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Developing a Comprehensive State-level Metric for Quantifying EV GHG Emissions in India

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Executive Summary

Adopting electric vehicles (EVs) is crucial for India's efforts to reduce transport-related emissions. However, their environmental impact is influenced by the electricity grid mix, vehicle efficiency, and local climate. This study develops the Electric Vehicle Emission Index (EVEI) to compare state-wise well-to-wheel emissions of electric four-wheelers with equivalent petrol vehicles. State-wise EV emission factors and total fleet emissions are quantified using regional electricity carbon intensities, ambient temperature, and vehicle stock data. EVEI, evaluated for four EV classes, reveals that higher energy-consuming models exhibit higher emissions. Regions with EVEI exceeding 1 increase from 14 for class 1 to 28 for class 4 vehicles. Total EV emissions are highest in regions with larger fleets, particularly Maharashtra, Telangana, Karnataka, and Delhi. Finally, regions are clustered into four groups based on grid mix, EVEI, vehicle stock, and temperature, revealing regional decarbonization potentials. Findings highlight the importance of state-level strategies aligning clean energy and transport electrification.

Keywords: Electric vehicle; environmental impact; climate change; life cycle analysis.

1 Background

India, the third largest greenhouse gas (GHG) emitter in the world, faces growing pressure to reduce emissions from the transportation sector. Passenger vehicles are significant GHG contributors within the road transport sector. As per the International Council on Clean Transportation, cars and heavy commercial vehicles contribute 60% of total transport emissions, with the passenger transport sector alone contributing 56% [1]. The rapid adoption of electric vehicles (EVs) is pivotal to India's climate strategy and emission reduction goals [2]. With a target of 30% EV penetration by 2030, achieving emission reduction depends on factors like electricity grid mix, ambient temperature, and energy economy, varying significantly across regions [3]. Although EVs have zero tailpipe emissions during the operation phase, their climate impact depends on the electricity carbon intensity used for charging [4,5,6]. Upstream emissions from electricity generation significantly influence the EV environmental benefits during use-phase, particularly in fossil-fuel-reliant countries [7,8,9].

The environmental benefits of EVs are not uniform at the state level in India, due to heterogeneous grid composition and diverse climate zones. While India's central grid is fossil-fuel dependent, significant regional disparities are driven by the renewable energy shares, local generation, and reliance on imports from the central grid [10]. Previous literature has provided foundational understanding of the factors impacting EV emissions during operation. A United States study introduced the concept of the Electric Vehicle Emission Index (EVEI), a metric to evaluate the ratio of EVs' well-to-wheel CO_2 emission factor to that of conventional petrol vehicles [7]. A Chinese study has further built on this metric to analyze regional EVEI variations across Chinese provinces, considering vehicle energy economy and climate conditions [11]. However, existing Indian studies often overlook per-vehicle EV emission reductions compared to internal combustion engine vehicles (ICEVs) at the state level. This is a critical gap given the nation's heavy fossil-fuel reliance and state-wise dependence on imports from the central grid [12]. India's complex climate and variations in grid mix and battery capacities of EV models impact their energy efficiency and associated emissions. While numerous studies have assessed GHG emissions of EVs in the global and national contexts, limited research has focused on state-level variability in India. Moreover, the impact of electricity transmission losses and imports from the central grid across states is not modelled in EV well-to-wheel (WTW) emission assessments [12]. Regional EV assessments rely on standard driving cycle-based energy consumption data, underestimating real-world energy usage and emissions [10]. There is a clear gap in understanding the impact of regional electricity consumption mix, climate, and battery size on the emissions from the electric four-wheeler fleet. Most previous analyses have focused on vehicle-level assumptions [10,12], often overlooking the cumulative emissions from the growing electric four-wheeler fleet.

To address these gaps, the present study aims to develop a comprehensive state-level assessment of EV emissions from four-wheelers in India by: (i) developing an Electric Vehicle Emission Index (EVEI) that compares EV WTW emissions to equivalent petrol vehicles, (ii) estimating the total CO_2 emissions from existing electric four-wheeler stocks across Indian states and union territories (UTs), (iii) quantifying the impact of key parameters such as electricity grid mix and ambient temperature on EV emissions, and (iv) clustering states based on EVEI, grid mix, temperature and EV stock, to identify areas where EV adoption offers significant environmental benefits. Unlike previous Indian studies that use marginal emission factors requiring strong future grid assumptions [10], the present study employs the real-world carbon intensity of state electricity consumption, accounting for transmission losses and import dependence on the central grid. The study insights will help policymakers design targeted regional decarbonization pathways, aligning with local electricity profiles and accelerating EV deployment.

2 Data and Methods

This study first employs a WTW life cycle assessment model to develop state-level EV CO_2 emission factors across India, considering regional electricity grid and real-world vehicle energy consumption. The study then develops an EVEI metric to compare the WTW emissions of EVs against an equivalent petrol vehicle for four vehicle types, as shown in **Table 1**. Then, a vehicle fleet and emission model is used to estimate the total annual electric four-wheeler emissions across states. Finally, a clustering analysis is employed to classify states with similar emission and grid profiles, based on multiple state-specific parameters. The detailed emission assessment methodology is shown in **Figure 1**.

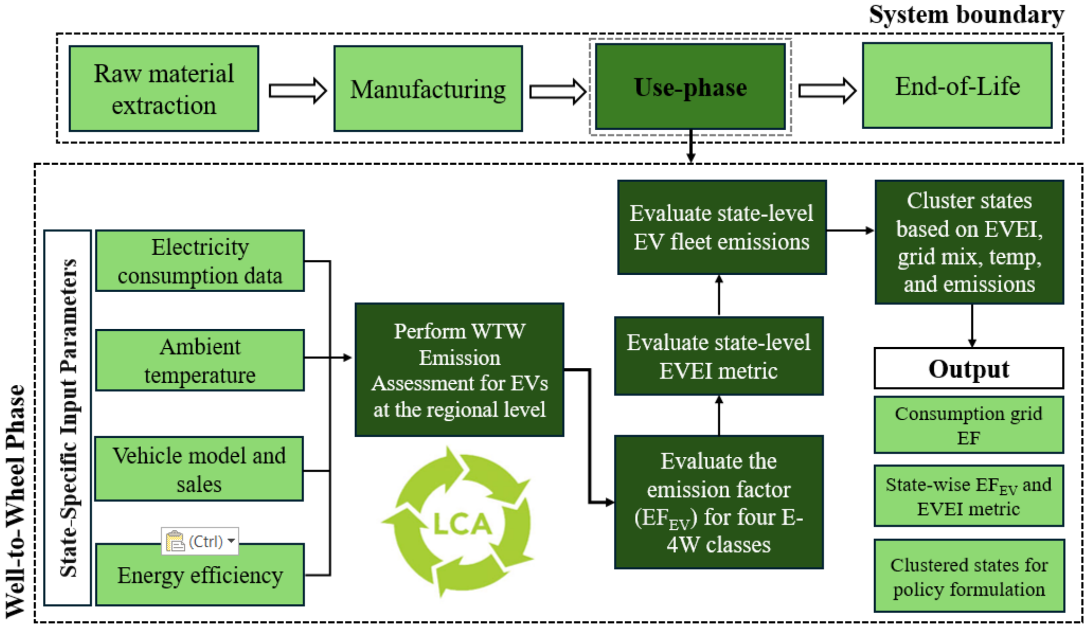

Fig 1. Detailed methodology adopted in this study.

2.1. WTW emission assessment model

The scope of the study is limited to the operational phase of an electric vehicle, particularly the WTW phase. Although the technical characteristics of EV batteries, like energy density and battery degradation, influence real-world energy consumption [13], the present study excluded them. The study uses data for the WTW emission analysis from various publicly available and validated datasets, as shown in **Table 1**. Four electric and petrol four-wheeler models with different weights and battery sizes are considered for the emission assessment, as shown in **Table 2.**

Table 1. Technical specifications of EV and ICEV models used in this study.

Vehicle EV	Weight	Battery	Range (ARAI)	Range (Real-World)	Equivalent ICEV	Weight	Mileage (ARAI)	Mileage (Real-World)	Class
MG Comet	815 kg	17.3 kWh	230 km	182 km	**Maruti Suzuki Alto**	790 kg	24.9 km/l	20 km/l	1
Tiago EV	1235 kg	24 kWh	315 km	214 km	**Tiago Petrol**	935 kg	20.1 km/l	17 km/l	2
Nexon EV	1400 kg	40.5 kWh	465 km	299 km	**Nexon Petrol**	1240 kg	17 km/l	16 km/l	3
MG ZS EV	1520 kg	50.3 kWh	461 km	350 km	**Hyundai Creta**	1200 kg	18.4 km/l	12 km/l	4

Table 2. Dataset description and sources used in this study.

Data type	Description	Source
Electricity generation	Regional grid mix and carbon intensity (kg CO_2/kWh)	[14]
CO_2 emissions	Upstream and emissions during electricity generation	[14]
Transmission and distribution losses	Grid transmission and distribution losses in the electricity supply chain	[14]
EV and ICEV models considered	Class 1 (Small Car), Class 2 (Sedan Car), Class 3 (SUV), and Class 4 (Large SUV) are categorized by kerb weight	[12], Manufacturer and researcher data
EV energy consumption	Standard reported and real-world energy consumption data by researchers	[12], Manufacturer and researcher data
ICEV emissions	Well-to-wheel emission factor data for petrol cars	[15]
ICEV fuel consumption	Standard reported and real-world fuel consumption data by researchers	[12], Manufacturer and researcher data
Ambient temperature	State-wise mean temperature data	[14]
EV stock and sales	Detailed state-wise annual EV sales and stock data	[16]
Charging efficiency	Average wall-to-wheel charging efficiency (90 to 95%)	[15]

2.1.1. EVEI metric

The study develops an EVEI metric to capture the climate footprint advantage of EVs over equivalent ICEVs, calculated using Equation 1. The EVEI is a dimensionless ratio that compares the WTW GHG emissions of an EV to those of a conventional internal combustion engine vehicle (ICEV). The regional grid carbon intensity of electricity generation is calculated using Equation 2. The operational CO_2 emissions (WTW) for EVs are calculated based on the regional grid carbon intensity of consumption, calculated using Equation 3 [17] and adjusted for temperature effects on battery performance. The influence of temperature factor on the battery capacity is considered, based on a temperature-capacity compensation coefficient, λ_C, from existing literature by [11]. The formula for calculating the EVEI metric is presented as follows -

$$EVEI = \frac{EF_{EV}}{EF_{ICEV}} = \frac{(\gamma_i^c \times \rho_{EV} \times \rho_{ICEV})}{(\eta_{EV} \times \eta_w \times \gamma_{ICEV} \times k \times 100 \times \lambda_C)} \quad (1)$$

$$\gamma_i^G = \frac{Total\ CO_2\ emissions}{Net\ electricity\ generation} \quad (2)$$

$$\gamma_i^c = \frac{\gamma_i^G \times g_i + \gamma^{grid} \times imp_i}{g_i + imp_i} \quad (3)$$

Where EF_{EV} and EF_{ICEV} (g/km) are the WTW emission factors of electric and petrol vehicles, respectively, γ_i^c and γ_i^G are the respective electricity consumption and generation carbon intensity of state i in $kgCO_2$/kWh, γ^{grid} is the carbon intensity of the central grid in $kgCO_2$/kWh, g_i, and imp_i are the respective electricity generated and imported from the central grid for each state i, γ_{ICEV} is the petrol carbon intensity in $kgCO_2$/L, ρ_{EV} is the EV energy efficiency (kWh/100km), ρ_{ICEV} is the fuel efficiency of petrol vehicle, η_{EV} is the EV WTW efficiency, η_w is the EV wall-to-wheel efficiency, k is the petrol upstream emission factor, and λ_C is the battery temperature-capacity compensation co-efficient. The γ_{ICEV} for petrol vehicles is 3009.75 gCO_2/L, based on the typical Indian car fleet average from existing literature by [15].

An EVEI value below 1 indicates that EVs produce a lower WTW emission factor than ICEVs per kilometer traveled. While an EVEI less than 1 suggests that EVs offer a net emissions reduction benefit compared to ICEVs.

2.1.2. Vehicle fleet and emission model

The vehicle fleet model estimates the total number of electric four-wheelers operating in each Indian state in 2023-2024 using historical sales and stock data. It accounts for the total vehicle fleet in each state. However, the vehicle scrappage is not considered in the study, as electric vehicle scrappage in the country has not been implemented yet. Due to the lack of detailed vehicle class distribution data across states, a Monte Carlo simulation approach was employed to sample fleet compositions and evaluate emissions. This method captures uncertainties and variability, providing robust estimates of weighted state-level EV emissions [18]. Once the EV stock is determined, the total annual emissions are estimated using EV stock, vehicle kilometer travelled (VKT), real-world energy consumption, and the regional consumption grid carbon intensity:

$$\text{EV Emissions (Kton)} = \text{EV Stock} * \text{VKT} * EF_{EV} * 10^{-6} \quad (3)$$

Where VKT is the annual vehicle kilometer travelled (km) by four-wheelers in India, EV_{EF} is the electric vehicle emission factor in $kgCO_2/km$. The regional generation grid carbon intensity is calculated using Equation 3. The annual VKT by cars is considered as 41 km to 44 km for EVs [19].

2.2. Clustering Analysis

The study then aims to cluster the states based on the following parameters related to EV use-phase environmental impact: EVEI metric, grid emission factor, renewable energy shares in grid mix, EV stock per state, average ambient temperature, and EV emissions. These indicators reflect a region's advancement in decarbonizing its four-wheeler segment and formulating policies for promoting electrification. First, the study employs principal component analysis to reduce the dimensionality of the parameters. Then, the study employs multiple unsupervised machine-learning techniques to identify patterns and group the states. The best clustering algorithm is chosen based on the silhouette score, Calinski-Harabasz, and Davies-Bouldin index. Finally, hierarchical agglomerative clustering is employed to identify patterns of similarity among the states and UTs. The regions are categorized into groups based on their transition to transport electrification, offering a foundation for tailored policy analysis.

3 Results and Discussions

3.1. Regional disparity on electricity grid carbon intensity

Electricity carbon intensity in India varies significantly across states and UTs due to differences in both electricity generation sources and consumption profiles. States vary in terms of their degree of reliance on imports from the central grid. The carbon intensity of electricity generation and consumption profiles varies across states, as shown in **Figure 2.** Carbon intensity (CI) of electricity consumption mix in $kgCO_2/kWh$ is dynamic across regions, reflecting the variability in regional grid energy consumption mix. Thirteen states in India have a carbon footprint of electricity consumption mix higher than the national average of 0.8 $kgCO_2/kWh$, as shown in **Figure 2,** with Haryana having the highest value. Chhattisgarh, Maharashtra, and West Bengal also have high carbon intensity values for the consumption mix due to higher fossil-fuel reliance. In the northern and eastern states, the state grid, which is dominated by renewable or nuclear energy sources, leads to low CI values. Union territories, particularly Andaman and Nicobar Islands and Lakshadweep, exhibit much lower electricity consumption CI than the national average. The variation in electricity grid CI across Indian states impacts their operation phase emissions. Therefore, evaluating EV emissions requires regional analysis rather than assuming a constant national average CI value. The carbon intensity of the electricity consumed for charging EVs is further employed to determine their regional well-to-wheel carbon footprint across states.

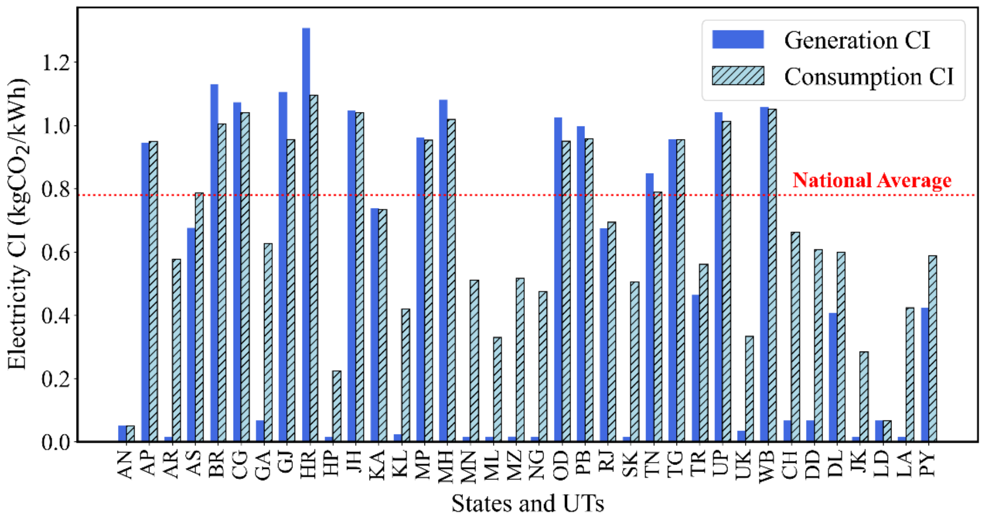

Fig 2. Electricity carbon intensity based on electricity generation and consumption carbon intensity.

3.2. EV emission factor for various vehicle classes

The study evaluates the EV emission factor (EF_{EV}) in $kgCO_2/km$ for four vehicle classes across Indian regions. EF_{EV} represents the indirect CO_2 emissions per kilometre driven by an electric vehicle. The EF_{EV} is influenced by the real-world energy consumption of different vehicles and the carbon intensity of the electricity usage, as shown in **Figure 3**. Under laboratory conditions, the Automotive Research Association of India (ARAI) tests EVs in idealized driving patterns using the Modern Indian Driving Cycle (MIDC) in India. Standard tests yield lower energy consumption values – typically around 0.07-0.11 kWh/km for four vehicle classes- Class 1 to 4. Real-world energy consumption data is collected from secondary sources, including user-reported performance data and automotive review websites. The values ranging from 0.09-0.14 kWh/km are comparatively higher due to the influence of traffic, terrain, and auxiliary loads. **Figure 3** demonstrates that the emission factors evaluated using ARAI values are lower than those evaluated using real-world energy consumption data. This highlights that reliance on ARAI-estimated data for WTW emission estimation of EVs in India can result in emission underestimation. **Figure 4** shows EF_{EV} for four vehicle classes, with Class 4 having the highest values across states due to higher energy consumption. Higher energy consumption of Class 4 vehicles is attributed to their larger battery size, which increases vehicle weight and requires more energy for operation.

The study also aims to understand how regional differences in electricity grid mix and ambient temperature influence variations in EF_{EV} across states. **Figure 5** highlights the percentage deviation of EF_{EV} of states from the national average EF_{EV}. The percentage increase indicates states with dirtier grids and hotter climates, such as Haryana, Gujarat, and Maharashtra, which face greater decarbonization challenges. In contrast, states like Himachal Pradesh, Uttarakhand, and Meghalaya rely on cleaner grids and comparatively cooler temperatures, offering more favorable conditions for transport electrification. Temperature affects EV emissions primarily by altering battery energy consumption efficiency. At low temperatures, particularly in Jammu and Kashmir and Ladakh, battery internal resistance increases, leading to higher vehicle energy consumption. Similarly, vehicle air conditioning increases energy needs in high-temperature environments, particularly Delhi and Daman and Diu.

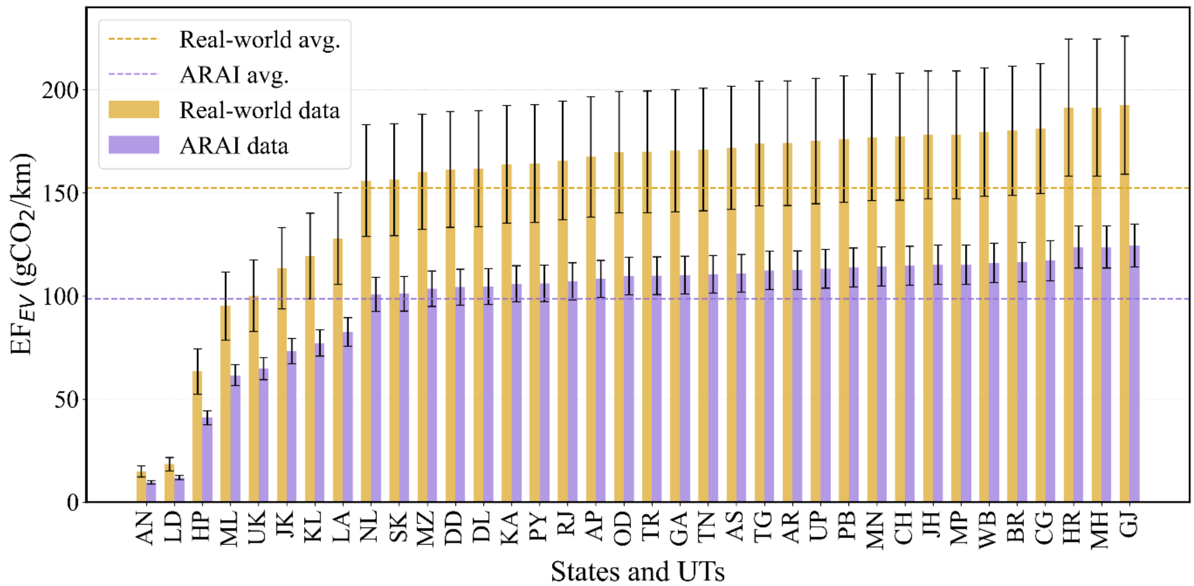

Fig 3. EV emission factor based on the real-world and ARAI energy consumption data.

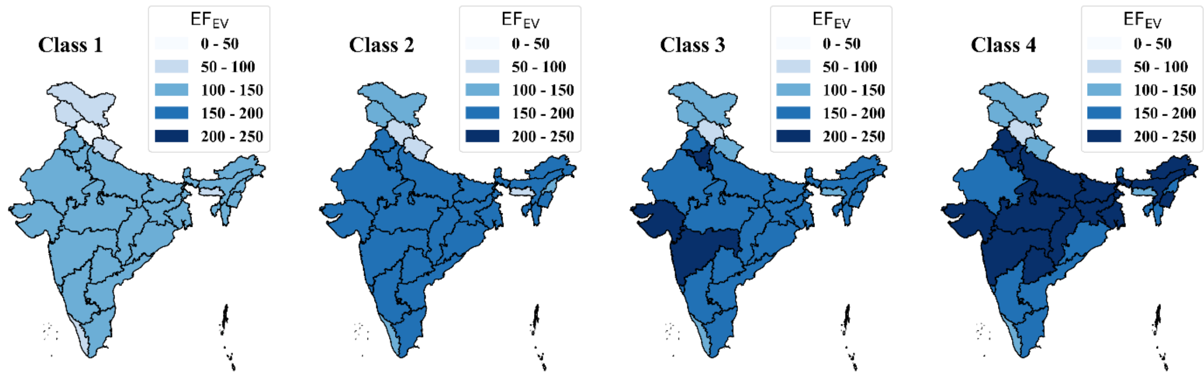

Fig 4. State-wise EV emission factor for four E-4W classes.

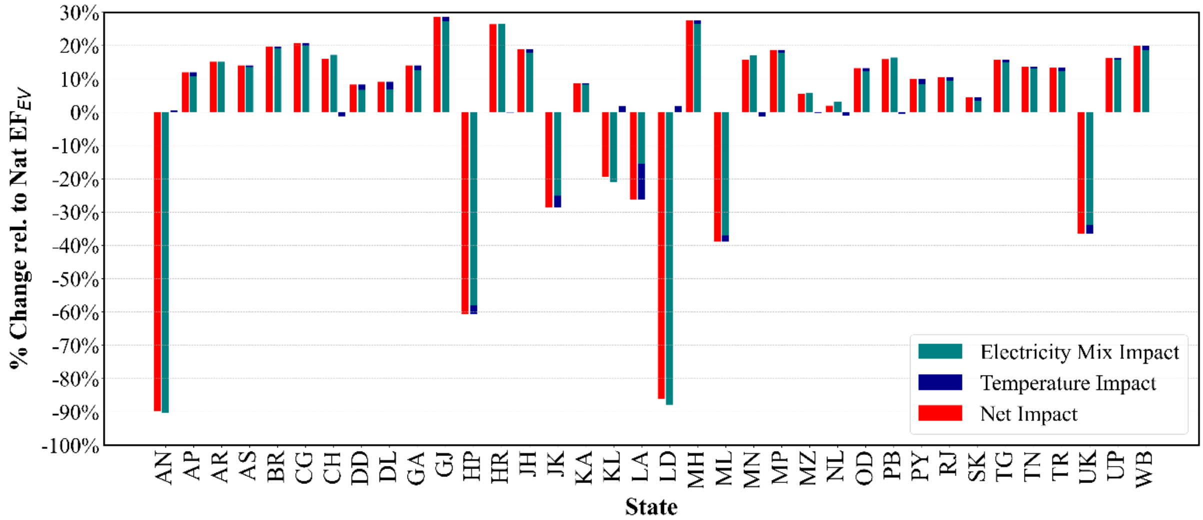

Fig 5. Deviations in state-wise EV emission factor relative to the national average due to electricity mix and temperature impacts.

3.3. State-wise variability in the EVEI metric

The EVEI metric is calculated across four categories based on real-world energy consumption data across 36 Indian states and UTs. The EVEI metric shows how the regional electricity grid mix and ambient temperature affect the CO_2 emission factor of EVs relative to equivalent ICEVs. **Figure 6** illustrates the EVEI value for various EV classes with ascending battery sizes (17.3–50.3 kWh) and weights (815–1520 kg), compared to equivalent petrol vehicles. Among all the vehicle classes, Class 4 exhibits the highest EVEI across all states due to its larger battery size and higher energy consumption. The EVEI metric varies across the four vehicle classes, indicating differing regional environmental performance. For Class 1 vehicles, 14 regions in India have an EVEI greater than 1. Similarly, the EVEI exceeds 1 in 19 states for Class 2, 26 for Class 3, and 28 for Class 4 vehicles. The emission reduction potential of EVs compared to ICEVs per vehicle is highly sensitive to the state's regional grid carbon intensity. In states such as Haryana, Gujarat, and Maharashtra, the EVEI values are the highest, as the states' electricity consumption mix heavily depends on non-fossil fuel sources. The electricity consumption grid carbon intensity is higher than 0.9 $kgCO_2/kWh$, resulting in more than 1.1 times higher WTW emission for EVs than equivalent ICEV. However, in UTs like Lakshadweep and Andaman and Nicobar Islands, and north-eastern states, grid emission factors are below 0.04 $kgCO_2/kWh$ due to dominant renewable and hydropower shares. In these states, the WTW CO_2 EF from EVs is around 8-60% of comparable ICEVs. These UTs demonstrate a strong environmental advantage for electrification across all vehicle categories. However, in coal-dominant regions, electrification of these classes may lead to marginal or even negative climate benefits under the present grid conditions.

These findings emphasize that EV climate performance is not uniform across India. A combination of vehicle category, real-world energy consumption, ambient temperature, and the carbon intensity of the local grid shapes it. Therefore, future EV promotion strategies must incorporate regional grid profiles and real-world operational data to ensure effective and equitable emission reductions.

Also, this study evaluates the total stock emissions of electric four-wheelers at the state level, as shown in **Figure 7(a).** The analysis accounts for both the total number of registered EVs and the regional electricity carbon intensity, offering a more realistic picture of their environmental impact. States with dirtier grids and higher EV penetration, particularly Maharashtra, Telangana, Delhi, and Karnataka, demonstrate notably higher total emissions, demonstrating the importance of aligning EV adoption with grid decarbonization efforts. This can be attributed to better charging infrastructure, higher urbanization rates, and supportive EV adoption policy environments. The northern and north-eastern states exhibit lower fleet emissions, largely due to slower electric four-wheeler adoption in these regions.

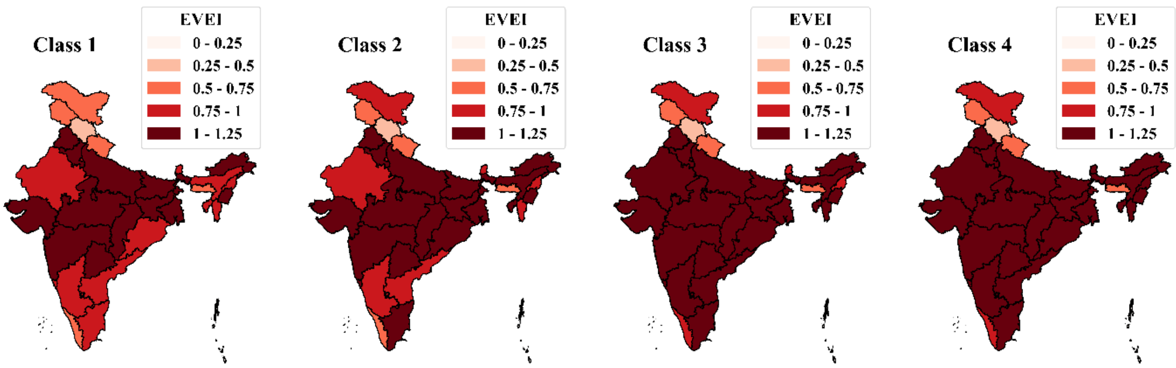

Fig 6. EVEI metric for four E-4W vehicle classes based on real-world energy consumption.

3.4. Clustering of states based on EV emissions

PCA is employed to reduce the dimensionality of the selected parameters to two principal components. A hierarchical agglomerative clustering approach is then employed to group Indian states and UTs into clusters, as shown in **Table 3**. The analysis has divided the regions into four distinct clusters- Clusters 1, 2, 3, and 4, as shown in **Figure 7(b).** Cluster 1 represents regions with high dependence on fossil fuels, high ambient temperature, and the highest EV adoption. Although EVs are growing rapidly in these regions, high fossil fuel dependence increases total EV emissions. These regions necessitate strong support for strengthening the clean electricity grid to reduce electric transport emissions. Also, policy support for better charging infrastructure and vehicle performance standards is necessary due to rapid EV growth. Cluster 2 represents regions with low EV adoption and comparatively lower dependence on fossil fuels than cluster 1. These regions have low EV emissions due to the lower EV stock. Policy support in these regions necessitates a major focus on promoting EV demand. The introduction of subsidies and pilot charging projects is necessary to start accelerating EV adoption. Cluster 3 represents regions majorly dependent on fossil fuels but with moderate EV adoption. These regions have moderate emissions from the EVs and represent emerging EV markets. These regions should focus on balanced policy support, combining faster EV adoption with grid decarbonization. Finally, Cluster 4 represents regions with high dependence on fossil fuels and high temperatures but very low EV adoption. These smaller regions, particularly the Andaman and Nicobar Islands and Lakshadweep, are early-stage EV adopters. Although these regions rely heavily on fossil-fuel-based small power generation units, overall electricity demand is very low compared to other states. These regions offer future potential for EV adoption, with policy investments focusing on basic EV infrastructure and EV awareness projects.

Notably, even states generating most of their electricity from renewables often rely on heavily fossil-fuel-dependent imports from the central grid, reducing potential EV emission reduction benefits. Region-specific policies are necessary to integrate EV promotion with grid decarbonization, ensuring EVs contribute effectively to climate goals. Policymakers must prioritize clean energy transitions in the regions, primarily belonging to clusters 1 and 3, as they have higher EV adoption. These insights indicate that the EV transition in India should be region-specific, data-driven, and adaptive to local conditions to ensure both market penetration and environmental benefits.

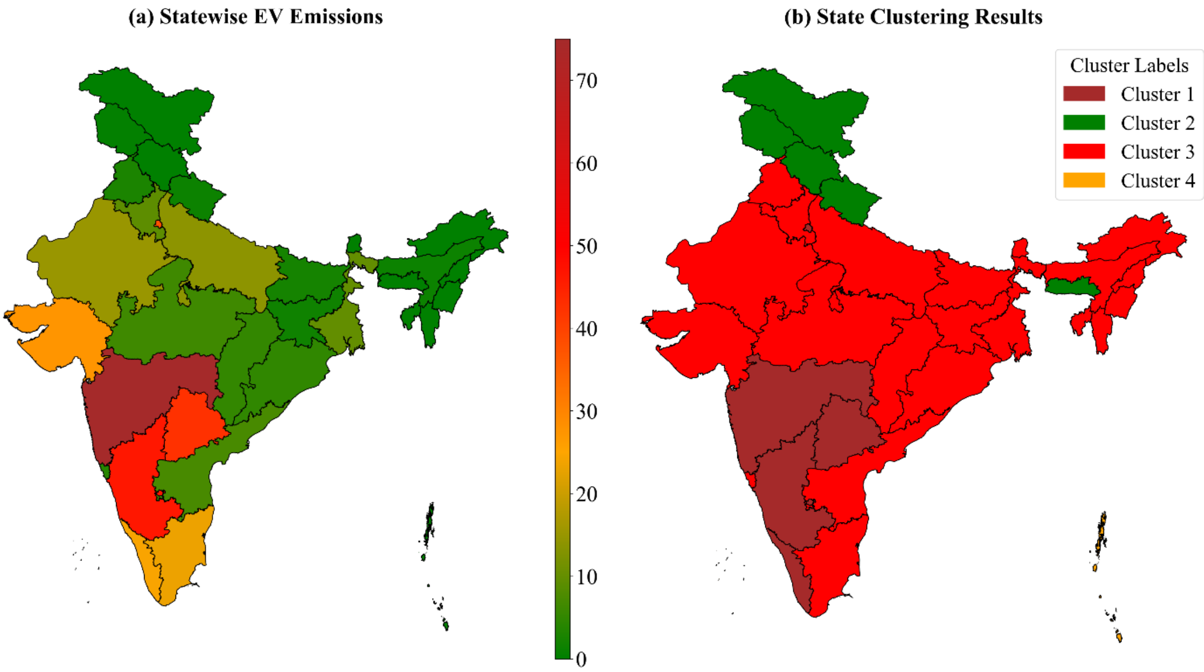

Fig 7. Emission Index for different vehicle classes based on real-world and ARAI-certified energy consumption data.

Table 3. Clustering results of Indian states.

Cluster	Name	Fossil share (%)	Mean temp (°C)	EV EF (kg CO_2/km)	Emissions (Kton)	EVEI
1	High CI, High EV adoption	69.20	26.71	125-235	45.43	0.93-1.05
2	Low CI, Low EV growth	42.29	14.82	77-145	0.44	0.57-0.65
3	High CI, Moderate EV growth	74.41	24.84	133-251	5.79	0.99-1.13
4	High CI, Negligible EV growth	94.66	26.4	12-24	0.01	0.09-0.11

4 Conclusion

Transport electrification promises significant climate benefits; however, its environmental impact is associated with regional electricity grid characteristics and climate. By developing an Electric Vehicle Emission Index for electric four-wheelers and assessing EV fleet emissions across Indian states and UTs, this study reveals spatial disparity in environmental performance. Differences in electricity carbon intensity, ambient temperature, and vehicle fleet composition drive spatial variations. Regions with coal-dependent consumption mix and hotter climates exhibit an EVEI value higher than 1, offsetting EV adoption benefits. EV models with larger battery capacities and energy consumption were found to have higher EVEI values across all regions. Regions with dirtier grids and higher EV adoption in southern and western states contribute to higher fleet emissions and delayed climate benefits. While regions with cleaner power mixes and slower EV adoption, such as parts of northern and north-eastern India, show enhanced environmental benefits. Clustering regions based on grid mix, EV stock, EVEI, temperature, and fleet emissions highlights the critical need for region-specific strategies to decarbonize the transport sector. Rapid EV adoption without parallel grid decarbonization risks undermining the environmental benefits of electrification. This study underscores that EV policies must be regionally tailored to meet the emission reduction benefits of EV adoption.

While the present study captures real-world climate benefits of EVs during operation, it does not consider the emissions during the entire lifecycle, including vehicle manufacturing and recycling. The scope of the study is limited to CO_2 emissions, and it does not consider air pollutants like PM, NO_X, and SO_X. This study is limited to electric four-wheelers and does not consider other vehicle segments. Future studies should consider cradle-to-grave lifecycle emissions, dynamic electricity grid projections, and air pollution impacts of electrification.

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Presenter Biography

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