheeled and Three-Wheeled Segments

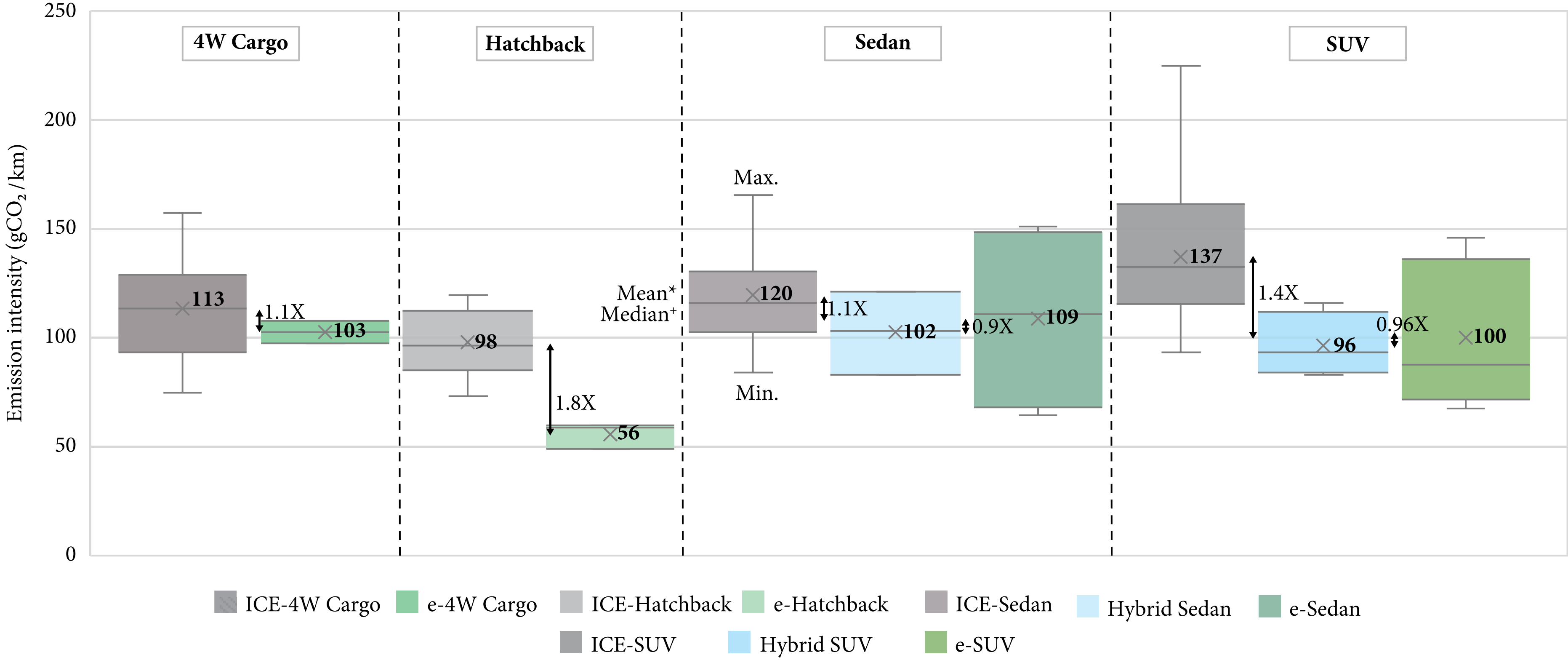


**Mean refers to the average of the CO_2 emission intensity values of different models in a segment. It is not a weighted average based on vehicle sales.*

+Median refers to the middle value of the CO_2 emission intensity data when all the values are arranged in ascending order.

Source: Author's analysis.

Figure 3B: Comparison of CO_2 Emission Intensities (gCO_2/ km) Between Electric and Conventional Vehicle Model Stocks in Four-Wheeled Segments



**Mean refers to the average of the CO_2 emission intensity values of different models in a segment. It is not a weighted average based on vehicle sales.*

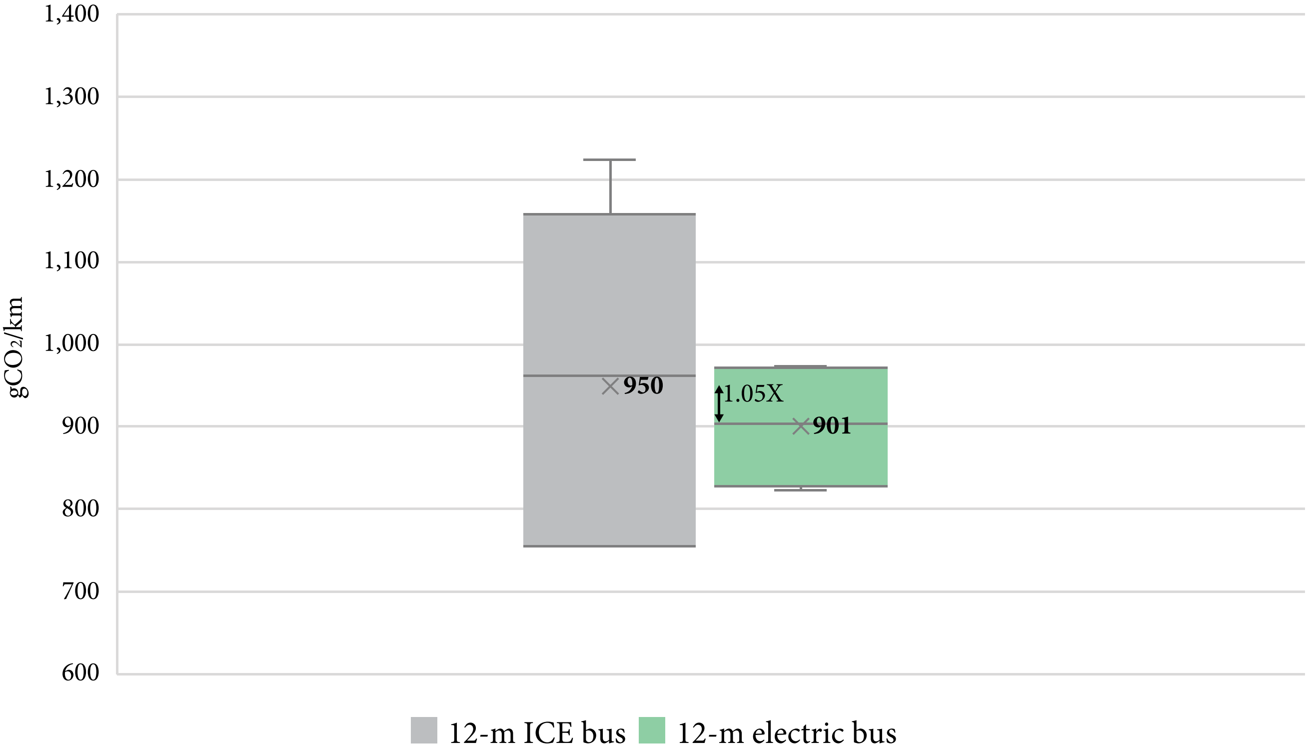
+Median refers to the middle value of the CO_2 emission intensity data when all the values are arranged in ascending order.

Source: Author's analysis.

Note:

- *Transmission and distribution losses are accounted for in the calculation of CO_2 emissions from EVs.*
- *The values on the box & whisker diagrams indicate the mean CO_2 emission intensities for the different variants in each vehicle segment.*
- *A line arrow indicates the estimated gap in average specific CO_2 emissions between electric and ICE or strong hybrid vehicle model stocks in a segment. The adjacent value shows how many times the mean CO_2 emission intensity of electric model stock is less than that of ICE or strong hybrid model stock in a vehicle segment.*

Figure 4: Comparison of Specific Emissions (gCO_2/ km) Between Electric and ICE Buses (Standard-Size)



Source: Author's analysis.

The impact of the present coal-dominated supply mix of India's grid electricity on the CO_2 emission intensity of electric model stock is discernible from the graphs. Across all the vehicle segments, the energy economy advantage of EVs translates to less-than-substantial CO_2 emission reduction benefit when mean specific CO_2 emissions of electric model stock and conventional vehicle model stock are compared. For example, where on average an electric scooter is estimated to be more than seven times more energy-efficient than its petrol counterpart, the operational CO_2 emissions (Scope-2 emissions) of the former are only 2.5 times less. The fall in climate benefit of the electric drivetrain is starkly apparent when compared with strong hybrid models in the SUV and sedan segments. The mean specific CO_2 emissions for both electric[22] and strong hybrid model stocks in these car segments are found to be nearly equal to or slightly less in the case of the latter. The impact of the carbon burden of grid electricity is also evident in the case of electric buses. The gap between average CO_2 emissions per kilometre of a standard-size electric bus and its ICE counterpart is significantly narrowed in contrast to when they are compared in energy economy terms.

To talk about emissions comparison across vehicle segments, although buses have lower energy economies and higher emission intensities than other passenger vehicle types, one should be mindful of the passenger-carrying capacity of each of these vehicles. As shown in Figure 5 which translates the emission intensity (gCO_2/km) results of the vehicles into emissions per passenger-km (gCO_2/passenger-km), an e-rickshaw has the lowest CO_2 emissions per passenger-km followed by electric versions of scooter, bike, and standard-size bus, all at full occupancies. Interestingly, an ICE bus is found to cause a similar level of emissions per passenger-km as that of an electric hatchback[23] and lower than a sedan or an SUV of any technology. This comparison will be starker if one considers lower occupancy of the cars which is often seen in the real world. This underlines the importance of modal shift from cars to public bus transport for effectively reducing GHG emissions.

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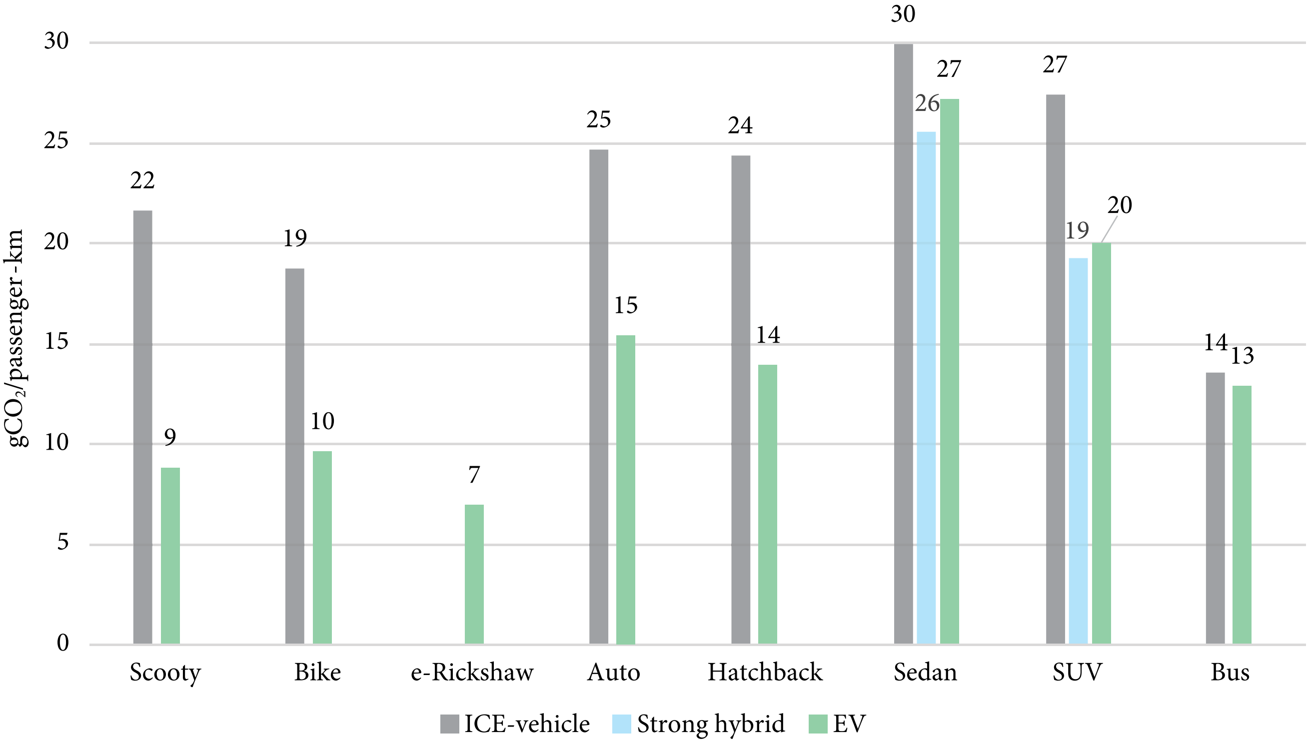
[22] Based on the weighted average emission factor of India's grid electricity (including renewable energy) for FY 2021-2022.
[23] Considering occupancy of four.

Figure 5: Comparison Based on CO_2 Emissions per Passenger-km Between Electric and Conventional Vehicles in Different Segments



Source: Author's analysis.

The significance of the supply-mix of grid electricity in making EVs a climate-friendly alternative is a major takeaway from the range of analyses presented above. While debating whether strong hybrid cars are better for the climate than pure electric, one should be mindful of the fact that the battery in the former being charged by burning oil is not going to change in the future from a technological point of view, whereas the energy transition to renewables potentially makes EVs progressively less carbon intensive. Vehicle electrification holds promise considering the share of zero-carbon electricity supply is expected to increase in the coming years in line with India's updated Nationally Determined Contribution (NDC) target of achieving 'about 50% cumulative electric power installed capacity from non-fossil fuel-based energy resources by 2030' (Press Information Bureau, 2022). However, there are potential challenges to make EV use truly carbon light. Some of these are highlighted in an ensuing section.

4. Do EVs Have Similar Carbon Footprints Across India?

The power grid can be regarded as a confluence of various streams and sub-streams of electricity supplied by respective distribution utilities,[24] each originating from different generation sources having varying shares of carbon. Therefore, on the one hand, an end-user based in a state is drawing electricity from the distribution network that is part of the common and shared national power grid. On the other hand, the electricity consumed by the end-user is provided by a certain distribution utility, which has its own unique basket of power procurements. This implies that the average CO_2 emission intensity (gCO_2/kWh) of the electricity mix in a distribution utility's supply—i.e., the stream—is likely to differ from the overall emission intensity of the grid electricity (i.e., the confluence). Extending this notion, the operational CO_2 emissions from EV charging potentially varies from one distribution utility to another and, for that matter, from one city or state to another.

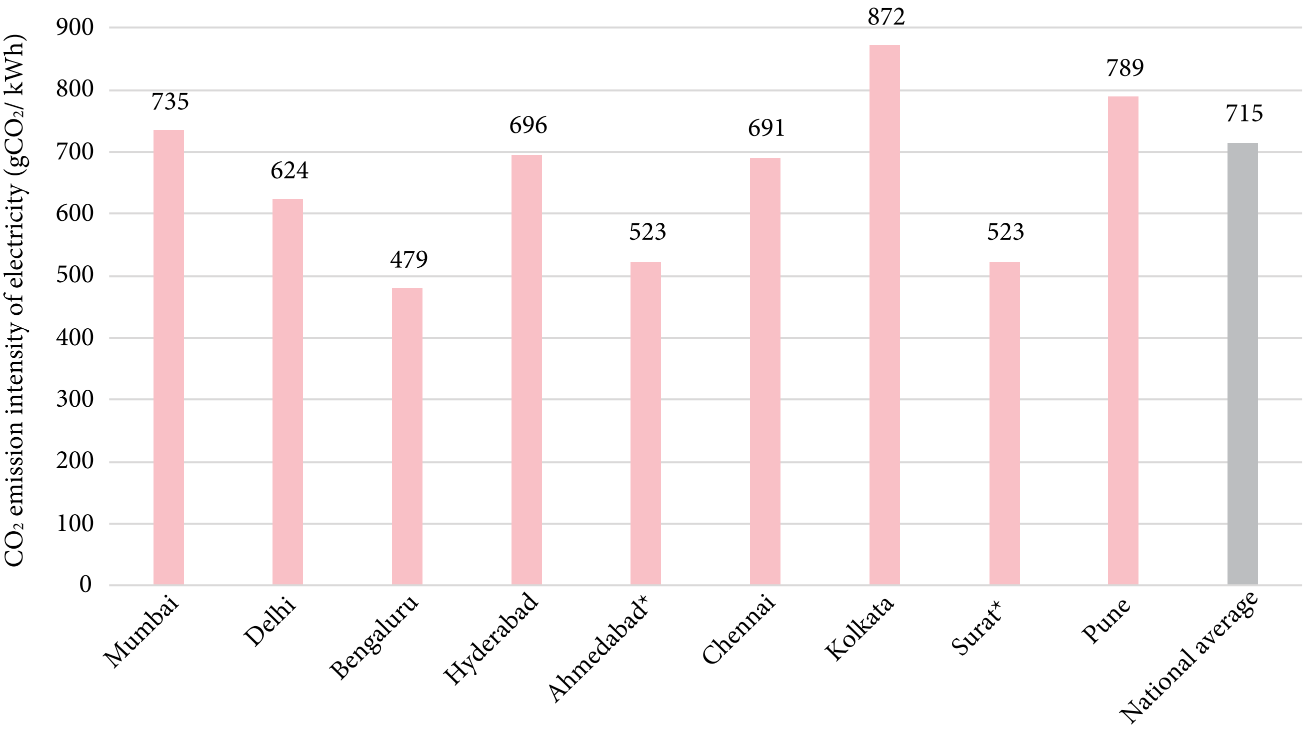
[24] Large electricity consumers have the option to procure electricity directly from specific sources through open access and from wholesale power markets via energy exchanges.

This paper sheds light on this aspect by estimating possible specific CO_2 emissions of EV use (gCO_2/km) in the nine Indian cities with populations of over four million that have been identified and listed in the revised consolidated EV charging infrastructure guidelines and standards for priority rollout of public charging stations (Ministry of Power, 2022). These cities are Mumbai, Delhi, Bengaluru, Hyderabad, Ahmedabad, Chennai, Kolkata, Surat, and Pune. Each of these cities comes under the service area of one or more distribution utilities (distribution licensees). The study estimates CO_2 emission intensity of the electricity (gCO_2 per kWh) supplied by each of these distribution utilities (refer to Appendix–B for details regarding the calculation approach). Figure 6 captures the variations in the CO_2 emission intensities of electricity across these nine Indian cities in FY 2021–2022.

The analysis shows that CO_2 emission intensity of utility-supplied electricity does vary quite considerably. Out of the nine cities, the electricity supplied to three cities is found to have a higher carbon load than the national average, and the maximum (as found in the case of Kolkata) and the minimum (as in the case of Bengaluru) emission intensity values differ by (+) 22% and (-) 33% respectively vis-à-vis the national average.

The derived emission intensities will have a proportionate impact on the specific CO_2 emissions (gCO_2/km) of an EV. To put this into perspective, the use of EVs in Kolkata potentially causes about 82% higher CO_2 emissions per kilometre than in Bengaluru. Figure 7 reflects the potential impact of the heterogeneity in electricity supply mix on the specific CO_2 emissions of EVs. The consequence is starker in the case of four-wheeled vehicle segments. On the one hand, an electric four-wheeled cargo vehicle or an electric sedan has higher operational emissions than an ICE counterpart when the former is charged in Kolkata or Pune. On the other hand, electric versions in the sedan and SUV segments are found to emit less than strong hybrids if EVs are charged in Ahmedabad, Bengaluru, Delhi, or Surat among the given nine cities in the present scenario. This highlights that the power procurement basket of a distribution utility does matter as far as the carbon footprint (Scope-2 emissions) of electricity end-users is concerned.

Figure 6: CO_2 Emission Intensities of Electricity Across Nine Indian Cities in FY 2021-2022

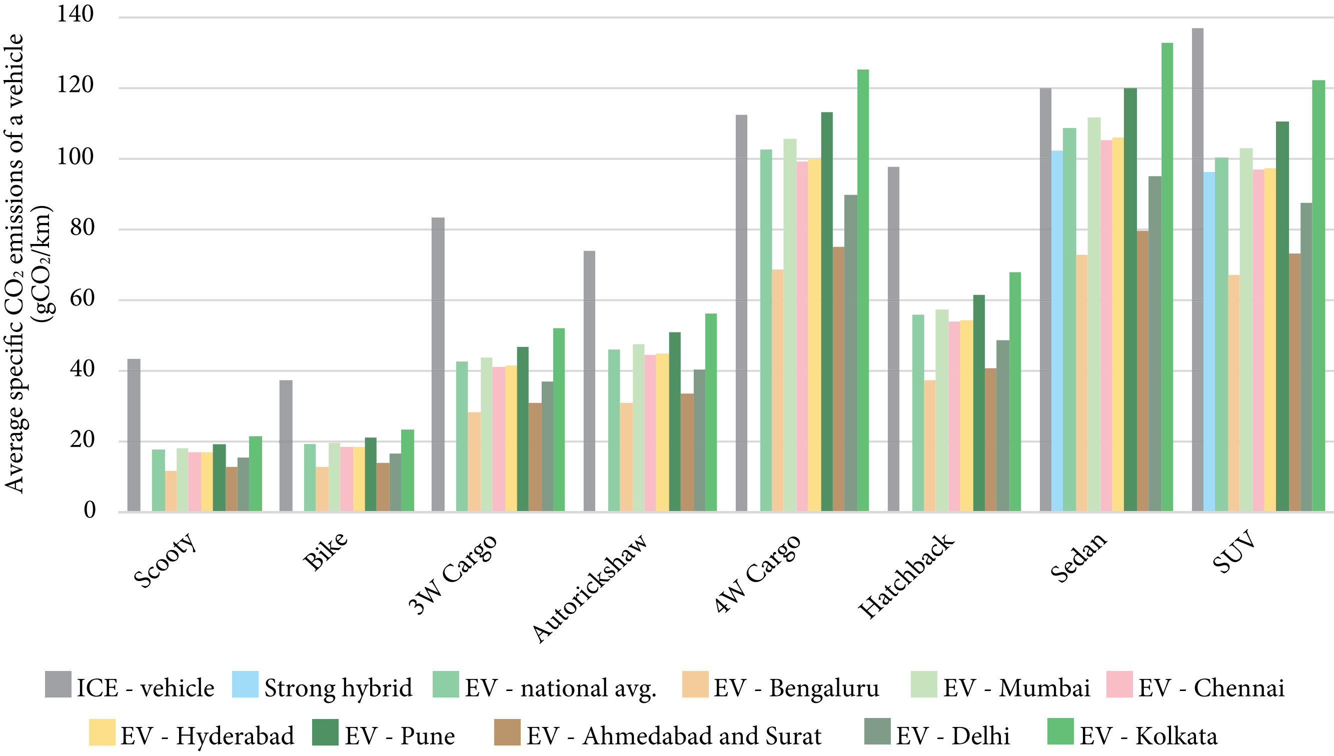


**Both Ahmedabad and Surat have the same distribution licensee, and the true-up petition filed by the licensee is common.*

Source: Author's analysis.

Note: The estimated CO_2 emission intensities of electricity for the nine cities should be considered indicative only. The purpose of this exercise is not to rank the states, cities, or distribution utilities. For this reason, the columns in the graph are not stacked in a specific order.

Figure 7: Specific CO_2 Emissions (gCO_2/ km) of EVs in Different Indian Cities



Source: Author's analysis.

Note: Strong hybrid models are commercially available only in SUV and sedan segments (as of September 2023).

Long-term power purchase agreements being the mainstay of most utilities, the carbon load of the electricity supplied by them is unlikely to change considerably from year to year. Regulations like Renewable Purchase Obligation (RPO) do play a role in aligning a utility's power procurement strategy with the agenda for increasing the share of non-fossil-fuel in the supply.[25] Long term growth trajectory of RPOs is prescribed by the Ministry of Power from time to time (Ministry of Power, 2022).

Utilities in renewable energy-rich states are found to be better placed to achieve the targets. As per India RE dashboard, out of the recorded distribution licensees, 11 were able to accomplish their Solar RPO targets for FY 2021–2022 and 13 fell short (Prayas (Energy Group), 2023). In the case of Non-solar RPO, eight licensees managed to meet the compliance while 16 could not.[26] This potentially highlights that the success of reducing the country's overall electricity emission intensity rests on the collective effort of distribution utilities who are responsible for procuring power, including from renewable sources, and supplying to the consumers.

5. The Curious Case of Time-of-Day Charging of EVs

At what time of day an EV is charged does matter if decarbonisation of motorised road transport through vehicle electrification is the objective. Neither the electricity supply mix nor the electricity consumption due to EV charging is constant throughout the day.

25 Under the RPO, the concerned State Electricity Regulatory Commission sets a minimum percentage of the total consumption of electricity in the licensed supply area of a distribution licensee—i.e., a utility—for the purchase of electricity from renewable energy sources, taking into account the availability of such resources and their impact on retail tariffs. Separate targets are fixed for the procurement of solar energy and from non-solar renewable sources.

26 The dashboard statistics are not validated by the author.

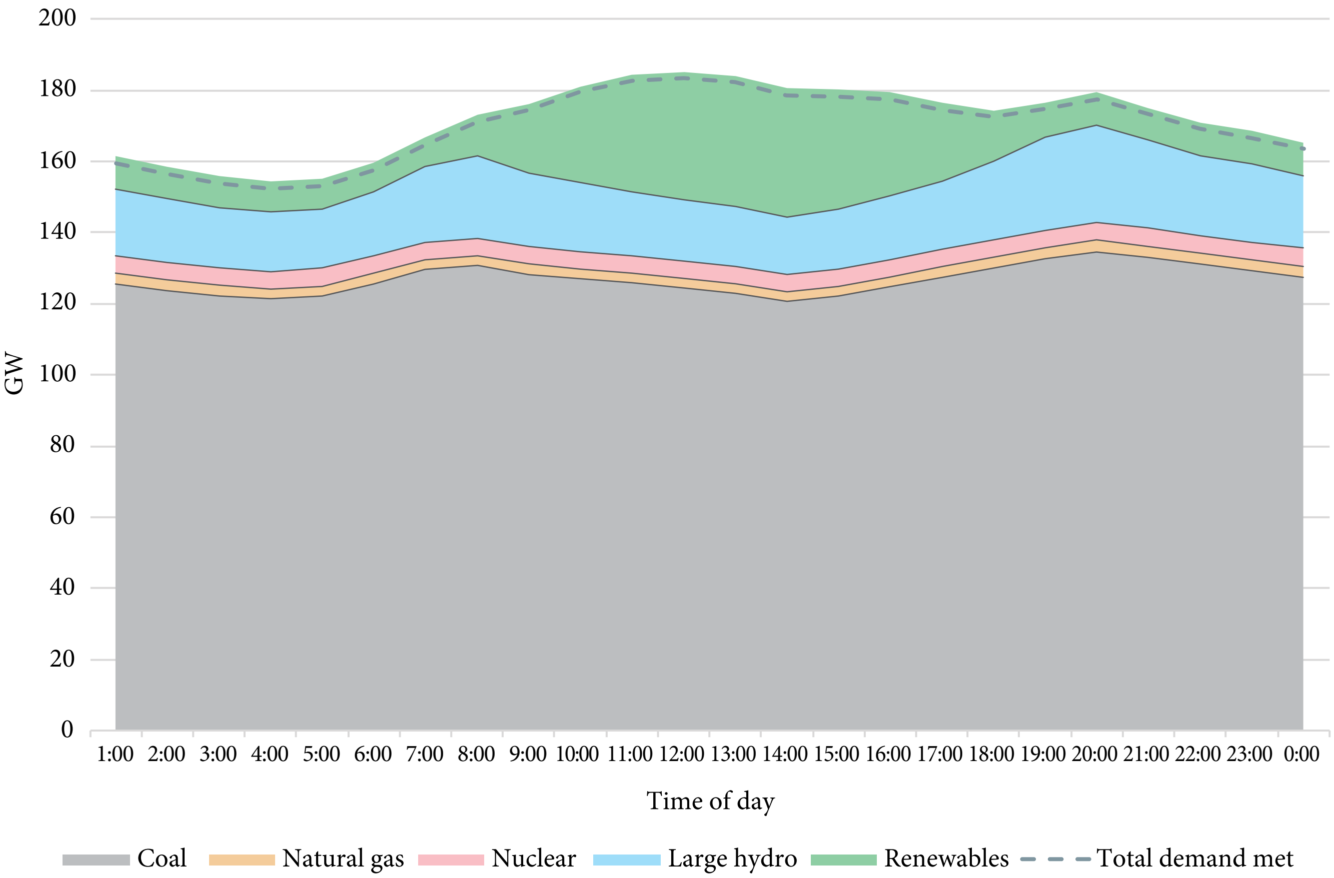
5.1 Carbon Load of India's Grid Electricity Varies with Time-of-Day

Time of day is increasingly becoming an important factor for power system planning in India as the share of variable renewable energy (VRE)—i.e., intermittent renewable energy sources like solar, wind, and small hydro that are not dispatchable due to their considerable fluctuating generation profile—rises rapidly but is not adequately complemented by energy storage capacities. The share of zero-carbon electricity in India's grid power supply is getting highly skewed with time of the day, particularly because of the rising share of solar energy. As a result, the emissions intensity of grid electricity becomes very low during midday, followed by emission-intensive hours during evening and night.

What is the significance of this skewness in carbon burden of grid electricity in the context of EV charging and corresponding carbon footprint? The real-world CO_2 emissions (indirect) from EVs may see both extremes–very high to really low–depending on when (time of day) they are charged and how long the charging sessions coincide with high renewable energy hours. This implies that, in the Indian context, daytime charging allows low CO_2 emissions due to the significant supply of solar energy, whereas emissions drastically increase when EV charging is carried out during the evening and night (non-solar hours) because of the greater share of fossil-fuel-based thermal power.

This warrants the need to take stock of the temporal pattern of CO_2 emission intensity of India's grid electricity. To this end, the real-time data on India's electricity generation by type of source, which is captured every 3 minutes by carbontracker.in, the Centre for Social and Economic Progress's (CSEP) webtool (CSEP, 2023), is analysed. The underlying generation data that is processed by the tracker is sourced from the Ministry of Power's (MoP) MERIT India portal (Ministry of Power, 2023).

Figure 8: Annual Average Daily Profile for Power Generation and Demand in India in 2022

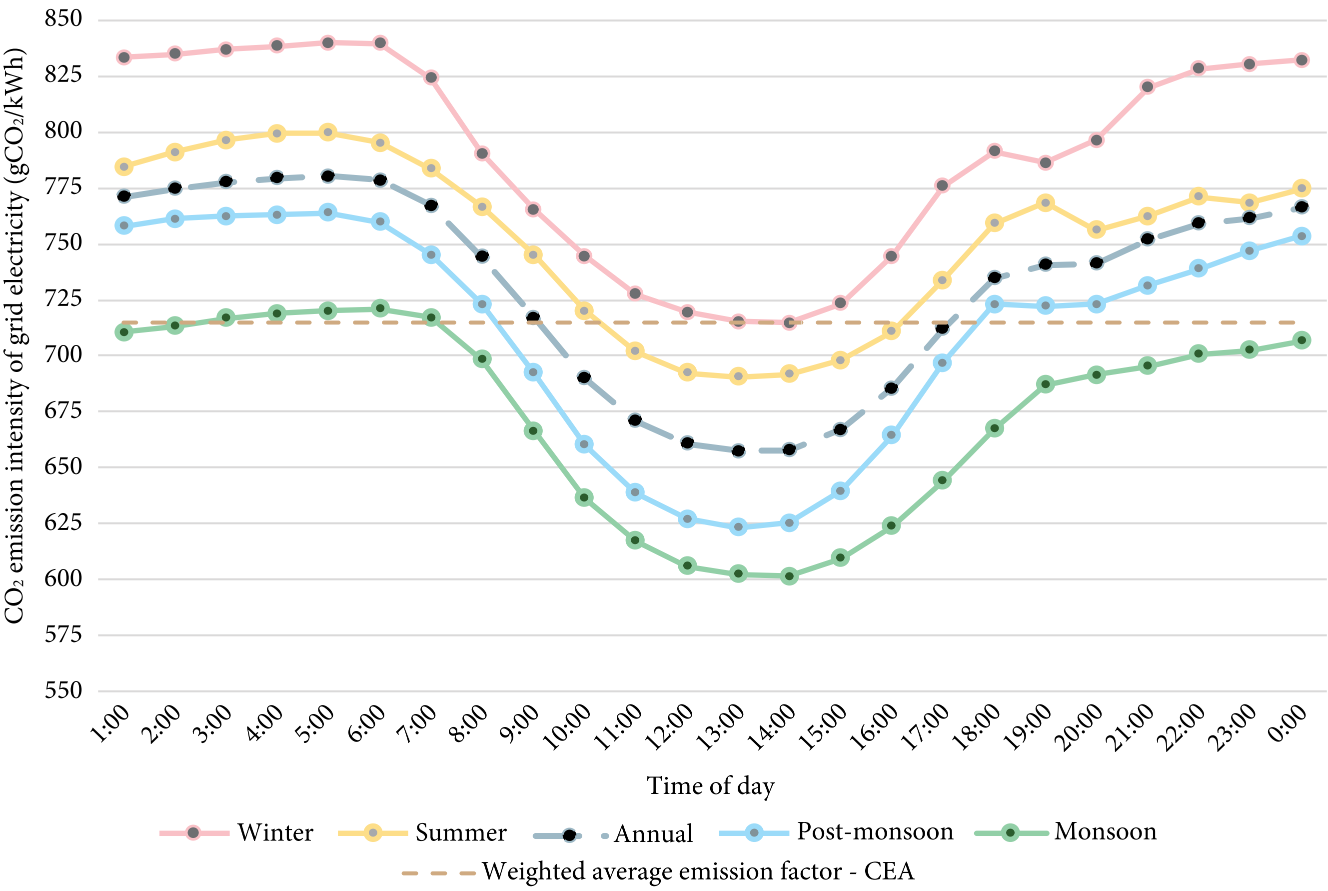


Source: Author's analysis.

Figure 8 clearly shows that a large share of the real-time power demand (expressed in gigawatts (GW)) in 2022, on average 75%, was met by coal-based thermal power. Zero-carbon sources— i.e., nuclear, large hydro, and renewables—together, managed to cater to 25% of the average real-time power demand in a year. This share comes down to 20% typically during late night and early morning (five hours of a day) and rises to 32% during mid-day (12 noon to 2 pm)—i.e., the difference between the maximum and the minimum annual average time-of-day (ToD) shares of zero-carbon electricity is as much as 63%. The above generation profile highlights that not only India's annual electricity supply is still dominated by fossil fuel-based power generation despite accelerated growth in renewables capacity,[27] the average ToD contribution of renewables to meet demand is highly variable.[28] One can see the reflection of the skewness in renewable energy supply on the ToD CO_2 emission intensity of India's grid electricity.

The study constructs a national-level ToD CO_2 emission intensity profile for each month based on the monthly generation profile by taking into account emission factors for fuels given in the CEA CDM–CO_2 Baseline Database (Central Electricity Authority, 2022). From the monthly emission intensity trend, a seasonality can be observed. Figure 9 plots the average hourly emission intensity of India's grid electricity in four different seasons in 2022, as well as the hourly annual average. The graph also draws a comparison of the temporal variation with the CEA-published weighted average annual emission factor of the country's grid electricity for FY 2021–2022.

Figure 9: Seasonal and Temporal Pattern of CO_2 Emission Intensity of Grid Electricity in India in 2022



Source: Author's analysis.

Note: Winter is from December to February, summer spans from March to May, monsoon lasts from June to August, and post-monsoon is from September to November.

[27] Cumulative installed generation capacity of nuclear, large hydro, and renewables is reportedly about 163 GW in comparison to 236 GW of fossil-fuel based power generation capacity as on March 31, 2022.

[28] Nuclear and large hydro are sources of firmed power, i.e., consistent supply of electricity throughout the day.

The hourly pattern reveals that CO_2 emission intensity of electricity supply varies considerably. The hourly annual average peaks at about 780 gCO_2/kWh at 5 AM and reaches a low of around 657 gCO_2/kWh at 1 PM—i.e., the gap between maximum and minimum hourly values is about 19%. In contrast, the weighted annual average emission factor for FY 2021–2022 (including renewable energy sources, excluding cross-border power transfers) as published by the CEA is reportedly 715 gCO_2/kWh. The comparison becomes starker when the seasonality in emission intensity is considered.[29]

5.2 Actual Climate Benefit of EVs is Highly Time Sensitive

The ToD CO_2 emission intensity of electricity supply is a critical factor in determining the real operational carbon footprint of EVs in India. The bulk charging of EVs tends to follow mobility patterns but in an inverse manner because one gets the opportunity to charge an EV when it is continuously parked for a decent duration. When an EV user gets an opportunity or prefers to charge can differ considerably. It is contingent on several factors such as the vehicle's duty-cycle (that in turn depends on its use-case), the user's preference or scope to charge (where, when, and how), a city's traffic pattern, road congestion, etc. For example, an electric car privately owned is likely be charged at home during evening hours, whereas an electric cab may require charging multiple times a day, some of which may coincide with solar hours. Given an opportunity to charge at the workplace, a private electric car might get top-up charging during the daytime as well. Dynamic electricity tariffs like ToD-tariff design involving a higher tariff rate during certain times of the day and a lower rate during specific time blocks also potentially influence the charging behaviour of EV users as the latter would try to make EV charging cost-effective. At what time of the day and to what extent an EV is charged, and what the ToD CO_2 emission intensity of grid electricity is during charging, are what determines the true emissions from an EV.[30]

There is a lack of publicly available real-world data on EV charging that could help decipher the current characteristics of charging sessions across different EV segments. Based on the broad temporal pattern of vehicle movement in a city, which is largely daytime-heavy, one could infer that the majority of EV charging sessions across different vehicle use-cases take place during the late evening. This is when most of the vehicles are parked idle for a long duration, and users can plug in their EVs. Consultations with EV fleet operators also confirm that the bulk of EV charging is carried out during the evening hours of the day when most EVs in a fleet are not in active operation. What does this mean in the context of CO_2 emissions from EVs?

To analyse the impact of ToD CO_2 emission intensity of grid electricity on emissions (indirect) due to EV charging, the specific CO_2 emissions of EVs (gCO_2/km) are estimated for different vehicle segments when charging is done during evening (6 p.m. to 11:59 p.m.), night (12 a.m. to 5:59 a.m.), morning (6 a.m. to 11:59 a.m.), or afternoon (12 p.m. to 5:59 p.m.). Based on the 2022 ToD pattern of grid electricity emission intensity, one can see that charging during evening potentially leads to 10% higher CO_2 emissions than during mid-day or afternoon (refer to Figure 10). Night-time charging is found to be even more carbon intensive. This diminishes the climate benefit of EVs in terms of mitigating road-transport-related CO_2 emissions.

Although two-wheeled, three-wheeled, and four-wheeled EVs are found to cause less CO_2 emissions than ICE-counterparts even when these EVs are charged during evening or night, an electric scooter could reduce 1.68 gCO_2 more per km and an electric sedan about 9.10 gCO_2 extra per km when they are charged mid-day than during evening. The emission benefits of daytime charging translate to achievement of additional annual emission reductions to the tune of 10 kg CO_2 in case of an electric scooter[31] and about 106 kg CO_2 for an electric sedan.[32] At a vehicle stock level—i.e., considering the total number of EVs on road—the cumulative emissions mitigation impact

[29] Interestingly, the CO_2 emission intensity is found to be higher during winter months than in other seasons. This can be attributed to lower wind power generation (due to fall in wind speed), less generation from some large hydropower plants (due to less water flow in snow-fed rivers), and decline in solar contribution (due to shorter daytime). The total absolute CO_2 emissions (tonnes of CO_2) are not necessarily high in winter as total electricity consumption is lower than, for example, during summer months.

[30] Variation in carbon burden of electricity with the power supply portfolios of distribution utilities is also a factor, as demonstrated before. However, currently it is not possible to study time-of-day CO_2 emission intensity profiles of states or distribution licensees due to a lack of real-time electricity supply mix data.

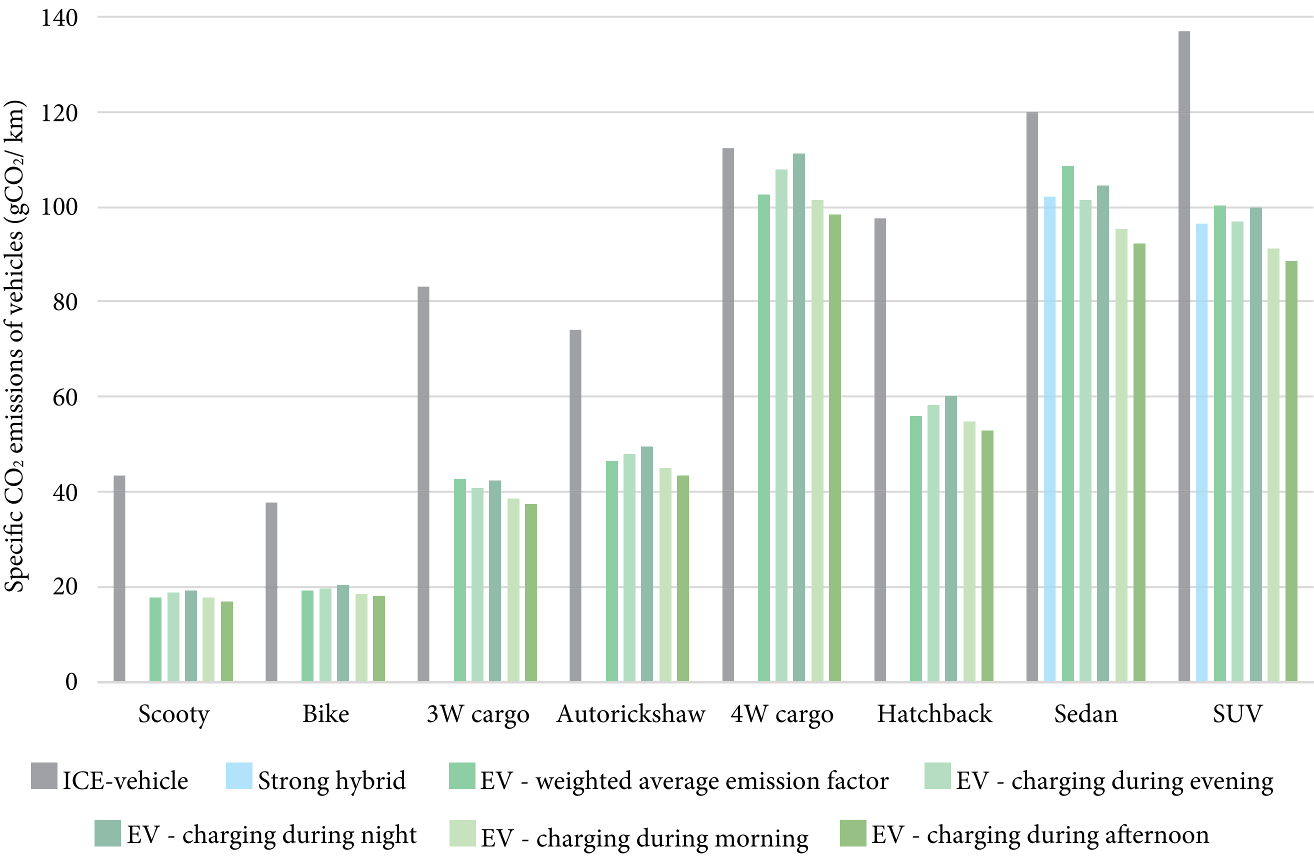
[31] Based on daily vehicle kilometre (vkm) of 17 kms for two-wheeled vehicles. Daily vkm refers to the distance travelled by a vehicle in a day.

[32] Based on daily vkm of 32 kms for cars.

from ToD charging of EVs is quite significant. To put this into perspective, based on the possible total number of electric two-wheeled vehicles and electric cars on road in India as on March 31, 2023,[33] mid-day or afternoon charging of these EVs could help avoid about 20 kilotonnes of CO_2 ($ktCO_2$) emissions more in a year as compared to evening charging. The benefit of day-time charging is even more in contrast to night-time charging. The opportunity to avoid GHG emissions would be increasingly lopsided in future as the share of VRE, especially solar, rises at a fast pace.

The importance of daytime charging cannot be overstated in case of electric buses (e-buses). As evident from Figure 11, the climate benefit of e-bus operation is contingent on whether the fleet is charged during the daytime. As in the case of other EV segments, afternoon charging is particularly beneficial for greater CO_2 emission reduction. Conversely, evening- and night-time charging that meets the bulk of the charging requirement of an e-bus fleet–as far as current charging practice is concerned–is likely to result in similar or even greater CO_2 emissions than ICE-buses. This implies that daytime charging is a make-or-break proposition to realise real CO_2 emissions abatement through bus fleet electrification.

Figure 10: Impact of Time-of-Day Grid Electricity Emissions Intensity on Specific Emissions of EVs at National Level (Excluding e-Buses)



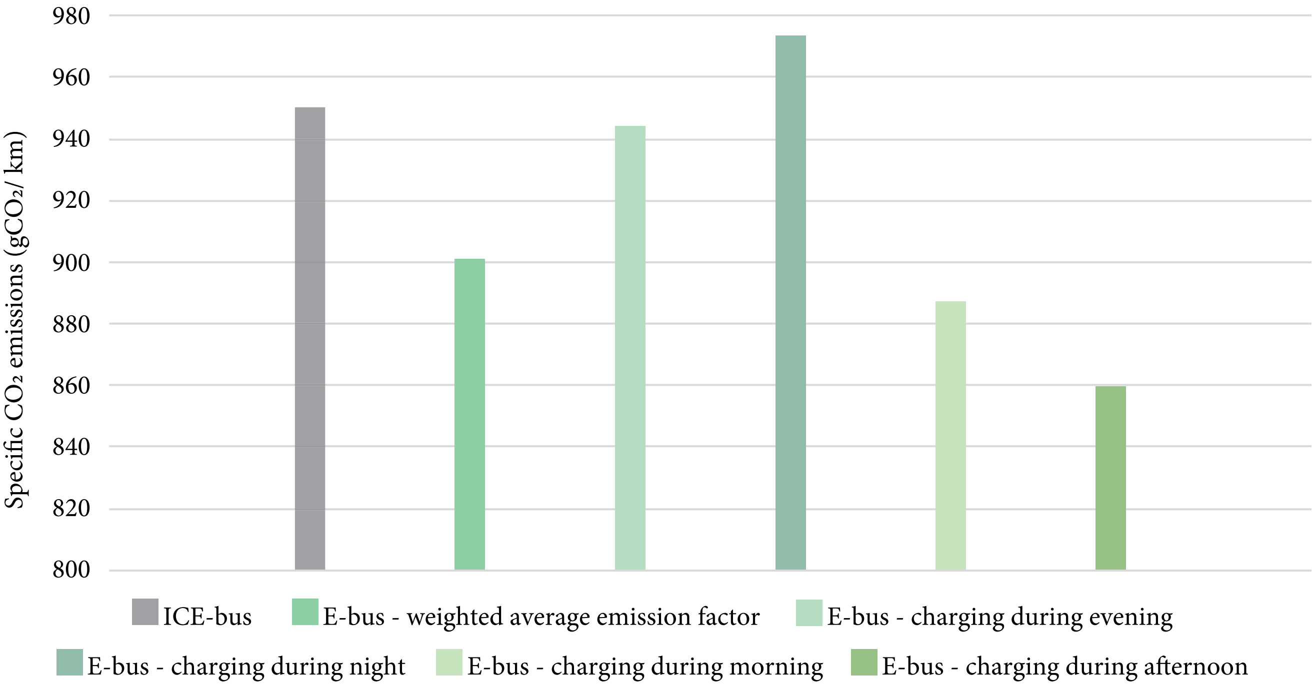
Source: Author's analysis.

Note:

- *Emission factor refers to the one published by CEA in FY 2021-2022.*
- *This study considers that evening, night, morning, and afternoon span from 6 p.m. to 11:59 p.m., 12 a.m. to 5:59 a.m., 6 a.m. to 11:59 a.m., and 12 p.m. to 5:59 p.m. respectively.*

[33] As per Vahan dashboard, about 10,85,748 electric two-wheeled vehicles and around 77,896 electric cars have been registered in India from FY 2016 till FY 2023.

Figure 11: Impact of Time-of-Day Grid Electricity Emissions Intensity on Specific Emissions of e-Buses at National Level



Source: Author's analysis.

Moreover, e-bus operation can potentially offer significant climate dividends compared to other EV segments if low-carbon electricity is fed for charging. For example, an e-bus in India can potentially help avoid 40 times more CO_2 emissions in a year than an electric two-wheeled vehicle.[34] Considering the need for transport during the daytime, it is challenging to align e-bus charging with solar hours. However, it is still relevant to operate e-buses during the day, given the potential benefits from shifting commuters from private motorised vehicles to public bus transport.

It is unequivocally clear that ToD emission intensity of grid electricity has a major bearing on the actual CO_2 emissions of EVs across segments, and daytime charging is essential to tap the climate benefit of vehicle electrification. Considering that EV charging sessions are presently evening and night-time heavy, one may infer that the ability of the deployed battery-driven vehicles to reduce GHG emissions is severely handicapped.

6. How the Future of India's Power Sector Augurs for EVs

Considering the source of the electrons to charge EV batteries is presently carbon heavy in India, the ability of EVs to decarbonise motorised road transport is contingent on the future energy transition in the country's electricity sector.

6.1 Desired Electricity Supply-Mix in Future

The future of India's electricity sector is likely to be shaped by the country's climate goals and objective to meet rising power demand, particularly the peak demand. This paper does not delve into projecting a possible electricity supply mix in a future year and the consequent grid electricity emission factor. Instead, the study takes into account power sector roadmaps published by a relevant authority. The National Electricity Plan published by the CEA in May 2023 is

[34] Average daily distance travelled by a bus is considered 200 km according to the requirements stipulated in many of the current e-bus service procurement tenders.

considered a fulcrum reference document in this regard. As stipulated by India's Electricity Act, 2003, CEA prepares and notifies a National Electricity Plan once in five years that indicates a five-year path forward while giving a longer-term perspective.

The Plan estimates a requirement of 349.7 GW of non-fossil-fuel-based installed power generation capacity by FY 2026–2027 and subsequently 616.1 GW of capacity by FY 2031–2032 (refer to Appendix–C for more details). This means that the share of non-fossil-fuel in total installed generation capacity would have to be about 57% and 68% in FY 2026–2027 and FY 2031–2032, respectively. As a sub-component of non-fossil-fuel-based capacity, VRE sources are projected to account for about 43.3% and 54.6% of India's total generation capacity by FY 2026–2027 and FY 2031–2032, respectively. These are significant jumps from the FY 2022–2023 level of 28% (approximately 43% considering all non-fossil-fuel sources) when the VRE capacity was reportedly about 114 GW (India's Climate and Energy Dashboard, 2024b). How does this reflect on the future emission factor of India's grid electricity?

Based on the required installed generation capacity of different sources, the National Electricity Plan projects that non-fossil-fuel sources would contribute around 38.9% and 48.7% of the country's cumulative gross electricity generation in FY 2026–2027 and FY 2031–2032 respectively (refer to Table 1). In FY 2022-2023, the share was about 25% (India's Climate and Energy Dashboard, 2024a). VRE's share too is expected to grow and would reach approximately 24.3% and 34.7% in FY 2026–2027 and FY 2031–2032 respectively from the FY 2022–23 level of 11.4%.

With the significant increase—by as much as 56% by FY 2026–2027 and 95% by FY 2031–2032 compared to FY 2022–2023—in the share of non-fossil-fuel-based electricity, the carbon burden of India's grid electricity is bound to decrease, which will result in a lower annual average emission factor. **The Plan estimates that the annual national average emission factor is expected to reduce to 548 gCO_2/kWh in FY 2026–2027 and to 430 gCO_2/kWh in FY 2031–2032** (Central Electricity Authority, 2023). In FY 2021–2022, it was 715 gCO_2 per kWh. These drastic reductions—23% by FY 2026–2027 and nearly 40% by FY 2031–2032—in annual average emission factor are contingent on the timely achievement of the required installed power generation capacities of the given energy sources and subsequently actual electricity generation. What does this sharp declining trajectory of grid electricity emission factor mean for EVs?

Table 1: Projected Gross Electricity Generation in FY 2026-2027 and FY 2031-2032 and Contribution of Non-Fossil-Fuel Sources

Energy Resource	Gross Generation in FY 2027 (TWh)	Gross Generation in FY 2032 (TWh)
Cumulative based on fossil-fuel and non-fossil-fuel sources	**2,025** (100%)	**2,665.7** (100%)
Solar PV	339.3 (16.8%)	665.6 (25%)
Wind	153.5 (7.6%)	258.1 (9.7%)
Hydro*	207.7 (10.3%)	246.2 (9.2%)
Other renewable sources	9.1 (0.4%)	10 (0.4%)
Nuclear	77.9 (3.8%)	117.6 (4.4%)
Total non-fossil-fuel-based	**787.5 (38.9%)**	**1,297.5 (48.7%)**
Total VRE-based	**492.8 (24.3%)**	**923.7 (34.7%)**

**Generation from hydro includes imported hydroelectricity.*

Source: National Electricity Plan 2022-2032 (Central Electricity Authority, 2023).

Note:

- *Terawatt-hour (TWh) is a unit of amount of electricity. 1 TWh is equal to 10^9 times of 1 kWh of electricity.*
- *Figures in brackets indicate the share of gross electricity generation from the listed energy sources in India's cumulative gross generation in a given year. Cumulative generation accounts for both fossil-fuel and non-fossil-fuel sources.*

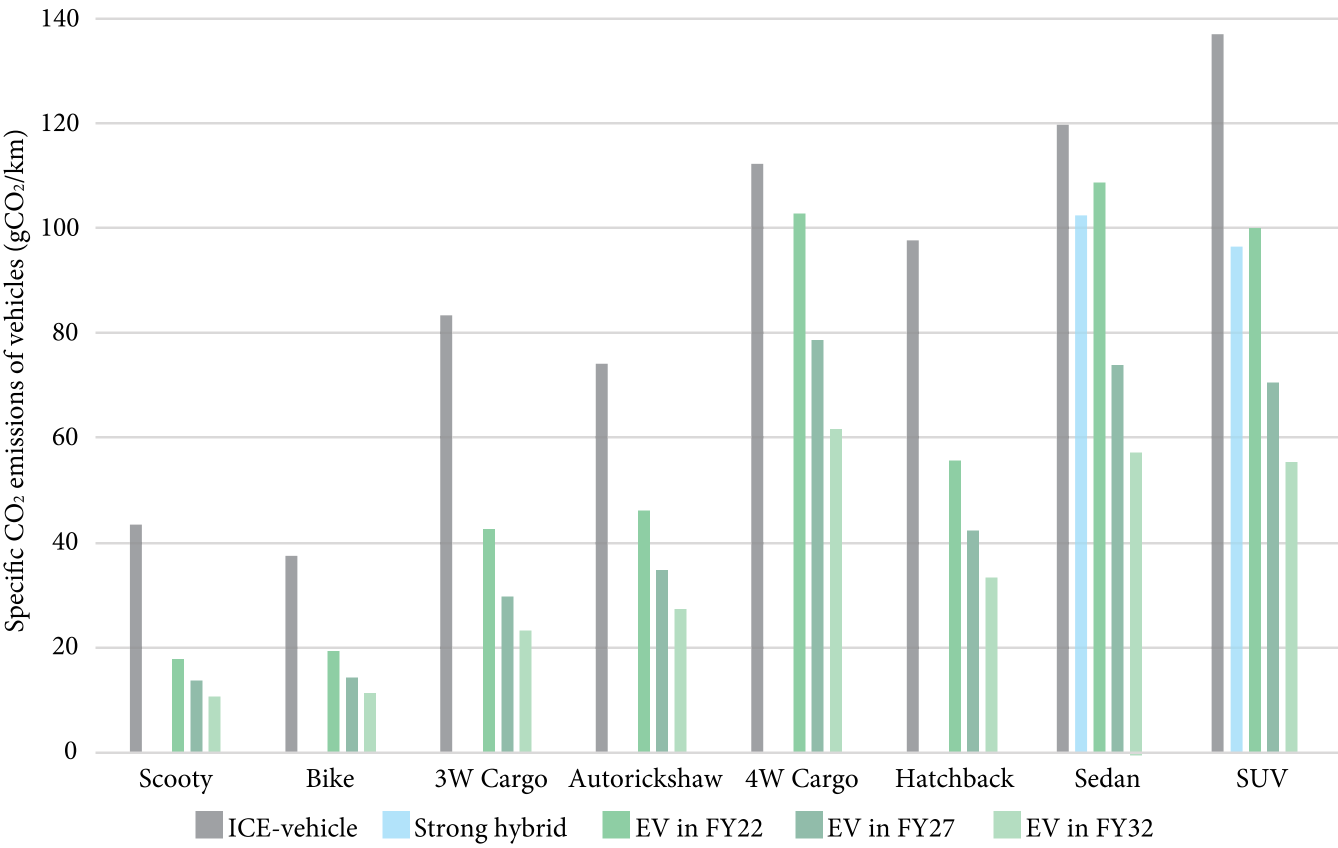
6.2 Rapid Fall in Grid Electricity Emission Intensity Great for Transport Decarbonisation

This study assesses how the possible decrease in annual average emission factor of grid electricity leads to improved CO_2 reduction in road transport due to EV deployment. To this end, the present-day vehicle models, both electric and conventional, are considered as the reference vehicles. Figure 12 compares per km CO_2 emissions (i.e., specific emissions) of EVs with ICE and strong hybrid vehicles across different segments. The comparison takes into account the as-is (as in FY 2021–2022) and the CEA-projected future annual average grid electricity emission factors.

In segments where EVs are already able to reduce CO_2 emissions compared to conventional variants, the mitigation potential improves. For example, an electric scooter will potentially avoid 16% more CO_2 emissions in FY 2026–2027, increasing to 27% in FY 2031–2032, compared to the current level of avoided emissions. In the case of electric SUVs and electric sedans, the possible sharp decline in the annual average emission factor of grid electricity becomes a game-changer.

While CO_2 emissions of electric variants of sedans and SUVs are slightly higher than those of strong hybrid versions at a national level in the current scenario, only a 6% decrease in the annual average electricity emission factor from the FY 2021–2022 level—that is, when the emission intensity of electricity reaches 672 gCO_2/kWh—negates the emission advantage of strong hybrids. This means that, provided the annual average emission intensity of grid electricity follows the projected declining trajectory, within this decade, electric drivetrains across all vehicle segments would be the most climate-friendly alternative among mainstream options,[35] as one can see in Figure 12. However, these

Figure 12: Specific CO_2 Emissions of EVs vis-à-vis Conventional Vehicles in as-is and Future Electricity Supply-Mix Scenarios



Source: Author's analysis.

[35] These include ICE and strong hybrid vehicles, if applicable, along with EVs.

estimations are inherently flawed since the annual average value of grid electricity emission intensity masks its large temporal variation.[36] Interestingly, in the as-is case, the average hourly CO_2 emission intensity of grid electricity between 11:00 AM and 4:00 PM is found to be 667 gCO_2/kWh. This implies that midday charging potentially allows electric cars to overtake strong hybrids even today in terms of reducing emissions in the true sense.

The impact of decarbonisation of grid electricity is more pronounced in case of large vehicle form-factors like buses. An e-bus, which is currently able to reduce about 3.6 tCO_2 of emissions annually (based on weighted average emission factor of grid electricity at the national level), can avoid five times greater emissions in FY 2026–2027 and eight times in FY 2031–2032.

Clearly, the ability of EVs to offer significant GHG abatement opportunity in this decade is predicated on the rapid increase in the share of non-fossil-fuel-based electricity.

6.3 Challenges to Achieve the Desired Impact

The potential opportunity to decarbonise motorised road transport through vehicle electrification is inextricably tied with the future electricity supply-mix. India has adopted an aggressive goal of increasing the generation capacity of renewable energy by this decade, which is reflected in the National Electricity Plan.

To reach the 2027 target for non-fossil-fuel-based capacity, the country has to achieve the installation of almost 43 GW every year on average from FY 2023–2024 till FY 2026–2027, out of which about 30 GW in solar photovoltaic (PV) and 7.6 GW in wind. If one considers the progress made since FY 2017–2018 till FY 2022–2023, i.e., in the past five years, India has been able to add around 11.5 GW of non-fossil-fuel-based capacity (9 GW solar PV and 1.7 GW wind) annually. This means that, at least in the next four years, almost four-fold higher capacity addition has to be realised each year compared to the last five-year average. In the last two years, i.e., FY 2021–2022 and FY 2022–2023, the annual clean energy capacity addition is found to be gathering steam, but it is still less than the required run rate. There is limited run-way available to accelerate.

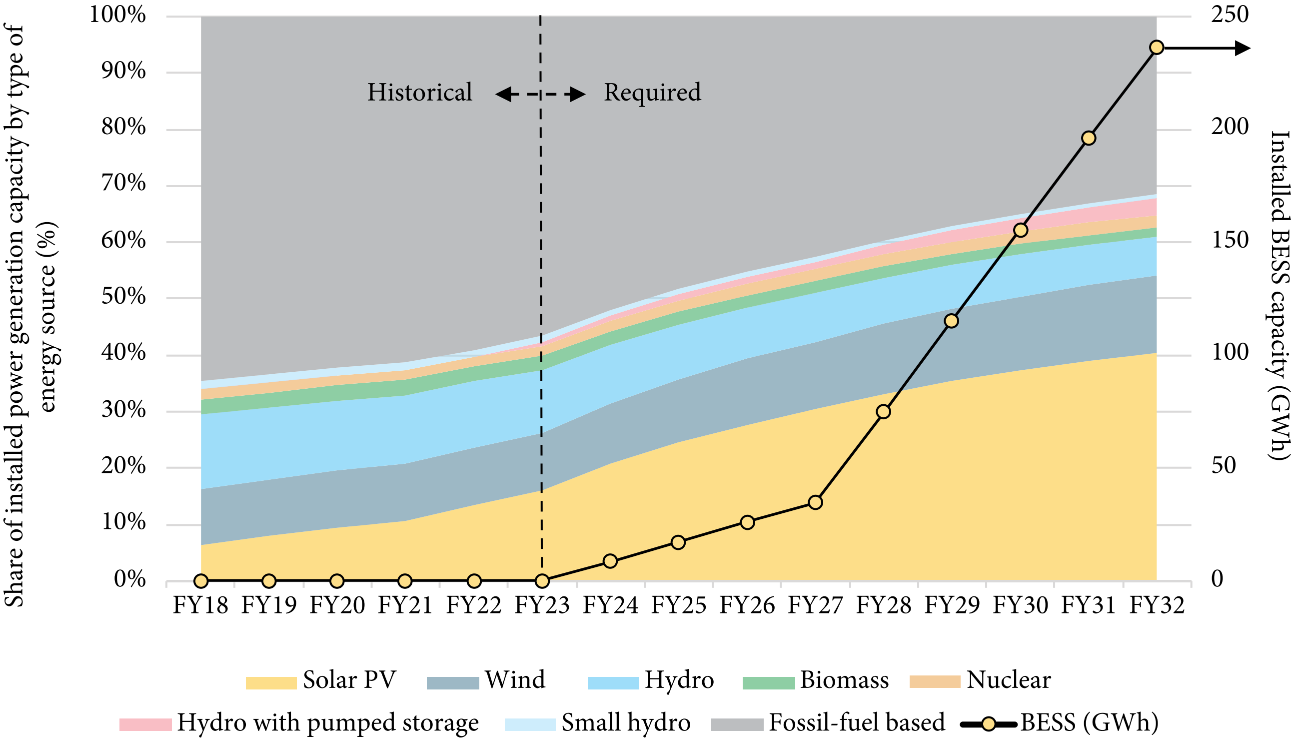
Assuming FY 2026-2027 generation capacity target is achieved, to reach to the FY 2031-2032 milestone, the country will have to materialise even greater yearly addition, on an average of 53 GW of non-fossil-fuel-based capacity, out of which almost 36 GW and 10 GW are in terms of solar PV and wind respectively. This steeper-than-current growth trajectory for non-fossil-fuel-based generation capacity is discernible from Figure 13.

Making EV charging truly low carbon potentially faces a greater barrier as the daily distribution of renewable energy supply would be heavily skewed towards midday owing to the greater share of solar energy. As flagged previously, evening and night-time are when the majority of EVs get charged. Without utility-scale energy storage, these are the times when the share of VRE considerably declines. The impact of this temporal variation in VRE supply is already seen in the case of the hourly profile of CO_2 emission intensity (gCO_2/kWh) of grid electricity.

To put this into perspective, the maximum hourly emission intensity is currently found to be 19% higher than the minimum when the share of solar PV in total yearly electricity supply (in terms of kWh) is around 6.32%. This difference in hourly emission intensity is expected to accentuate as the share of solar energy supply nearly triples to reach about 17% by FY 2026–2027 and quadruples by FY 2031–2032 from the present level. Therefore, unless adequately complemented by pumped storage and battery energy storage capacities, the midday drop in net demand—i.e., the total power demand (MW) at a given time minus the power supply from VRE—is going to be steeper in the next 10-odd years, and the availability of zero-carbon electricity during the rest of the day will remain limited (refer to Appendix–D for more details about possible net demand in a high VRE scenario).

[36] CSEP has taken up an initiative to project future ToD emission curve based on the planned generation capacity additions.

Figure 13: Historical and Required Power Generation Capacity Mix



Source: Author's analysis.

Note:

- *Historical installed power generation capacity data are sourced from India's Climate and Energy Dashboard (2024b).*
- *According to a 2023 study by The Energy and Resources Institute, six hydro projects are operating in pumping mode (Shankar, Saxena, & Mazumdar, 2023).*
- *Battery energy storage systems (BESS) installed at the renewable energy generation sites have been considered here.*

Currently, the capacity of pumped reservoirs of hydropower plants is negligible. The 3.3 GW cumulative power generation capacity of hydropower plants with pumped storage is supported by a small pumped-reservoir capacity. Also, there is no grid-scale VRE-integrated BESS in operation until now. From this level of energy storage capacity, the National Electricity Plan envisages a requirement of 7.5 GW of hydropower with pumped storage and 34.7 GWh of BESS by FY 2026–2027. The storage capacity requirements between FY 2026–2027 and FY 2031–2032 go up over three times for pumped hydro and nearly sevenfold for BESS. These are very steep requirements to fulfil in the given time. This study does not evaluate how much and how long the proposed storage capacity additions will be able to supply VRE during non-solar hours daily all year round. Unless the carbon load of grid electricity is brought down considerably during evening and nighttime or the bulk of EV charging demand is shifted to solar hours, it would be challenging to unlock the climate benefit of vehicle electrification despite the potential sharp fall in the annual average CO_2 emission factor of India's grid electricity in the next 10-odd years.

There is another perspective to evaluating GHG mitigation potential of EVs in India's context. The common notion that shifting variable power demand like EV charging to high VRE hours of the day leads to greater renewable energy offtake may not be true unless the net-demand bottoms out. In the case of India, thermal power plants complemented by large hydro are usually the 'swing' producer, which means to meet real-time incremental power demand, coal-based thermal power is often the lever for incremental electricity supply[37] (Tongia, 2023). Renewable energy has a 'must-run' status in the country[38] and, therefore, change in power demand does not impact its offtake. This implies that any increase in electricity

[37] Due to very limited natural gas availability for power generation and inadequate surplus reservoir capacity of the large hydro power plants.
[38] Subject to grid stability requirements.

consumption, be it in the form of EV charging even during daytime, is likely to result in a greater need for coal-based thermal power until renewable energy reaches surplus and curtailment stage.

7. Conclusion: Major Findings and Policy-Relevant Recommendations

The range of analyses on operational GHG emissions of EVs vis-à-vis conventional vehicles in different contexts leads to several major findings and in turn, warrants some key policy actions.

7.1 Key Findings

Following are the 10 major outcomes of this research:

- The climate dividends from the energy efficiency superiority of EVs over ICE and strong hybrid vehicles are diminished significantly by the current coal-dominated supply mix of India's grid electricity. This is especially conspicuous when the electric format is pitted against the strong hybrid version in the sedan and SUV segments.

- The electricity supply blend across the country is not homogeneous owing to the varied power procurement baskets of distribution utilities (licensees). Electricity supplied in Kolkata, Pune, and Mumbai is more carbon intensive than the national average, while Bengaluru has the greenest power among the sampled nine cities. Consequently, CO_2 emissions from EV charging differ considerably from one city or state to another.

- The rapid rise in the share of VRE, especially solar, and the absence of long-duration energy storage capacity potentially skews the daily distribution of low-carbon electricity. Emissions calculations based on the annual average emission factor of grid electricity mask the impact of temporal variation in electricity supply mix, which is especially important in the case of a dynamic load like EV charging.

- Considering the majority of EV charging sessions occur during the evening and night-time when the share of renewable energy plummets, the ability of EVs to decarbonise India's motorised road transport needs to be properly qualified. There is an urgent need for interventions to encourage and enable daytime alignment of EV charging.

- The importance of daytime charging cannot be overstated in case of e-buses. Evening and night-time charging that meets bulk of the charging requirement of an e-bus fleet currently is likely to cause similar or even greater CO_2 emissions than conventional buses.

- Two-wheeled and three-wheeled EVs are found to emit less CO_2 emissions than their ICE-counterparts even when they are charged during the evening or night. Alignment of their charging with solar hours potentially offers significant emission cuts.

- Provided future power generation capacity addition follows the projected low-carbon trajectory, as per the National Electricity Plan, within this decade vehicles with electric drivetrain will be able to curb GHG emissions across all vehicle segments.[39] Interestingly midday charging gives EVs a similar emissions edge over conventional vehicles even today.

- Solar-heavy decarbonisation efforts in the power sector will be a challenge for making EV charging green unless adequately complemented by long-duration energy storage capacities.

- The conditional climate benefit of vehicle electrification is valid for other types of electricity end-uses too, particularly one with a variable daily demand profile like residential electricity consumption.

- EVs can potentially enhance their energy efficiency supremacy over conventional vehicles in the coming years on the back of improvement in the energy density of EV batteries and increased efficiency of electric drivetrains, whereas realisable improvement in fuel economy of ICE powertrains has almost plateaued.

Based on the range of insights into the real or conditional opportunity to avoid GHG emissions through EV transition, and the associated challenges, ministries, regulators, and implementing authorities at both Central and State levels may be able to take more informed policy decisions.

[39] This is with a caveat that the highly skewed daily profile of renewable energy availability due to VRE and lack of flexibility of charging demand to shift to solar hours may pose a major challenge.

7.2 Action Points

A major goal of transitioning to vehicles with electric drivetrain is to decarbonise motorised road transport. This study examines the ability of EVs to offer deep and credible emission cuts in the Indian context. Based on the above findings, the research proposes the following 10 possible interventions.

- State Electricity Regulatory Commissions (SERCs) should introduce ToD electricity tariffs for EV-metered connections. The tariffs should be designed in a way that incentivises charging when the share of renewable energy in the supplied electricity is high and discourages electricity consumption during low renewable energy hours.[40] The ToD tariff regime should be tailored according to the daily and seasonal electricity supply mix profile of a distribution utility considering the wide utility- or state-level differences in power procurement baskets. One risk to consider is whether consumers would opt for separate EV-metered connections versus charge EVs with their existing regular residential connections.

- State nodal agencies for charging infrastructure should fast-track public charging infrastructure rollout, especially at business districts, transit nodes,[41] and community centres and marketplaces. This is likely to encourage daytime charging of EVs.

- Policies and regulations should provide a level playing field to battery swapping, which entails interchanging drained-out EV batteries with charged ones, to position it as a mainstream public charging solution (along with plug-in charging). Swapping gives the flexibility to charge EV batteries during the daytime without requiring the EVs to be parked for that period.[42] However, its application is likely to remain limited to electric two-wheeled and electric three-wheeled vehicles due to practical reasons. Swapping also requires a larger pool of batteries and is a more expensive solution compared to plug-in charging of EVs during high renewable energy hours.

- SERCs should bring necessary regulations to promote innovative renewable-energy-as-a-service models to facilitate meeting electricity requirements of a charging facility by renewable energy cost-effectively. Variants of net metering, namely Group Net Metering and Virtual Net Metering, are practical solutions to overcome the limitations in the case of on-site renewable energy generation.[43] End-of-mobility-life batteries can be an affordable and sustainable energy storage solution at the charging stations for storing and delivering clean energy from distributed renewable energy resources.

- Policymakers should focus on scaling up utility-scale renewable energy capacity, integrated with long-duration energy storage to make clean energy available during non-solar hours. This is a lasting solution for reducing the carbon footprint of EV use in the country.

- SERCs should strictly enforce Renewable Purchase Obligation (RPO) targets, both solar and non-solar, and ensure that the respective distribution utilities' power procurement plans adhere to the obligations.

- Bureau of Energy Efficiency (BEE) should assess the specific CO_2 emissions (gCO_2/km) of electric passenger cars based on the latest applicable grid electricity emission factor while checking compliance of upcoming CAFE-III and CAFE-IV norms[44] by the automakers. More stringent CO_2 emission targets should be set for the CAFE cycles.[45] Also, there is a need to rationalise the proposed Super Credits for EVs. Credits should

[40] ToD tariffs are an effective near-term intervention. However, this may induce high concentration of EV charging to specific hours, which may result in a surge in power demand (often localised) causing overloading and high energy loss at the distribution network level. Staggering the tariff rebate with time is a possible solution to this.

[41] For example, metro and suburban railway stations.

[42] Decrease in operational GHG emissions through battery swapping may not guarantee reduced life-cycle emissions considering more than one battery is usually required per EV.

[43] Integrating charging infrastructure with on-site renewable energy (e.g. solar PV system) may not be an effective way to charge EVs with renewable electricity unless supported by BESS, considering the intermittency in EV charging requirement during daytime and practical difficulties to generate electricity at the site (e.g. shading issues). Owing to some of these challenges, Green Energy Open Access too does not guarantee offtake of renewable energy for charging.

[44] Imposed on a carmaker's entire production fleet, and not on an individual model, Corporate Average Fuel Economy (CAFE) is a limit set on the total emissions of CO_2 produced. These norms force manufacturers to make more efficient cars, which impacts many other things.

[45] With only 9% EV sales, an automaker can fulfil the CAFE-III requirement over the period 2027-2032 as per the analysis done by India Energy & Climate Center.

only be allowed to the models that overachieve a set emission threshold specific to EVs.

- A CAFE regime with differentiated CO_2 emissions targets by vehicle-type (form-factor) should be introduced to cover other segments, particularly heavy-duty vehicles (with a gross weight of minimum 12 tonnes) because of their outsized emissions impact.
- BEE should make existing "Standard and Labelling" programme for high-energy lithium-ion traction battery packs and systems mandatory. It should also set progressive labelling standards to avoid circulation of inefficient battery packs in the market.
- The Ministry of Road Transport and Highways should only allow type approval of vehicles based on Worldwide Harmonised Light Vehicles Test Procedure (WLTP). This procedure includes as many actual driving conditions as possible and hence, provides a closer to real-world vehicle performance results than the existing Modified Indian Driving Cycle (MIDC) regime.[46]

Other actors also have their roles cut out. Distribution utilities should acknowledge that the success of reducing the country's electricity emission intensity rests on their collective effort. They should monitor the temporal pattern of EV charging demand (recorded through EV-metered connections) pre and post implementation of ToD tariffs to evaluate the tariff impact. Being more informed by this study, EV fleet operators should be receptive to the idea of bringing EV charging under the ToD tariff regime.

Automobile manufacturers too may find this research helpful in charting their future strategies in terms of whether to prioritise investment in developing EV-line of product offerings and launching new EV models with improved energy efficiencies.

The study helps flag and address deliberate or uninformed attempts at greenwashing by some players (e.g., claiming zero-carbon footprint of a fleet operation just by switching to EVs even when the latter is primarily charged with grid electricity during evening).

Finally, this investigation helps address the misgivings among the public about whether EVs are a cleaner alternative and influence the charging behaviour of EV users to an extent.

[46] BEE has proposed to switch to WLTP from MIDC effective from March 31, 2027.

Appendix

Appendix A: Other Alternative Vehicle Powertrain and Fuel Options

Mild hybrids and plug-in hybrids are not part of this assessment. Mild hybrid models have not been considered for comparison because of their limited fuel-economy-related difference vis-à-vis pure ICE car models (Autocar India, 2022). A mild hybrid vehicle is propelled by an engine and an electric motor. The vehicle cannot run solely on electric power. The latter can only assist the engine by providing short bursts of torque. While a vehicle may have regenerative braking, mild hybrid technology does not offer substantially improved fuel efficiency or emission reductions. Plug-in hybrid cars are also not part of this assessment. Currently, plug-in hybrid is not a mainstream vehicle technology in the Indian market. There is also apprehension regarding its real CO_2 mitigation benefit. Because of the easy option to switch to liquid fuel during driving whenever the user wants, it is hard to ensure that the battery of the vehicle is the major source of energy for the car. According to the European Court of Auditors, the average gap between lab-tested and real-world emissions from a plug-in hybrid car is 250% (European Court of Auditors, 2024).

Futuristic vehicle technologies like fuel-cell powertrains, flex-fuel engines, etc. are not part of the scope of this study. Fuel cells work like batteries to produce electricity and heat, except the cells do not require recharging. Instead, fuel such as hydrogen has to be replenished. A flex-fuel engine is an internal combustion engine that is designed to run on a combination of petrol and ethanol or methanol in any ratio of mix.

E20 petrol, which is a blended petrol having 20% anhydrous ethanol by volume, is an alternative motor vehicle fuel currently available in some fuel refilling stations in India. E20 helps reduce the share of fossil-fuel in the motor vehicle fuel for petrol-based cars and two-wheeled vehicles. However, fuel efficiency reportedly decreases by about 7% and 4% in the case of four-wheeled and two-wheeled vehicles, respectively (NITI Aayog & Ministry of Petroleum and Natural Gas, 2021). The source of ethanol used in blending in the country is primarily molasses made from sugarcane, and not agricultural residues or any waste. *Roadmap for Ethanol Blending in India 2020–25* prepared by NITI Aayog and the Ministry of Petroleum and Natural Gas highlights the potential to reduce vehicular emissions such as carbon monoxide, hydrocarbons, and oxides of nitrogen only. There is no clear reference to GHG emission abatement opportunity. The roadmap also flags the possibility of negative ecological impacts due to the current sourcing of ethanol. It mentions that the task force on sugarcane and the sugar industry constituted under the Chairmanship of Professor Ramesh Chand, Member (Agriculture), NITI Aayog, emphasised the need to move to environmentally sustainable crops for ethanol production, such as maize, and promote second-generation biofuels with suitable technological innovations. According to the task force, sugarcane and paddy combined are using 70% of the country's irrigation water, thus depleting water availability for other crops.

Like in the case of any biofuel use, to assess the GHG mitigation potential from fuel-switch to E20, a well-to-wheel approach has to be adopted, taking into account the source(s) of the ethanol and GHG emissions during its production. The Clean Development Mechanism (CDM) methodology, *Biofuel Production and Use for Transport Applications,* Version 3, also known as AMS-III.AK, stipulates the inclusion of biofuel production in the scope of the GHG emissions assessment of a project (United Nations Framework Convention on Climate Change, 2018). This methodology comprises project activities for cultivation or sourcing of biomass residues, seeds, crops, or waste oil/fat for the production of biofuel for use in transportation applications. In contrast, the project boundary for accounting GHG emission mitigation by EVs (and hybrid vehicles) delineated by the applicable CDM methodology, *Emission Reductions by Electric and Hybrid Vehicles,* Version 16, also known as AMS-III.C, comprises only the vehicles and the geographic area where the vehicles are operated, the charging stations and the electricity supply sources (e.g. electricity grid and/or dedicated renewable energy generation source). Project emissions include the electricity and fossil fuel consumption associated with the operation of vehicles (United Nations Framework Convention on Climate Change, 2022). This methodology applies to project activities introducing new electric and/or hybrid vehicles that displace the use of fossil fuel vehicles in passenger and freight transportation. CDM methodologies are developed under the aegis of UNFCCC and widely recognised. They provide information that is required to estimate the possible GHG emission reduction of a mitigation project activity. The CDM allows emission-reduction projects in developing countries to earn Certified Emission Reduction credits, each equivalent to one tonne of CO_2.

Since the scope of this study includes only tank-to-wheel assessment of GHG emissions for motor vehicles, the GHG emissions impact of driving vehicles on E20 has not been analysed.

Appendix B: Estimation of CO_2 Emission Intensity of Electricity in Cities

The exercise to estimate CO_2 emission intensity of electricity supplied in each of the cities is found to be complex. It peruses the true-up petitions for FY 2021–2022 or the latest available before, filed by the respective distribution utilities, to get data on power procured from different generators, generating sources or market instruments (e.g., bilateral, spot purchase, etc.). A true-up petition includes the audited reports and accounts to show an electricity distribution utility's actual financial and technical performance in terms of expenses, income, and technical losses, etc. The generators or sources mentioned in a true-up are subsequently matched with the CO_2 emission factors as given in the CEA's CO_2 Baseline Database (version 18). By weighting the corresponding CO_2 emission factors by the volume of electricity procured by the utility from the different generators or sources, the study could estimate the representative CO_2 emission intensity of the electricity supplied by the utility in the given year. In the case of the power purchased through market or other trading mechanisms, it was not possible to ascertain the source of the electricity. The CEA-published weighted average emission factor of India's grid electricity has been considered as the proxy emission intensity of this kind of electricity procurement. In a few cases where the electricity sources are not clearly mentioned in the filed true-up petitions, a similar approach has been adopted.

For cities like Delhi and Mumbai, which are catered to by more than one distribution licensee, the city-level CO_2 emission intensities have been derived by weighting the estimated emission intensities of these utilities by their respective total volumes of electricity purchased in the given year.

Appendix C: Projected Power Generation Capacity

Among different factors, the National Electricity Plan takes into account the Government's existing policies, schemes and future targets, the country's short-term and long-term demand forecast, and fuel choices based on economy (cost of supply), energy security and environmental considerations (Central Electricity Authority, 2023). Energy generation resources considered include fossil-fuel sources (including coal and lignite, and natural gas) and non-fossil-fuel sources (such as solar, wind, biomass, large and small hydro,[47] geothermal, waste-to-energy, nuclear among others). In addition, the Plan envisages requirement of pumped storage projects, battery energy storage systems, and green hydrogen.[48]

Based on the present installed power generation capacity, the capacity additions that are in the pipeline, and the need for additional power generation to meet the projected peak power demand, the Plan estimates a requirement of 349.7 GW of non-fossil-fuel based installed power generation capacity by FY 2026–2027 and subsequently 616.1 GW of capacity by FY 2031–2032. Table A-1 shows the break-up of the generation capacity by source.

With the increase in the share of non-fossil-fuel-based installed power generation capacity, the share of electricity generation from these sources is expected to rise. As a result, the emission factor of electricity on an annual basis will decrease. However, the limitation is the possible increase in actual electricity generation from non-fossil-fuel sources is not proportionate to the augmentation of their installed capacities on account of lower capacity utilisation factors of these power plants.

To put this into perspective, a coal-based thermal power plant is likely to produce a higher volume of electricity per megawatt (MW) of installed capacity than a solar or wind power plant due to the latter's generation intermittency influenced by natural or non-controllable factors.

[47] According to the policy parlance in India, small hydro power plants have generation capacities up to 25 MW. Rest (with capacities over 25 MW) are considered large hydro projects. Government has taken a policy decision to recognise hydro power projects up to 25 MW as renewable energy source.

[48] Hydrogen, a potential energy carrier which is produced using renewable energy, is regarded as green hydrogen.

Table A-1: Required Installed Power Generation Capacity by FY 2026-2027 and FY 2031-2032

Energy Resource	Capacity by FY 2027 (in GW)	Capacity by FY 2032 (in GW)
Cumulative based on fossil-fuel and non-fossil-fuel sources	**609.6** (100%)	**900.4** (100%)
Solar PV	185.6 (30.4%)	364.6 (40.5%)
Wind	72.9 (12%)	121.9 (13.5%)
Hydro*	52.4 (8.6%)	62.2 (6.9%)
Biomass	13 (2.1%)	15.5 (1.7%)
Nuclear	13.1 (2.1%)	19.7 (2.2%)
Hydro with pumped storage	7.5 (1.2%)	26.7 (3%)
Small hydro	5.2 (0.9%)	5.5 (0.6%)
Total non-fossil-fuel based	**349.7 (57.4%)**	**616.1 (68.4%)**
Total variable renewable energy based#	**263.7 (43.3%)**	**492 (54.6%)**
BESS	8.7 (34.7 GWh)	47.2 (236.2 GWh)

**In addition, India has an import contract of 5.9 GW hydro power from Nepal and Bhutan.*

#Variable renewable energy sources include solar PV, wind, and small hydro.

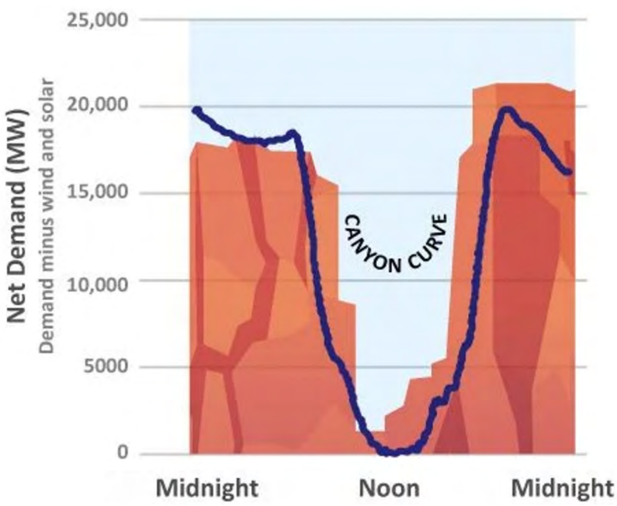
Source: National Electricity Plan 2022-32 (Central Electricity Authority, 2023).

Note: The figures in brackets indicate the shares of the installed capacities of the listed energy sources in India's cumulative installed power generation capacity in a given year. Cumulative capacity accounts both fossil-fuel and non-fossil-fuel sources.

Appendix D: Net Demand in a VRE-Heavy Power Generation Scenario

Considering the ongoing solar-heavy decarbonisation effort in India's power sector, there is a possibility that net demand may bottom out during mid-day but rise sharply during the evening and night, leading to a 'canyon' shaped daily net demand profile (refer to Figure A-1). Arshad Mansoor, President and CEO of the Electric Power Research Institute, first made this observation and also highlighted that sometime in 2023, the California Independent System Operator registered zero or negative net demand (Power, 2023). This potentially signifies that further renewable energy dispatch during midday, might face the prospect of curtailment due to oversupply and not enough demand at a given time, and the need to run coal-fired power plants at a technical minimum capacity (also known as loading, of about 55%) (Press Information Bureau, 2024). Absence of long-duration energy storage capacity and lack of demand flexibility[49] may limit the opportunity for further offtake of renewable energy. This results in skewed CO_2 emission intensity (gCO_2/kWh) of daily electricity supply—very low emissions in a certain time block followed by emission-intensive hours. This poses a major challenge from the power system decarbonisation point of view.

Figure A-1: Possible Daily Net-Demand Curve with Growing Share of Solar Energy and Lack of Storage and Demand Flexibility



Source: Power (Power, 2023).

[49] For example, the ability to shift a share of power demand from non-solar hours to solar time, so that more volume of electricity consumption is catered by renewable energy and the latter is not curtailed due to lack of demand.

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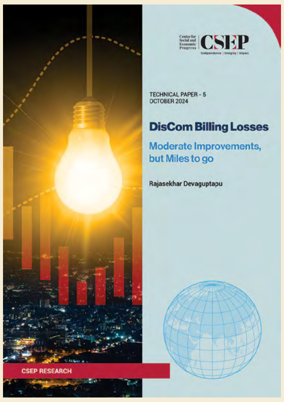
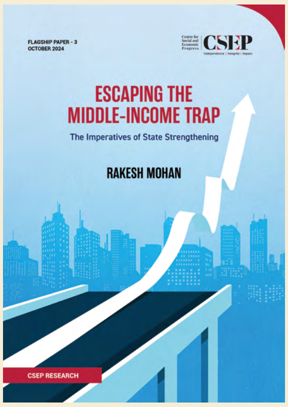
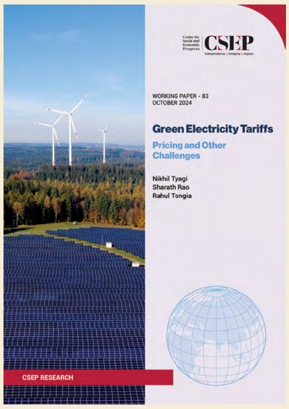
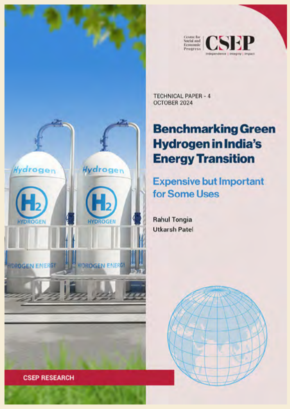
Shyamasis Das, Fellow, CSEP, has over 15 years' experience in dealing with core and cross-cutting energy and climate change issues such as energy transition, electricity distribution, mobility, demand response, emissions mitigation stocktaking, energy subsidies, etc. He has devoted past several years in understanding and decoding different aspects of electric mobility. He has led several marquee initiatives that included authoring on behalf of Ministry of Power and NITI Aayog India's first handbook on EV charging infrastructure, developing the draft Battery Swapping Policy as announced in the 2022 Union Budget speech, and carrying out the first ever study on vehicle-grid integration in Indian context. He contributed to the Clean Energy Ministerial's policy report on EVs and was invited by International Energy Agency to support GEF Global E-Mobility Programme - Managing Grid Integration of Electric Vehicles. He also has hands-on experience in carrying out greenhouse gas emissions accounting and guiding a number of mitigation projects for carbon credits registration under UNFCCC's Clean Development Mechanism.

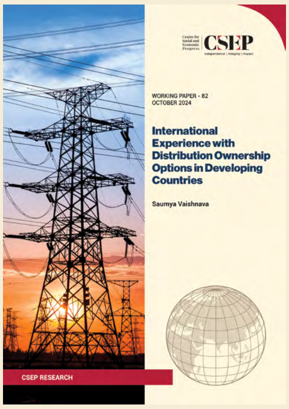
Other publications

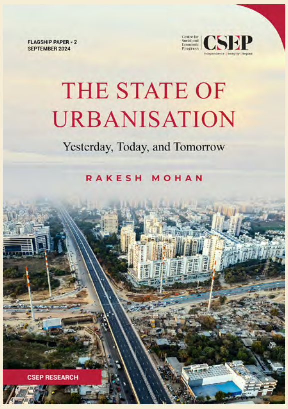


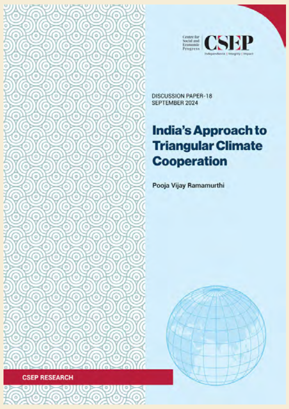


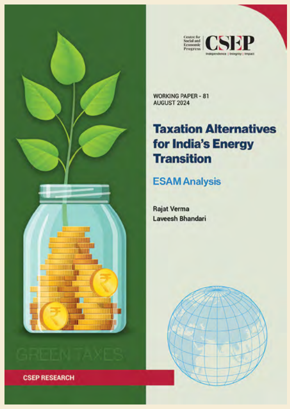


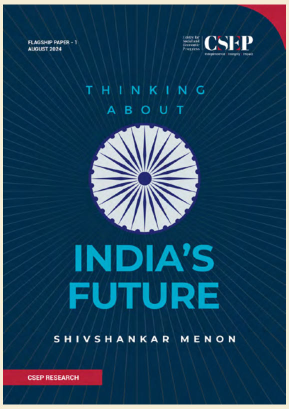


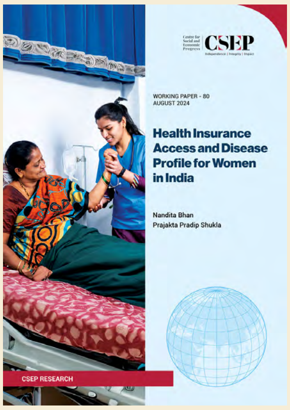


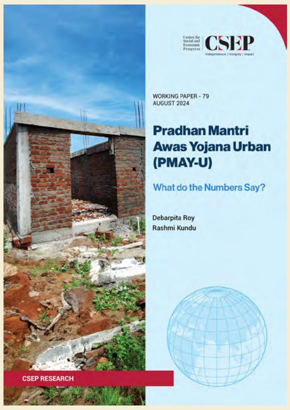


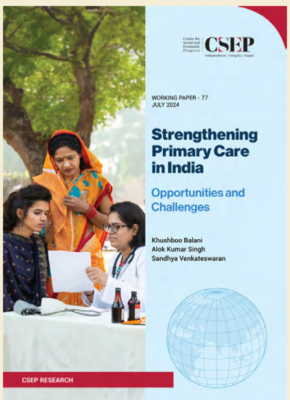


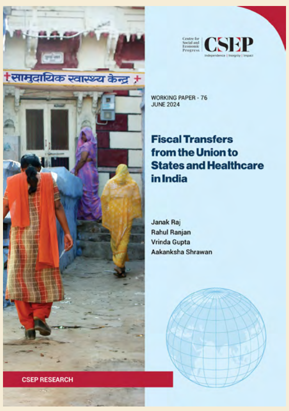


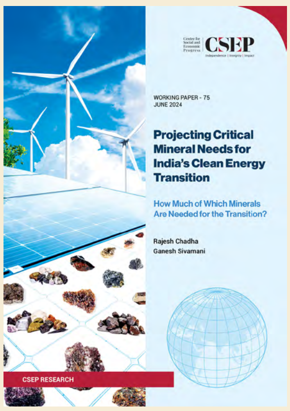


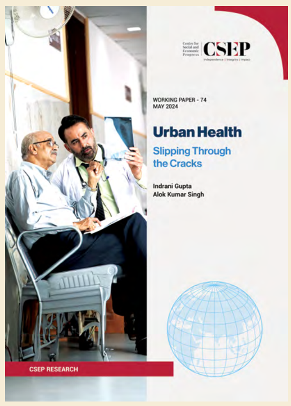












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