



A Report On

Countermeasures for Reducing Emissions from Electric Vehicle Charging in India

A study conducted by Grid Integration Lab, IIT Bombay



2026

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Acknowledgement

This publication has been prepared by **Grid Intergration Lab**, Indian Institute of Technology Bombay (IITBombay) under the **Mapping the Impact Of EV Charging and Associated Emissions on the Power Grid** project.

We Would also like to acknowledge the valuable technical input and guidance provided by Mr.Rishabh Sethi from the Electric Mobility Initiative (EMI) towards the conceptualization and successful undertaking of this study.

we would also like to thank various stakeholders including representatives from CPOs, DISCOMS, EV and Charger OEMs, Think Tanks for their valuable feedback/inputs on the outcome of this study.

we also acknowledge the continued leadership, Guidance ,and support of Indtitute of Technology Bombay in executing this project.



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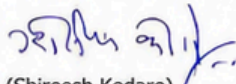
Foreword

India's transition towards electric mobility is an important component of the country's broader efforts to reduce dependence on fossil fuels, improve air quality, and decarbonise the transport sector. However, the environmental benefits of electric vehicles cannot be assessed solely on the basis of the absence of tailpipe emissions. In a power system such as India's, where coal continues to contribute to electricity generation though with falling proportion due to RE integration, it is equally important to quantify the emissions associated with producing the electricity used for charging electric vehicles. The carbon footprint of an electric vehicle is therefore closely linked to the generation mix of power system from which it draws electricity for charging demand. As the number of electric vehicles in India increases substantially over the coming years, understanding this interaction between electric mobility and the electricity sector becomes increasingly important.

This set of two reports on "**Mapping the Impact of EV Charging and Associated Emissions on the Power Grid**" undertaken by **Grid Integration Lab**, Department of Energy Science and Engineering, IIT Bombay, addresses this important question through a detailed assessment of the emissions associated with electric vehicle charging in India. The work evaluates the impact of India's present EV fleet while also examining how electricity demand and associated emissions may evolve as EV adoption increases towards 2030 and beyond. Rather than treating the Indian power system through a single average emission factor, the analysis considers regional differences in generation mix, temporal and seasonal variations in grid emission intensity, differences among vehicle categories, charging behaviour, and the losses associated with delivering electricity to the vehicle.

Importantly, this work goes beyond quantifying the problem. Building upon the assessment of present and future EV-related emissions, the reports identify pathways and recommendations for reducing the carbon footprint of electric vehicle charging. These include better alignment of charging demand with renewable energy availability, smart and coordinated charging, appropriate charging strategies for energy-intensive vehicle fleets, renewable energy integration at charging facilities, improvements in grid infrastructure and flexibility, and continued decarbonisation of electricity supply. The findings therefore underline that electric mobility and power-sector decarbonisation must be viewed as interconnected transitions. Increasing the number of electric vehicles is an important step, but maximising their climate benefit requires parallel attention to how the electricity supplying these vehicles is generated and how charging demand is managed.

I would like to congratulate the **Grid Integration Lab**, authors, researchers, reviewers, participating stakeholders, and supporting organisations whose contributions have made this work possible. I hope that this work will contribute to a more informed discussion on India's electric mobility transition and provide useful insights for policymakers, utilities, industry, researchers, and other stakeholders involved in shaping the future of transportation and the power sector.


(Shireesh Kedare)

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Executive Summary

Electric vehicles (EVs) are central to India's transition towards a lower-carbon transport system. However, the climate benefit of electrification depends not only on vehicle efficiency but also on where, when, and how the electricity used for charging is generated and delivered. Report 1 of this study demonstrated substantial regional, seasonal, and diurnal variation in EV-related emissions across India. Building on that baseline, this report identifies, evaluates, and prioritises practical countermeasures for reducing emissions associated with EV charging under present and near-term Indian power-system conditions.

The baseline assessment highlights the importance of targeted interventions. Grid emission intensity varies considerably across India's regional grids. The North Eastern Region has the lowest emission intensity due to its hydro-dominated generation mix, whereas the Eastern Region remains highly carbon intensive because of its strong dependence on coal. The Northern and Southern regions exhibit substantial diurnal variability, creating opportunities to shift EV charging towards cleaner periods. Consequently, compared with equivalent internal combustion engine vehicles (ICEVs), EV emission reductions range from more than 60% in the North East to marginal or even negative values in the Eastern Region during some seasons.

EV-related emissions are determined by two interacting components: the electricity required to meet charging demand, and the carbon intensity of electricity supplied during charging. The first is influenced by vehicle efficiency, distance travelled, charger efficiency, charging rate, and user behaviour. The second depends on generation mix, renewable availability, thermal plant characteristics, dispatch practices, network losses and congestion, storage availability, and electricity-market design. Reducing EV emissions therefore requires interventions extending beyond vehicles and chargers to the wider power system.

On this basis, the report classifies emission-reduction countermeasures into four complementary domains. The first comprises charging behaviour and demand-side interventions, including mandatory smart-charging capability, EV aggregators, emission-aware charging algorithms, demand response, and bidirectional charging. The second comprises charging-depot and fleet-level interventions, including solar canopies, renewable-plus-storage depot microgrids, energy management systems, and opportunity or flash charging for buses. The third addresses power-sector decarbonisation, through stronger transmission infrastructure, utility-scale battery storage, greater renewable-energy deployment, second-life EV battery storage, and integration of EV demand into system planning. The fourth comprises electricity-market, regulatory, and policy measures, including time-of-day tariffs, carbon-aware electricity markets, and favourable green-power procurement mechanisms for large charging consumers. Together, these interventions recognise that EV decarbonisation requires

coordinated changes in charging technology, operational practices, electricity supply, and market design rather than reliance on any single measure.

A quantitative assessment was undertaken to examine the effectiveness of charging flexibility and Vehicle-to-Grid (V2G) under wholesale market-price signals, carbon-price signals, and carbon-price signals combined with explicit emission constraints. The results show that price-driven charging does not necessarily reduce emissions. Under the BAU scenario, market-price-based demand flexibility lowers daily system operating cost but results in a small net increase in emissions. Carbon-price-based flexibility performs somewhat better, although outcomes remain seasonally inconsistent. In contrast, explicitly emission-aware charging produces reductions across all seasons.

The strongest national performance is obtained when V2G is combined with carbon pricing and emission awareness. Under BAU conditions, this strategy achieves an average emission reduction of approximately 13.4 ktCO₂ while reducing daily generator-dispatch cost by about ₹14.6 lakh. Under the Stated Policies scenario, emission-aware V2G achieves an average reduction of approximately 10.2 ktCO₂ together with daily operating-cost savings of about ₹56.4 lakh. These costs represent only generator-dispatch costs in the power-system simulation; investments in chargers, communications, battery degradation, and other implementation costs are not included.

The analysis further demonstrates that no single countermeasure is optimal across all regions. In the Northern and Southern regions, strong variation in renewable generation creates substantial potential for smart and emission-aware charging. The Western Region also benefits from coordinated charging, although its large thermal-generation backbone requires careful scheduling. In the Eastern Region, where emission intensity remains high throughout much of the day, temporal shifting alone offers limited benefit; renewable-energy procurement and accelerated grid decarbonisation become more important. In the already low-carbon North Eastern Region, the incremental emission benefit of shifting charging is smaller, and the value of interventions increasingly lies in grid flexibility, reliability, and preparation for future EV growth.

To translate these findings into region-specific priorities, the report uses an Analytic Hierarchy Process (AHP) considering emission impact, implementation cost, implementation time, and technical maturity. Smart charging emerges as a high-priority measure in several regions, while green electricity procurement, emission-aware charging, renewable-integrated depots, opportunity charging, and renewable capacity expansion gain importance depending on regional grid conditions. The Eastern Region is notably different, with green procurement, solar charging infrastructure, and additional renewable generation receiving greater priority than charging flexibility alone.

Overall, the findings show that India's EV transition must be accompanied by a parallel transition in charging practices and electricity supply. In the near term, priorities should

include smart-charging capability, aggregator frameworks, emission-aware algorithms, green electricity procurement, and solar-integrated charging infrastructure. In the medium term, renewable-plus-storage depots, advanced energy management systems, utility-scale storage, and demand response can provide additional flexibility. Over the longer term, V2G, second-life battery storage, transmission expansion, renewable-energy deployment, and carbon-aware electricity markets can integrate EVs as active resources within a progressively decarbonised power system.

The central conclusion is that electrification alone is not the end objective; low-carbon electrification is. Region-specific combinations of charging flexibility, renewable integration, power-system decarbonisation, and appropriate market mechanisms are required to ensure that India's growing EV fleet produces real and measurable reductions in transport-sector emissions rather than merely transferring emissions from vehicle tailpipes to the electricity sector.

Chapter 1 Introduction And Motivation

Electric vehicles are widely regarded as a cornerstone of transport sector decarbonization, offering the potential to significantly reduce greenhouse gas emissions and local air pollutants. In the Indian context, large scale EV adoption is being actively promoted across vehicle segments, supported by national level policy initiatives, declining battery costs, and rapid expansion of charging infrastructure. However, the actual climate benefit of EVs is not intrinsic to the vehicle itself and critically depends on how, when, and where electricity is generated and consumed for charging.

Conventional emission assessments of electric vehicles often rely on annual average grid emission factors to estimate charging related emissions. While such approaches are useful for high level comparisons, they fail to capture the strong temporal and spatial variability of electricity generation in India. Grid emission intensity varies substantially across regions due to differences in installed capacity, fuel mix, and renewable energy availability, and within a day due to the dispatch order of generators and demand patterns. As a result, two identical electric vehicles charged in different regions or at different times of the day can have markedly different emission footprints.

Recent evidence as shown in Report 1 of this study showed that unmanaged EV charging can overlap with emission intensive periods, particularly during evening and night hours when coal-based generation dominates the marginal supply in many regions. In such cases, shifting charging to off peak periods based solely on price signals may not deliver emission reductions and can even increase system wide emissions. These effects are further amplified for commercial fleets and public transport vehicles that rely on large scale depot charging, where charging demand is concentrated in limited time windows and flexibility is constrained by operational requirements.

At the same time, electric vehicle charging infrastructure represents a unique opportunity to actively reduce emissions through targeted operational and infrastructural interventions. Unlike many other electricity loads, EV charging is partially flexible in time, location, and rate, and can be coordinated with renewable generation availability, regional grid conditions, and system level constraints. Leveraging this flexibility requires moving beyond generic smart charging narratives toward clearly defined countermeasures that are grounded in power system realities and fleet specific behavior.

Against this background, there is a need for a systematic assessment of potential countermeasures that can reduce emissions associated with EV charging under current and near term Indian grid conditions. Such countermeasures may include renewable aligned charging, emission aware control strategies, strategic siting of charging infrastructure, depot level renewable integration, and coordinated fleet charging for heavy duty and public transport applications. Importantly, the effectiveness of these measures is not uniform and depends on region, season, vehicle segment, and charging context.

This report addresses this gap by identifying and evaluating a set of practical countermeasures for reducing EV related emissions using a high resolution, spatio temporal modelling framework. By explicitly linking EV charging demand with time resolved regional grid emission intensity, the study moves beyond static averages and provides quantitative insights into where and under what conditions emission reductions can be maximized. The findings aim to support policymakers, system operators, and infrastructure planners in designing EV charging strategies that deliver real and measurable climate benefits alongside electrification.

1.1 Objectives of The Report

The primary objective of this report is to systematically identify and evaluate potential countermeasures that can reduce emissions associated with electric vehicle charging under present and near term Indian power system conditions. Recognizing that EV related emissions are strongly influenced by temporal, spatial, and fleet specific factors, the report seeks to move beyond aggregate emission estimates and provide actionable insights grounded in operational realities of both the transport and power sectors.

Specifically, the objectives of the report are to:

- Identify and classify practical emission reduction countermeasures spanning operational, infrastructural, and system level interventions, with clear definitions of their scope and applicability.
- Assess the effectiveness of temporal charging strategies, including renewable aligned charging and emission aware control approaches, in comparison to conventional price driven or off peak charging mechanisms.
- Evaluate fleet specific emission reduction potential, highlighting cases where EV adoption delivers strong climate benefits and cases where additional interventions are required to avoid marginal or negative outcomes.
- Provide comparative insights on countermeasure feasibility and impact, supporting prioritization of interventions based on emission reduction potential, implementation complexity, and system compatibility.
- Inform policy and planning decisions by translating modelling results into evidence based recommendations for regulators, distribution utilities, system operators, and charging infrastructure developers.

Chapter 2 Baseline Emission Framework

This chapter summarizes the baseline emission framework used in Report 1 of this study to evaluate the effect of EV integration in the Indian grid on the emissions from the transport sector and compares them against emissions from internal combustion engine vehicles (ICEV)s. The baseline represents EV charging related emissions under current charging behaviour, infrastructure deployment, and regional grid conditions, without the application of targeted mitigation strategies.

The baseline framework builds on a high resolution spatio temporal emission modelling approach that explicitly links electric vehicle charging demand with time varying regional grid emission intensity. This approach reflects real world operating conditions more accurately than conventional average emission factor based methods and is essential for identifying when and where EV charging contributes most to system wide emissions.

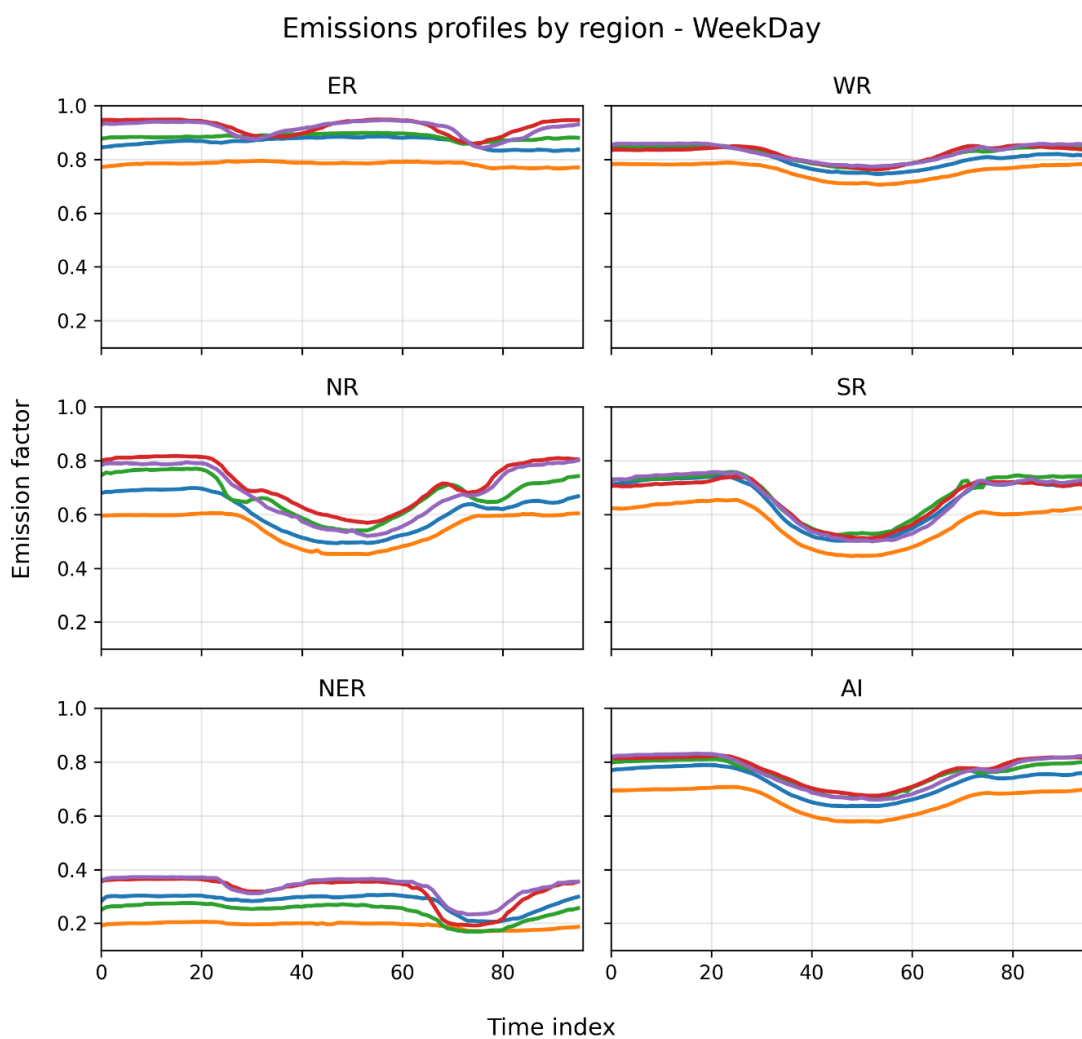
2.1 Grid Emissions Factors

Weekday diurnal emission factor profiles across India's regional grids show strong spatial and temporal heterogeneity as shown in Figure 1. The Northern region exhibits pronounced intra day variability, with emission factors falling from morning levels of approximately 0.75–0.80 tCO₂/MWh to mid day of 0.50–0.55 tCO₂/MWh due to solar generation, before rising again to 0.75–0.80 tCO₂/MWh during evening and night hours as coal based generation ramps up. This wide swing makes charging time a critical determinant of emissions in the Northern grid.

The Eastern region records the highest and most persistent emission intensity, with emission factors remaining consistently in the range of 0.85–0.95 tCO₂/MWh throughout the day, indicating strong coal dependence and limited potential for emission reduction through temporal shifting alone. The Western region shows moderate emission intensity with a relatively flat diurnal profile, typically ranging between 0.72–0.85 tCO₂/MWh, with only a modest mid day dip reflecting partial solar contribution.

In contrast, the Southern region maintains lower emission factors overall, varying approximately from 0.45 to 0.75 tCO₂/MWh, and exhibits a deep and sustained mid day trough reaching around 0.45 tCO₂/MWh, supported by high solar and hydro generation. The North Eastern region is the cleanest nationally, with emission factors largely confined between 0.18 and 0.35 tCO₂/MWh across the day, owing to hydropower dominance. Collectively, these results demonstrate that EV charging emissions are highly region dependent, with the largest temporal optimization potential in regions exhibiting strong diurnal variability and high renewable penetration.

Figure 1 Timevarying emission factors of Indian regional grids (Weekday)(shown for ER: Eastern Region, WR: Western Region, NR: Northern Region, SR: Southern Region, NER: North Eastern Region, AI: All India)



2.2 Emission Estimation from EVS and Comparison with ICEVS

At the national level, EV related CO₂ emissions exhibit a strong and consistent diurnal pattern across all seasons. On weekdays, emissions peak during late night and early morning hours, reaching approximately 120–135 tCO₂ between 20:00 and 03:00, while minimum emissions of about 30–40 tCO₂ occur around 06:00–08:00, representing a 70–75% reduction relative to night time peaks. Weekend profiles follow the same temporal shape but remain systematically lower, with night time peaks below 95–100 tCO₂ and mid day of 25–30 tCO₂. Seasonal

variation in magnitude is evident, with winter and autumn exhibiting the highest emissions (weekday peaks of 125–130 tCO₂), while monsoon and spring show lower peaks (110–120 tCO₂) due to cleaner grid conditions rather than changes in charging behaviour. Fleet wise, national EV emissions are highly concentrated. Three wheelers (3W) are the dominant contributor, accounting for approximately 1.15 million tCO₂ per year, followed by system losses, which contribute a substantial 0.4–0.45 million tCO₂ annually. Two wheelers (2W), light passenger vehicles (LPV), and heavy passenger vehicles (HPV) each contribute roughly 0.3–0.4 million tCO₂ per year, while goods vehicle categories (LGV, HGV) remain below 0.1 million tCO₂ annually, despite higher per vehicle energy intensity.

Regionally, the Northern grid emerges as one of the largest contributors to national EV emissions, with pronounced diurnal variability. Weekday emissions peak at 45–52 tCO₂ during late night and evening hours and drop to 8–12 tCO₂ in the early morning, a reduction of nearly 75–80%. Annual emissions are dominated by 3W (0.55–0.6 million tCO₂), with system losses contributing 0.15–0.18 million tCO₂, reflecting the combined impact of high fleet activity and coal intensive generation.

The Southern grid records substantially lower emissions, with weekday peaks of only 18–21 tCO₂ and minima of 4–6 tCO₂. Annual emissions are dominated by private vehicle categories, with 2W (≈0.12 million tCO₂) and LPV (≈0.11 million tCO₂) accounting for most emissions, supported by a relatively clean generation mix that limits seasonal variability.

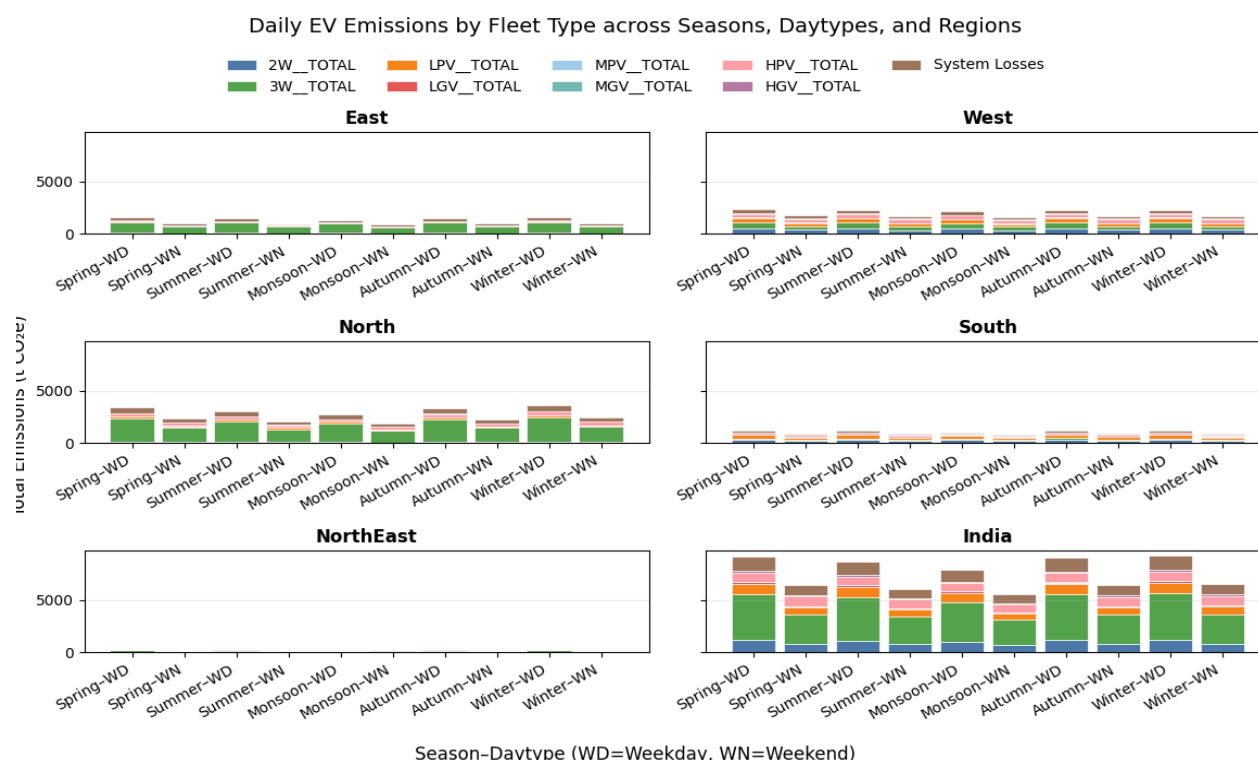
In the Western grid, weekday EV emissions peak at 32–36 tCO₂ and fall to 8–10 tCO₂ during early morning hours. Emissions are driven primarily by high private and para transit energy demand from 2W and 3W, with moderate seasonal variation reflecting partial solar penetration and continued coal marginality.

The Eastern grid, despite lower absolute EV demand, exhibits elevated emissions due to a coal dominated generation mix and higher system losses. Weekday peaks reach 18–21 tCO₂, with minima of 4–6 tCO₂, and annual emissions are dominated by 3W (≈0.27 million tCO₂) and losses (≈0.08 million tCO₂), highlighting the amplification effect of grid characteristics.

The North Eastern grid remains the cleanest region by a wide margin. Daily weekday emissions peak at only 2.5–3.2 tCO₂ and fall to 0.4–0.6 tCO₂ during early morning hours. Annual emissions are an order of magnitude lower than other regions, dominated by 3W (≈0.045 million tCO₂) and minimal system losses (≈0.01 million tCO₂), reflecting both low EV penetration and hydro dominated generation. The daily emissions from different fleet types across seasons, day types and regions are given in Figure 2. Across all regions, weekday emissions are systematically higher than weekend emissions, reflecting higher aggregate charging energy rather than changes in charging timing. Seasonal variation is evident but secondary to regional effects: monsoon and spring generally show lower emissions, while winter and autumn exhibit higher totals, particularly in coal intensive regions

From a fleet perspective, three wheelers and light passenger vehicles dominate emissions in most regions, underscoring the importance of high utilisation fleets, while heavy vehicle categories contribute comparatively less at the aggregate level despite higher per vehicle energy intensity. Importantly, system losses form a visible and non negligible component of total emissions across all regions, reinforcing that neglecting network losses can lead to systematic underestimation of EV related emissions.

Figure 2 Regional, seasonal, and fleet wise distribution of daily EV related CO₂ emissions across India.



2.2.1 Comparison with ICEVs

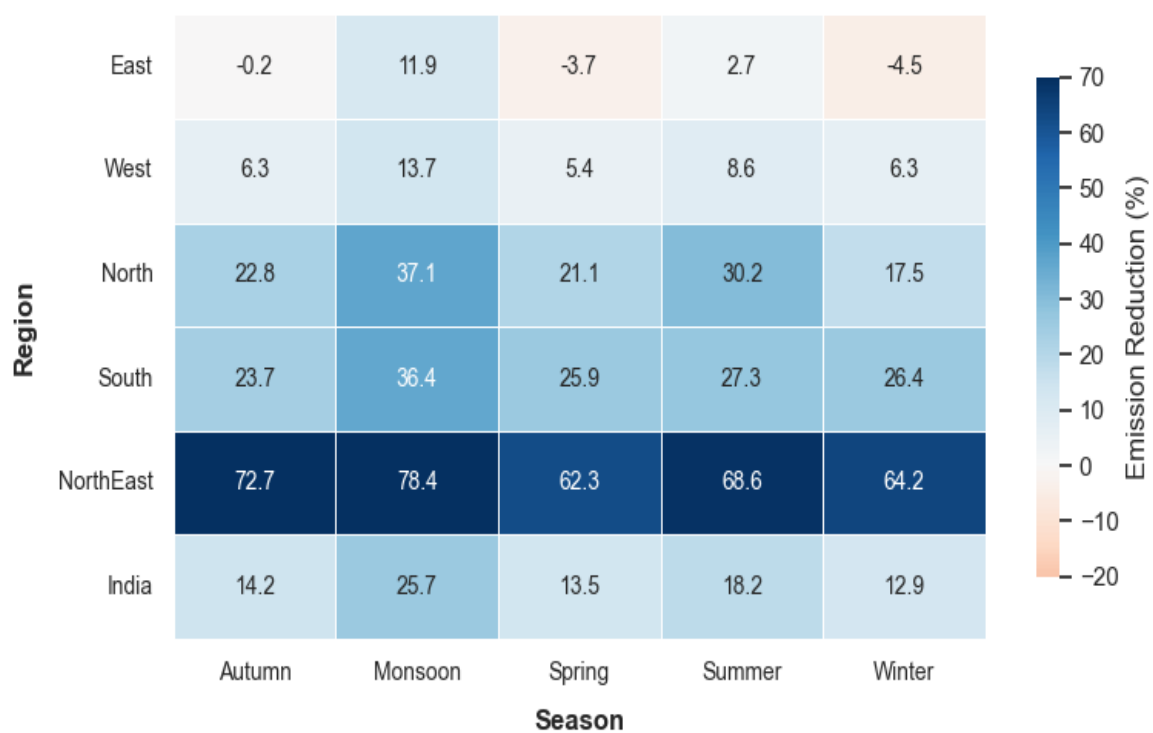
The emission reduction benefits of electric vehicle adoption in India exhibit strong regional and seasonal heterogeneity, driven by differences in grid generation mix, renewable energy availability, and the temporal alignment of charging demand. At the regional level, the North Eastern grid consistently delivers the highest emission reductions, exceeding 60% in all seasons and reaching up to 78% during the monsoon, reflecting its hydro dominated and low carbon generation mix. Seasonal variability in this region is limited, indicating robust emission benefits irrespective of charging timing as shown in Figure 3.

The Southern and Northern grids achieve moderate to strong emission reductions, typically in the range of 20–37%, with the highest benefits observed during the monsoon and summer when solar and hydro availability is high. In contrast, reductions decline during winter and spring, when coal based generation increasingly meets marginal demand. The Western grid exhibits modest but consistently positive reductions of 5–14%, with limited seasonal spread due to a relatively balanced but still carbon intensive generation mix.

The Eastern grid shows the weakest and most volatile performance, with emission outcomes ranging from –4.5% to +11.9% across seasons. In winter and spring, electrification can lead to marginal emission increases, underscoring that EV adoption in coal dominated regions does not automatically deliver climate benefits in the absence of complementary measures. At the national level, average emission reductions range from approximately 13–26%, peaking during the monsoon and reaching their lowest levels in winter and spring, in line with seasonal renewable availability.

Across vehicle classes, electrification delivers the strongest and most consistent emission benefits in light duty segments, particularly two wheelers, three wheelers, and light passenger vehicles, with national average reductions of roughly 13–27%. Medium duty vehicles achieve moderate benefits, while heavy passenger and heavy goods vehicles remain close to emission parity under current grid and charging conditions. Despite lower per vehicle savings, light duty vehicles dominate the aggregate impact, contributing the majority of the approximately 560 kT CO₂ annual national reduction due to their large fleet sizes and high utilisation.

The analysis highlights that temporal alignment between charging demand and grid emission intensity is a decisive factor, especially for buses and heavy vehicles that rely on overnight depot charging during emission intensive hours. These results imply that near term emission gains are maximized by prioritizing light duty electrification and renewable rich regions, while unlocking meaningful benefits from heavy duty and public transport electrification requires targeted charging strategies such as opportunity charging, renewable integrated depots, emission aware managed charging, and continued grid decarbonization.

Figure 3 Regional and Seasonal impact on EV Emission Reduction

Chapter 3 Factors Affecting Emission From Evs

Reducing emissions from electric vehicles requires first understanding the mechanisms through which EV charging translates into grid level carbon impacts. As demonstrated in the baseline analysis, EV related emissions are not determined solely by vehicle efficiency or fleet size, but emerge from the interaction of multiple factors spanning the transport system, charging infrastructure, and the power grid. These factors ultimately define when, where, and under what conditions EV charging contributes to higher or lower emissions.

This chapter identifies and examines the key factors that influence EV charging emissions, with a specific focus on how each factor can be influenced through targeted countermeasures. Rather than treating these drivers as fixed system characteristics, the analysis highlights their role as intervention points where policy, operational control, or infrastructure design can materially alter emission outcomes. Understanding these factors is therefore essential for designing strategies that move EV adoption from passive electrification toward actively managed emission reduction.

Total electric vehicle related emissions can be conceptually represented as the product of two interacting components: the amount of electricity drawn from the grid to meet EV charging demand and the carbon intensity of the electricity supplied at the time of charging. The total electricity requirement includes not only the energy consumed by the vehicle fleet at the wheels, but also additional energy drawn to account for charging inefficiencies and transmission and distribution losses across the power system.

EV emissions = (Energy consumed by the fleet + network losses) × (Emission intensity of electricity generation)

The first term, energy consumed by the fleet plus network losses, captures the scale of electricity demand imposed by EV charging. This component is influenced by factors such as fleet size, vehicle energy efficiency, daily distance travelled, charging power levels, and the extent of system losses between generation and the charging point. The second term, emission intensity of electricity generation, reflects the carbon content of the electricity used for charging and varies significantly across regions, seasons, and time of day depending on the underlying generation mix. This component is shaped by the availability of renewable energy, the dispatch order of thermal generators, and system level operational constraints.

3.1 ENERGY CONSUMED PER KM OF TRAVEL

This section presents a structured decomposition of the key factors influencing EV energy consumption per kilometer and, by extension, total charging related emissions. The framework distinguishes between vehicle and drivetrain characteristics, charging behaviour, and user level micro factors, providing a clear basis for linking emission outcomes to targeted technological, operational, and policy interventions discussed in subsequent sections.

3.1.1 Vehicle and Drivetrain factors

Vehicle and drivetrain factors determine the intrinsic energy efficiency of an EV^{1,2} by influencing the amount of electrical energy required to travel a given distance. These factors are primarily governed by vehicle design, propulsion system characteristics, and component efficiencies, and remain largely independent of user charging decisions. Improvements in these parameters directly reduce energy consumption per kilometre and consequently lower charging-related emissions under a given electricity grid mix

3.1.1.1 Drivetrain efficiency

Drivetrain efficiency determines how effectively electrical energy is converted into mechanical motion at the wheels. Electric drivetrains typically achieve efficiencies of 85–90%, significantly higher than internal combustion engines, but real world efficiency varies with speed, torque demand, and auxiliary loads. Losses in inverters, motors, and power electronics directly increase energy consumption per kilometer.

3.1.1.2 Battery energy density

Battery energy density influences vehicle mass and indirectly affects energy consumption. Higher energy density batteries reduce vehicle weight for a given range, lowering rolling resistance and acceleration energy demand. Conversely, heavier batteries increase per kilometer energy use, particularly in stop start urban driving.

3.1.1.3 Vehicle aerodynamics

Aerodynamic drag becomes a dominant loss mechanism at higher speeds, particularly for passenger cars and buses. Poor aerodynamic design significantly increases highway energy consumption and reduces the benefits of electrification for long distance travel.

3.1.1.4 Vehicle mass

Vehicle mass affects rolling resistance and acceleration energy, making heavier vehicles more energy intensive, especially in urban conditions. Battery size, structural reinforcements, and payload all contribute to mass related energy penalties[S].

3.1.1.5 HVAC and accessory loads

Heating, ventilation, air conditioning, and auxiliary systems can consume a substantial share of total EV energy, particularly in extreme climates. In cold or hot conditions, HVAC loads can increase energy consumption by 10–30%, reducing effective range and increasing emissions.

3.1.1.6 Regenerative braking efficiency

Regenerative braking allows recovery of kinetic energy during deceleration, reducing net energy demand. Its effectiveness depends on driving conditions, control strategies, and battery acceptance limits. Urban stop start traffic offers the highest regeneration potential.

¹ Argonne National Laboratory. ²⁰²³. The Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET®) Model, ²⁰²³. Lemont, IL: Argonne National Laboratory. <https://greet.es.anl.gov>

² Zhai, Zhiqiang, Leqi Zhang, Guohua Song, Xiao Li, and Lei Yu. “Modeling energy consumption for battery electric vehicles based on in-use vehicle trajectories.” *Transportation Research Part D: Transport and Environment* ¹³⁷ (2024): 104509

3.1.2 Charging Behaviour Factors

3.1.2.1 Charger Efficiency

Charger efficiency determines how much grid energy is required to deliver a unit of energy to the battery. Losses occur in AC/DC conversion, power electronics, and thermal management, with typical efficiencies ranging from 90–96%. Lower efficiency chargers increase upstream generation requirements and associated emissions³

3.1.2.2 Type of Charging (slow or fast).

Fast charging typically has higher power losses and reduced temporal flexibility compared to slow charging. It also concentrates demand during peak or operationally constrained periods, potentially increasing marginal emissions.

3.1.3 Behavioural factors

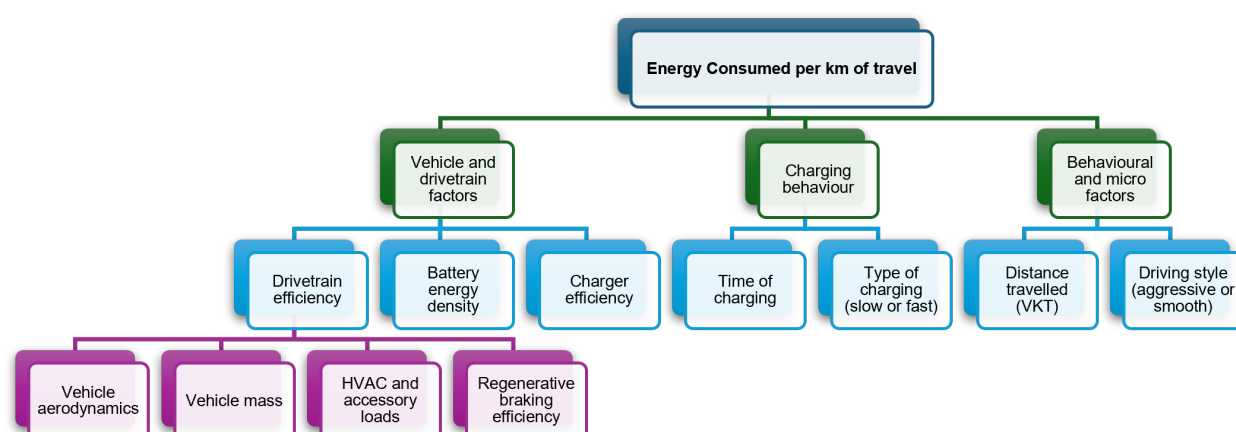
3.1.3.1 Distance Travelled (VKT)

Vehicle kilometers travelled directly scale total energy demand and emissions. High utilization fleets deliver larger absolute emission reductions when electrified, but also impose higher grid demand if charging is unmanaged.

3.1.3.2 Driving Style (aggressive or smooth)

Aggressive driving increases energy consumption due to rapid acceleration and higher peak power demand, reducing drivetrain and regenerative efficiency. Smooth driving improves energy efficiency and extends vehicle range.

³Georg Bieker ²⁰²¹. A Global Comparison of Life-Cycle Greenhouse Gas Emissions of Combustion Engine and Electric Passenger Cars. International Council on Clean Transportation (ICCT) https://theicct.org/sites/default/files/publications/Global-LCA-passenger-cars-jul2021_0.pdf

Figure 4 Summary of factors affecting the energy consumed per km of travel of an EV

3.2 EMISSIONS FROM THE POWER SECTOR

While electric vehicles have zero tailpipe emissions, their overall environmental impact is strongly influenced by the carbon intensity of electricity generation and delivery. EV charging emissions are determined by the carbon intensity of electricity generation and the additional energy required to deliver electricity through the transmission and distribution network. Both components are shaped by power sector planning decisions, operational constraints, and market design, making them critical levers for emission reduction beyond the transport domain. This section discusses the key grid side factors that determine emissions per unit of electricity supplied to EVs.

3.2.1 Grid emission factor and energy mix

The grid emission factor represents the amount of CO₂ emitted per unit of electricity generated and delivered to the end user. This factor varies significantly across time, location, and system operating conditions. Since EVs do not produce tailpipe emissions, their operational emissions are transferred upstream to the power sector. Therefore, the environmental benefit of EV adoption depends strongly on the emission intensity of the electricity used for charging.

3.2.1.1 Energy mix

The grid emission factor is primarily driven by the relative contribution of coal, gas, hydro, nuclear, and renewable energy sources at any given time. Higher renewable and hydro penetration lowers marginal emissions, while coal dominated systems exhibit persistently high emission factors. Policy driven capacity additions therefore directly influence EV emission outcomes.

In the Indian context, this distinction is critical because the regional grids have very different resource compositions. The Southern and North-Eastern grids benefit from relatively higher renewable and hydro contributions, resulting in lower emission factors. In contrast, coal-heavy regions, particularly the Eastern grid, tend to have higher emission factors, which can reduce or even offset the emission benefits of EV adoption for energy-intensive vehicle categories.

3.2.1.2 Policy Targets

National and state level renewable energy and coal retirement targets shape long term emission trajectories by altering installed capacity and dispatch priorities. However, capacity targets alone do not guarantee low emission charging unless operational alignment is achieved.

3.2.1.3 Renewable Energy Availability

Renewable generation varies strongly across time and space, creating large differences in emission intensity even within the same grid.

- Day vs night variability: Solar dominated systems exhibit low mid day emissions and high nighttime emissions when coal ramps up.
- Seasonal variability: Monsoon and spring months typically show lower emission factors due to higher hydro and wind output.
- Geographic variability: Regions with hydro or wind dominance consistently deliver lower charging emissions than coal heavy regions.

3.2.1.4 Thermal Generation

Thermal plant characteristics determine the emissions of marginal electricity.

- Coal type: Subcritical plants and high ash domestic coal result in higher emissions per unit of electricity.
- Ramp rates: Limited ramping capability forces coal units to remain online during low demand periods.
- Plant efficiency: Older plants with low efficiency increase emissions during partial load operation.

3.2.2 Dispatch and Renewable Energy Curtailment

The presence of renewable generation does not guarantee that it will be used to supply EV charging demand. System level dispatch decisions determine which resources are actually called upon.

3.2.2.1 Grid Stability Requirements

Minimum inertia, voltage control, and frequency response requirements often necessitate keeping thermal units online, even during high renewable availability. This constrains emission reduction potential through charging time shifts alone.

3.2.2.2 Ramping Requirements

Steep evening ramps driven by demand and solar decline increase reliance on fast ramping coal and gas units, raising marginal emission intensity during common EV charging periods.

3.2.2.3 System Reserves

Spinning and contingency reserves are frequently provided by thermal units, indirectly increasing emissions even when renewables are available.

3.2.2.4 Renewable forecasting accuracy

Poor renewable forecasts lead to conservative dispatch and curtailment of low carbon generation, increasing reliance on fossil backup.

3.2.2.5 Dispatch Operational Rules

Dispatch operational rules play a decisive role in shaping grid emission outcomes, often outweighing the influence of installed capacity composition. Even with identical generation assets, different dispatch frameworks can result in substantially different marginal emission intensities during EV charging hours. These rules govern which generators are committed, how they are scheduled, and how flexibly they can respond to changes in demand and renewable output.

Merit order-based dispatch prioritizes generating units with the lowest short-run marginal cost, typically favouring coal-fired generation over natural gas or energy storage in the Indian context due to prevailing fuel prices and regulated tariffs. Although this approach minimizes operating costs, it does not account for carbon externalities. Consequently, carbon-intensive generators often remain the marginal source of electricity, resulting in higher marginal emission factors, particularly during off-peak and nighttime EV charging periods when coal-dominated generation is prevalent.

Security-Constrained Economic Dispatch (SCED) improves short-term operational efficiency by optimizing generator dispatch while satisfying transmission and system security constraints. However, SCED operates within the unit commitment schedule determined in the day-ahead stage. Coal-fired units committed to satisfy forecast demand, reserve requirements, or technical minimum operating limits continue to remain online, thereby influencing the marginal generation mix. As a result, the marginal emission factor during EV charging may remain high despite SCED achieving economically efficient dispatch.

Inertia constraints further limit the displacement of synchronous thermal generation. Maintaining system frequency stability requires a minimum level of rotational inertia, which in the current Indian power system is predominantly provided by coal- and hydro-based generators. Consequently, thermal units may need to remain online even during periods of high renewable generation, increasing the marginal emission intensity of electricity supplied to EV charging.

Technical minimum operating limits impose a lower bound on the output of thermal power plants, requiring coal-fired units to remain operational even during periods of low system demand. Operating at these minimum loading levels generally reduces plant efficiency and increases specific CO₂ emissions per unit of electricity generated. This effect is particularly pronounced during nighttime charging periods, when EV demand is met by an already inflexible and carbon-intensive generation mix.

Renewable Purchase Obligations (RPOs) primarily influence long-term renewable energy procurement rather than real-time dispatch decisions. Although RPO compliance increases the overall share of renewable generation, it does not guarantee that renewable energy is available or dispatched during periods of EV charging. Consequently, EV charging may continue to be served by carbon-intensive marginal generators despite high renewable energy penetration. Unless complemented by emission-aware operational strategies, existing market and regulatory frameworks continue to prioritize system security, reliability, and economic efficiency over carbon emission minimization.

3.2.3 Grid Infrastructure

Grid infrastructure plays an important role in determining the actual emissions attributable to EV charging. While grid emission factors are often discussed in terms of generation mix, the electricity consumed by an EV is also shaped by the efficiency and condition of the network through which that electricity is delivered. Therefore, the emissions associated with EV charging are not only a function of when and where electricity is generated, but also of how efficiently it is transmitted and distributed to the charging point.

Transmission and distribution losses directly increase the upstream emissions associated with EV charging. For every unit of electricity delivered to the charger, a higher amount of electricity must be generated at the power plant to compensate for network losses. As a result, the same EV consuming the same amount of energy at the battery can have a higher well-to-wheel emission footprint in a region with higher T&D losses than in a region with a more efficient network.

Feeder length also affects EV-related emissions through its influence on technical losses. Long radial feeders, especially in distribution networks with relatively low voltage levels, high resistance, or dispersed loads, tend to experience higher voltage drops and higher losses.

Transformer loading and **Line Loading** also dictate the losses in the network. As EV charging increases transformer and line loading, particularly during evening or night-time

charging peaks, copper losses increase with the square of current. A transformer or line operating near or above its efficient loading range can therefore impose additional losses for the same delivered EV energy.

Overall, grid infrastructure affects EV emissions by modifying the effective electricity requirement at the generation end. From a planning perspective, this implies that EV emission reduction cannot be treated only as a generation-side problem. Renewable energy integration and low-carbon charging windows are essential, but distribution network efficiency, feeder design, transformer adequacy, loss reduction, metering, and local congestion management are equally important. High-loss and heavily loaded networks can erode part of the climate benefit of EV adoption.

3.2.4 Grid Operational Practises

Grid operational practices strongly influence the emissions associated with EV charging because they determine how the power system responds to additional electricity demand. Even when the installed generation mix remains unchanged, the real-time dispatch of generators, availability of network capacity, renewable curtailment, and flexibility of demand can alter the effective carbon intensity of electricity supplied to EVs. Therefore, EV emissions are not determined only by the average grid emission factor, but also by how the grid is operated during the charging period. A well-operated and flexible grid can absorb EV charging demand during periods of renewable surplus, avoid unnecessary thermal generation, reduce curtailment, and shift charging away from congested or high-emission periods. In contrast, a less flexible grid may rely on coal or gas-based generation to meet additional EV load. This can reduce the environmental advantage of EVs even if the overall share of renewable energy in the grid is increasing.

3.2.4.1 Feeder Hosting Limits

Feeder hosting capacity refers to the amount of additional load or generation that a distribution feeder can accommodate without violating thermal, voltage, or power quality limits. EV charging affects feeder hosting limits by adding new demand, while distributed renewable energy affects hosting limits through local generation injection. The interaction between these two factors can significantly influence emissions.

Voltage limits can restrict the amount of renewable energy that can be injected into distribution feeders. High solar generation during low-load periods can raise local voltages, particularly at the end of long radial feeders. If voltage exceeds permissible limits, renewable generation may need to be curtailed. This reduces the availability of low-carbon electricity and can increase the effective emissions of EV charging.

EV charging can either worsen or help manage voltage constraints depending on when and where it occurs. If EV charging is scheduled during high solar output periods, it can absorb local renewable generation and reduce overvoltage, thereby increasing renewable hosting capacity. This can lower EV charging emissions by allowing a greater share of energy to be supplied from local clean generation. However, if EV charging is concentrated during evening or night-time periods, it does not help absorb solar generation and may instead increase peak loading and losses.

3.2.4.2 Transmission Congestion

Transmission congestion affects EV emissions by limiting the ability of low-carbon electricity to reach demand centres. If the transmission network is congested, renewable-rich regions may be unable to export surplus power, and demand centres may continue to rely on local or regional thermal generation. In such cases, the average renewable capacity of the national grid may not translate into lower emission factors at the point of EV charging. The relevant emission factor depends on the electricity that can actually be delivered to the charging location under prevailing network constraints. Therefore, transmission congestion can create spatial differences in EV emissions even within an interconnected grid.

3.2.4.3 Inter-Regional Transfer Limits

Inter-regional transfer limits determine how much electricity can be exchanged between regional grids. These limits are important in a country with strong geographic diversity in generation resources. Some regions may have abundant solar, wind, or hydro generation, while others may depend more heavily on coal. If inter-regional transfer capacity is limited, regional emission factors remain strongly differentiated.

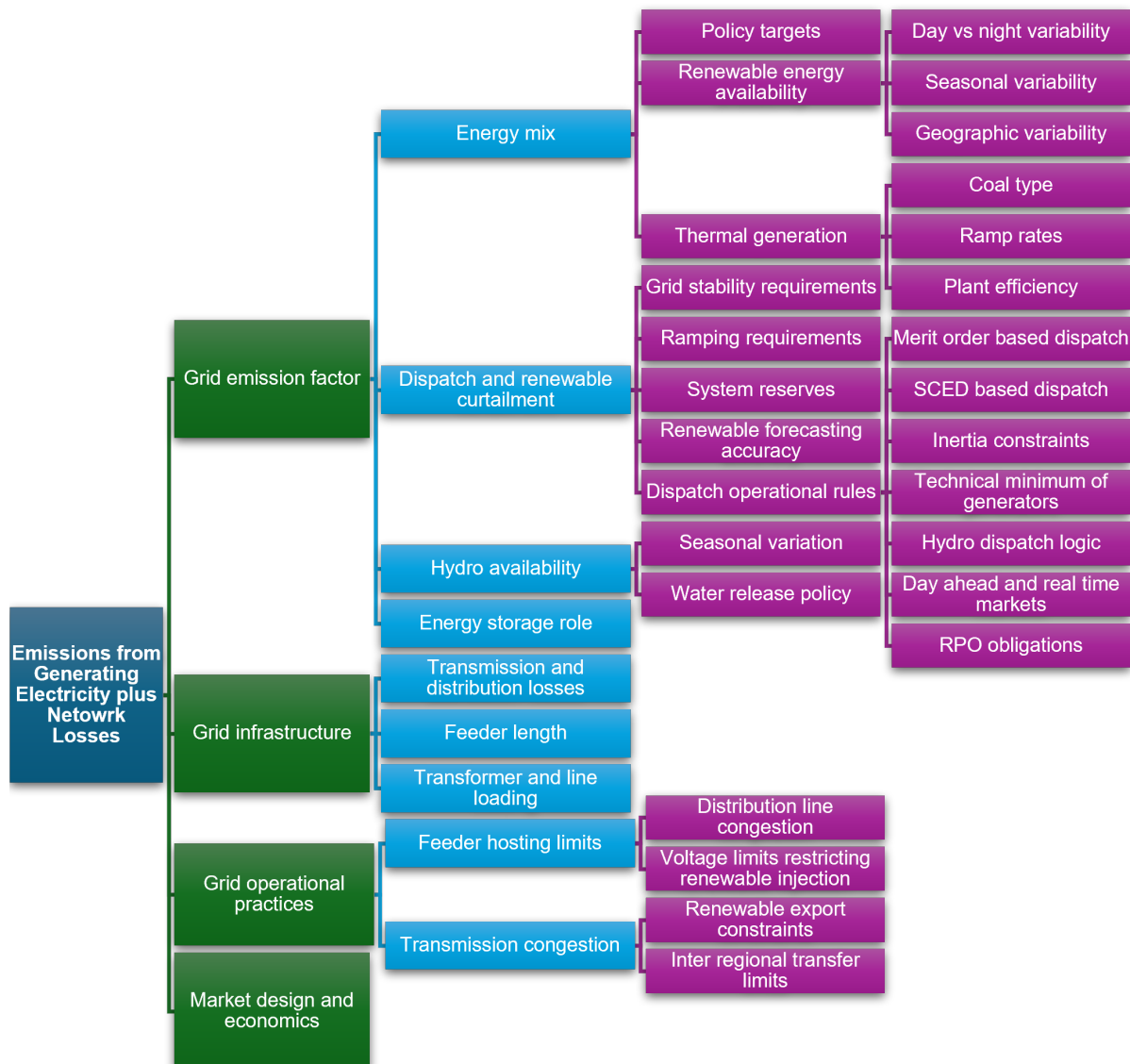
3.2.5 Market Design and Economics

Market design and electricity pricing structures play an important role in shaping the emissions associated with EV charging. While the physical emission intensity of EV charging is determined by the generation mix and network conditions, the timing and source of electricity consumption are strongly influenced by economic signals. Tariffs, wholesale market prices, renewable energy certificate prices, carbon market mechanisms, and bilateral procurement arrangements determine whether EV users and charging operators are incentivized to charge during low-cost periods, low-emission periods, or renewable-rich periods.

This distinction is important because low-cost electricity is not always low-carbon electricity. In coal-dominated systems, off-peak electricity may be cheap because demand is low and baseload thermal plants remain online, but its emission intensity may still be high. Conversely, mid-day electricity may have lower emissions due to solar generation, but the retail tariff may not always reflect this reduction in carbon intensity. Therefore, market design can either support or weaken the emission benefits of EV adoption depending on how well price signals align with grid carbon intensity.

The overall factors that impact emissions from the power sector have been summarized in Figure 5

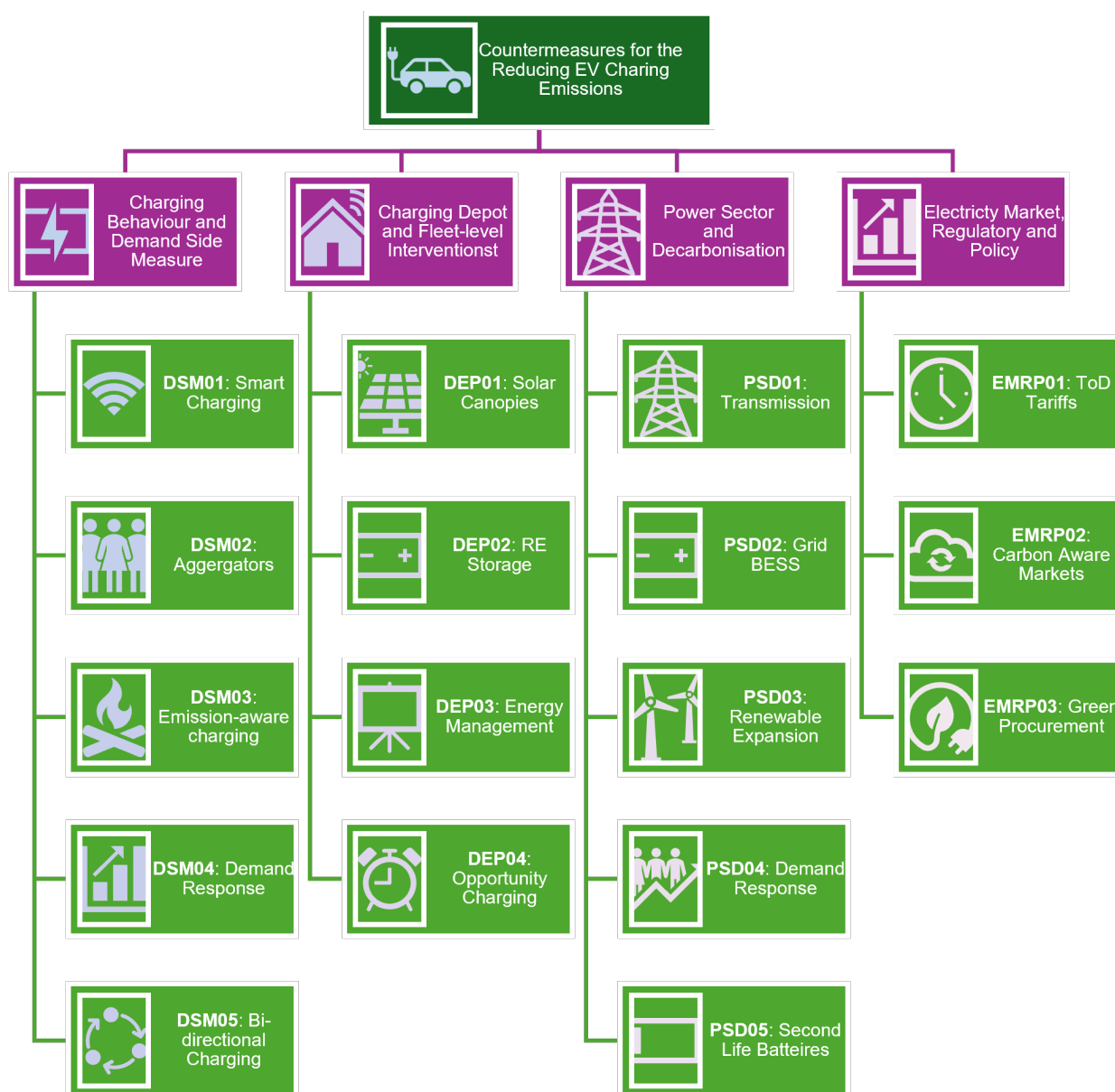
Figure 5 Factors affecting emissions from the power sector



Chapter 4 Classification Of Emission Reduction Countermeasures

The preceding sections established that the emission performance of electric vehicles in India is strongly shaped by where, when, and how electricity is generated and consumed. While EVs eliminate tailpipe emissions, their net climate benefit depends on the interaction between charging demand, grid carbon intensity, and system losses. As demonstrated through the high-resolution modelling framework developed in this study emission outcomes vary significantly across regions, seasons, vehicle categories, and charging windows.

Figure 6 Road for reducing EV charging emissions This variability highlights a critical insight:



This variability highlights a critical insight: electrification alone is not sufficient to guarantee emission reduction. Instead, a coordinated set of technical, operational, and policy interventions is required to maximise the decarbonisation potential of EV adoption. The emission reduction countermeasures operate across both the transport and the power sectors.

The integrated actions required to reduce EV charging-related emissions can be broadly classified into four key categories:

- Charging behaviour and demand side measures
- Charging depot and fleet-level interventions
- Power sector and decarbonisation measures
- Electricity market, regulatory and policy instruments

Each category encompasses a set of targeted and actionable countermeasures aimed at reducing the carbon intensity of EV charging. The hierarchical framework of these countermeasures is illustrated in Figure 1.

4.1 Charging Behaviour and demand-side Measures

These measures target the temporal mismatch between EV charging and low-emission generation.

4.1.1 DSM01: Mandate smart charging capability for all new public and private EV chargers

The modelling results presented in this study clearly demonstrate that the timing of EV charging is as important as the volume of charging in determining emission outcomes. Grid emission intensity in India varies significantly across the day and across regions, with midday periods often characterised by lower carbon intensity due to solar generation, and night-time periods typically dominated by coal-based generation. Under unmanaged charging, especially residential overnight charging and depot-based bus charging, a substantial share of EV electricity demand coincides with high-emission hours.

Mandating smart charging capability for all new EV chargers, both public and private, is therefore a foundational countermeasure to unlock emission reduction potential without constraining user mobility.

The benefits of smart charging are region-specific:

- In the Southern and Northeastern grids, smart charging amplifies already strong emission reductions.
- In the Northern and Western grids, smart charging reduces exposure to evening coal ramping.
- In the Eastern grid, smart charging alone may not fully offset coal dominance but can mitigate worst-case outcomes.

Thus, smart charging does not replace grid decarbonisation but complements it. It does not require immediate behavioural change but preserves the ability to:

- Implement emission-aware charging
- Integrate EVs into demand response
- Optimise under future high EV penetration

Given the strong diurnal and regional emission variability demonstrated in this study, failure to mandate smart charging capability risks locking India into carbon-intensive charging patterns for the next decade.

4.1.2 DSM02: Enable and regulate aggregators to manage EV charging as a flexible resource

While mandating smart charging capability creates the technical foundation for flexible charging, the real system-level benefits materialise only when charging is coordinated at scale. Individual EV owners responding independently to time-of-day signals may not provide predictable or optimised flexibility. Aggregators act as intermediaries that pool large numbers of EVs and chargers into a controllable portfolio, transforming dispersed charging loads into a dispatchable and market-participating resource.

An EV aggregator is an entity that:

- Pools multiple EV charging points across residential, commercial, and depot sites
- Optimises charging schedules collectively
- Responds to grid signals such as price, carbon intensity, or system constraints
- Participates in demand response and ancillary service markets
- Potentially coordinates bidirectional power flows

Instead of thousands of chargers operating independently, aggregators create a coordinated control layer between EV users and the grid operator. They complement:

- Smart charging mandates (technical capability)
- Emission-aware algorithms (optimisation logic)
- Carbon-indexed tariffs (economic signals)
- Bidirectional charging (flexibility expansion)

Aggregation is the institutional mechanism that unlocks the value of these technical capabilities.

In the context of India's coal-dominated evening ramps and strong midday solar variation, aggregators represent a high-impact operational countermeasure that can significantly enhance emission reduction without requiring immediate grid restructuring.

4.1.3 DSM03: Emission-aware charging and discharging algorithms

The analysis in this study demonstrates that grid carbon intensity in India exhibits strong diurnal, seasonal, and regional variability, with differences of nearly twofold between low-emission mid-day periods and high-emission night-time or evening peak hours in certain regions. Under such conditions, charging decisions based purely on electricity price or user convenience may not minimise emissions. Emission-aware charging and discharging algorithms directly address this issue by embedding carbon intensity signals into the optimisation logic governing EV charging behaviour. Instead of responding solely to tariff signals, these algorithms prioritise periods with lower marginal emissions, while respecting user mobility constraints and grid reliability requirements.

Emission-aware algorithms use real-time or forecasted grid emission factors as an input variable in scheduling decisions. The objective function is modified to minimise carbon emissions, or a weighted combination of cost and emissions, subject to operational constraints.

In its simplest form, charging energy is allocated preferentially to time blocks where the grid emission factor is lowest. In more advanced implementations, optimisation considers, forecasted carbon intensity, user departure time and minimum state of charge, charger power limits, network constraints, renewable generation forecasts, electricity price signals. For bidirectional chargers, the algorithm may also schedule controlled discharge during high-emission periods

to displace marginal fossil generation.

4.1.4 DSM04: Integrate EV charging into broader demand response programmes

In several regions, particularly under the 2030 Stated Policies scenario, EV charging becomes a non-trivial share of peak demand. If unmanaged, this load may reinforce coal-dominated evening peaks and increase marginal emissions. Integrating EV charging into formal demand response (DR) programmes transforms EVs from passive loads into controllable system assets that can actively support grid stability and emission reduction.

Traditionally, demand response programmes have focused on industrial and commercial consumers capable of reducing load during peak periods. However, EV charging possesses inherent flexibility characteristics that make it particularly suitable for demand response participation. Charging is temporally shiftable within defined user constraints, the charging rate is electronically controllable, and aggregate energy requirements are predictable. These attributes enable EV charging to be treated as a controllable demand-side resource rather than a fixed load.

Incorporating EV charging into demand response programmes allows utilities or aggregators to temporarily delay, reduce, or reschedule charging in response to grid stress conditions. During high-emission evening peaks, coordinated demand response can reduce aggregate charging load, thereby limiting reliance on marginal coal generation. Conversely, during periods of surplus renewable generation, such as midday solar peaks in the Southern grid or hydro-dominant monsoon conditions, demand response mechanisms can actively increase charging uptake to absorb low-carbon electricity that might otherwise be curtailed. This flexibility enhances both emission performance and system efficiency.

4.1.5 DSM05: Bidirectional EV Charging

Bidirectional EV charging, commonly referred to as Vehicle-to-Grid (V2G) or Vehicle-to-Everything (V2X), represents an advanced flexibility mechanism that extends beyond managed charging. Whereas smart charging and demand response focus on controlling the timing and rate of electricity consumption, bidirectional charging enables EVs to discharge stored energy back to the grid or local loads. This transforms EV batteries into distributed energy storage assets capable of actively supporting grid operations and emission reduction.

The emission reduction potential of bidirectional charging arises from its ability to displace high-emission marginal generation. Under controlled operation, EVs can charge during low-emission periods characterised by high renewable output and discharge during high-emission peak hours dominated by coal-based generation. For example, electric buses charging during midday solar peaks and partially discharging during evening demand surges can reduce coal ramping requirements. At scale, such coordinated behaviour may meaningfully lower system-wide emission intensity during peak periods.

Beyond emission reduction, bidirectional fleets can provide ancillary services including frequency regulation, voltage support, and spinning reserve substitution. Fast-response inverter-based discharge can stabilise frequency deviations more rapidly than conventional thermal plants, reducing the need for fossil-based balancing reserves. In distribution networks with high EV penetration, controlled discharge can mitigate transformer loading and improve voltage profiles.

4.2 Charging Depot And Fleet-Level Interventionsu

Unlike distributed residential charging, depot-based charging aggregates large amounts of power demand at specific nodes in the distribution network, often within short time windows. This concentration has two important implications. First, it can intensify local grid stress and increase technical losses. Second, when charging occurs predominantly during evening and night hours, it may coincide with periods of higher grid carbon intensity, thereby limiting the emission reduction potential of electrification.

Charging depots therefore represent high-leverage intervention points within the EV ecosystem. Unlike private residential chargers, depot charging is centrally managed, predictable, and operationally structured. This makes depots particularly suitable for implementing renewable-aligned and emission-aware charging strategies. The following countermeasures target depot-level infrastructure and operations to enhance emission performance and system integration.

4.2.1 DEP01: Solar canopies over parking and charging areas

Installing solar photovoltaic (PV) canopies over parking and charging areas enables direct on-site renewable energy generation that can partially or fully supply EV charging demand during daylight hours. Given the strong midday solar generation profile observed across most Indian regions, particularly in the Southern and Western grids, on-site solar deployment at depots creates a direct pathway for low-carbon charging.

Solar canopies serve a dual purpose. Structurally, they provide shaded parking and protection from weather conditions, improving operational comfort and asset longevity. Electrically, they convert otherwise unused surface area into distributed renewable generation capacity. When integrated with smart charging systems, solar output can be prioritised for EV charging, reducing reliance on grid electricity during high-emission periods.

In addition to emission benefits, on-site solar reduces peak demand charges and improves energy cost stability. For large urban bus depots with predictable daytime dwell periods, solar canopies offer an effective mechanism to align charging with renewable availability. However, standalone solar deployment may be insufficient for evening charging unless combined with storage solutions, which leads to the next countermeasure.

4.2.2 DEP02: Dedicated renewable plus storage microgrids for high-capacity depots

High-capacity depots, particularly those serving electric bus fleets, often operate at megawatt-scale charging levels. In such contexts, integrating dedicated renewable generation with battery energy storage systems within a microgrid configuration can significantly enhance emission performance and grid independence.

A renewable-plus-storage microgrid enables the depot to capture and store solar generation during the day and utilise it during evening or night charging periods. This reduces reliance on grid electricity during high-emission hours and mitigates peak demand stress on the distribution network. Storage also smooths variability in renewable output, ensuring charging reliability without compromising operational schedules. From an emission perspective, microgrids alter the temporal profile of energy consumption. Instead of drawing high-emission grid electricity during evening ramps, depots can discharge stored solar energy. This directly addresses the temporal mismatch identified in this study between bus charging patterns and low-emission grid windows.

Moreover, microgrids enhance resilience and reliability. During grid disturbances, depots equipped with storage can maintain essential charging operations, ensuring continuity of public transport services. While capital-intensive, renewable-plus-storage microgrids represent a structural solution for large fleet operators seeking long-term decarbonisation and cost stability.

4.2.3 DEP03: Mandatory Energy Management Systems for large depots

As depot charging scales in size and complexity, manual scheduling becomes insufficient to optimise cost, emissions, and grid impact simultaneously. Mandatory deployment of advanced Energy Management Systems (EMS) for large depots provides the computational and operational intelligence necessary for coordinated control.

An EMS integrates real-time data on charger status, vehicle state-of-charge, renewable generation output, storage levels, grid tariffs, and carbon intensity signals. Using optimisation algorithms, it schedules charging sequences to meet fleet operational requirements while minimising emissions and peak demand.

The emission benefits of EMS deployment are derived from intelligent load shaping. Instead of all vehicles charging immediately upon return to the depot, the EMS staggers charging, prioritises renewable-rich periods, and limits simultaneous high-power draw. When integrated with storage and solar systems, the EMS can further optimise charging-discharge cycles to maximise low-carbon energy utilisation.

4.2.4 DEP04: Opportunity and flash charging for buses

The modelling results highlight a structural issue in bus electrification under current grid conditions: the predominance of overnight depot charging aligns poorly with India's emission intensity profile. Evening and night hours frequently correspond to higher carbon intensity due to coal-dominated generation. Relying exclusively on overnight charging therefore limits emission reduction potential.

Opportunity charging and flash charging provide an alternative operational model. Instead of concentrating charging at night, buses can recharge partially during scheduled layovers, terminal stops, or route endpoints during the day. These charging sessions often coincide with periods of higher solar generation and lower grid emission intensity.

By distributing charging demand across the day, opportunity charging reduces the magnitude of overnight peaks and aligns a larger share of energy consumption with renewable availability. Even partial midday charging can significantly lower the average carbon intensity of electricity consumed by the fleet.

Flash charging infrastructure requires higher-power chargers and appropriate grid connections, but when strategically deployed along routes or at depots, it reduces dependency on emission-intensive night-time charging. From an emissions standpoint, opportunity charging represents one of the most effective operational strategies for improving the carbon performance of electric bus fleets without increasing total energy consumption.

4.3 Power Sector Decarbonization Measures

While managed EV charging can reduce the emissions associated with electrification, its effectiveness is ultimately constrained by the carbon intensity of the electricity available on the grid. The preceding analysis shows that EV emission outcomes vary strongly across regions and time blocks, with lower emission intensity generally observed during renewable-rich periods and higher emission intensity during coal-dominated evening, night, and early morning periods. This indicates that transport electrification must be supported by wider power sector decarboniza-

tion measures. The following interventions are therefore introduced as system-level measures that can reduce the carbon intensity of EV charging and improve the overall climate benefits of electrification.

4.3.1 PSDM01: Strengthen transmission corridors to evacuate renewable energy from generation-rich regions to load centres.

A key barrier to deeper decarbonization of EV charging is the spatial mismatch between renewable energy generation and electricity demand. Large solar and wind resources are often concentrated in generation-rich states and regions, whereas EV charging demand is concentrated in urban and industrial load centres. Without adequate transmission capacity, surplus renewable generation may remain underutilized or curtailed, while load centres continue to rely on local or regional fossil-based generation. Strengthening inter-regional and intra-regional transmission corridors can help address this mismatch by enabling greater transfer of renewable electricity from resource-rich areas to high-demand regions. For example, solar-rich western and northern states, wind-rich southern and western states, and hydro-rich regions can provide cleaner electricity to urban load centres where EV penetration is expected to grow rapidly.

This is particularly important for regions where the current grid emission factor remains high due to coal dependence. From an EV decarbonization perspective, transmission strengthening should therefore be viewed not only as a renewable energy integration measure, but also as an enabling intervention for cleaner transport electrification. Improved transfer capability can reduce renewable curtailment, improve the availability of low-carbon electricity during charging periods, and support wider balancing of variable renewable generation across regions.

4.3.2 PSDM02: Deploy utility-scale battery energy storage systems to absorb surplus renewable energy and serve peak demand.

Utility-scale battery energy storage systems can play a critical role in reducing the temporal mismatch between renewable generation and electricity demand. The analysis shows that grid emission intensity is generally lowest during mid-day hours, when solar generation is high, and highest during evening, late-night, and early-morning periods, when coal-based generation plays a larger role. Battery energy storage can address this problem by absorbing surplus renewable electricity during low-emission periods and discharging it during high-demand or high-emission periods. At the system level, storage also improves operational flexibility. It can provide peak shaving, frequency support, ramping support, congestion relief, and reserve capacity.

4.3.3 PSDM03: Focus on utility scale RE installation

A key power sector intervention for reducing EV-related emissions is the accelerated deployment of utility-scale renewable energy projects in regions where electricity generation remains dominated by coal and other thermal sources. In thermal-heavy grids, the electricity used for charging may continue to be supplied predominantly by fossil-based generation, thereby limiting the climate benefit of transport electrification. Utility-scale solar, wind, hybrid renewable parks, and renewable energy zones can directly reduce the average and marginal carbon intensity of electricity in these regions. By increasing the share of low-carbon generation within thermal-dominated grids, such installations can reduce the emissions associated with both existing electricity demand and additional EV charging load. Therefore, renewable energy expansion must be prioritized not only at the national level, but also in regions where the grid emission factor remains persistently high.

4.3.4 PSDM04: Integrate Ev Charging Into Broader Demand Response Programmes

In several regions, particularly under the 2030 Stated Policies scenario, EV charging becomes a non-trivial share of peak demand. If unmanaged, this load may reinforce coal-dominated evening peaks and increase marginal emissions. Integrating EV charging into formal demand response (DR) programmes transforms EVs from passive loads into controllable system assets that can actively support grid stability and emission reduction.

Traditionally, demand response programmes have focused on industrial and commercial consumers capable of reducing load during peak periods. However, EV charging possesses inherent flexibility characteristics that make it particularly suitable for demand response participation. Charging is temporally shiftable within defined user constraints, the charging rate is electronically controllable, and aggregate energy requirements are predictable. These attributes enable EV charging to be treated as a controllable demand-side resource rather than a fixed load.

Incorporating EV charging into demand response programmes allows utilities or aggregators to temporarily delay, reduce, or reschedule charging in response to grid stress conditions. During high-emission evening peaks, coordinated demand response can reduce aggregate charging load, thereby limiting reliance on marginal coal generation. Conversely, during periods of surplus renewable generation, such as midday solar peaks in the Southern grid or hydro-dominant monsoon conditions, demand response mechanisms can actively increase charging uptake to absorb low-carbon electricity that might otherwise be curtailed. This flexibility enhances both emission performance and system efficiency.

4.3.5 PSDM05: Second-Life Ev Battery Banks

Second-life EV battery banks can provide a cost-effective and circular-economy pathway for stationary energy storage. EV batteries that no longer meet vehicle performance requirements may still retain sufficient capacity for less demanding stationary applications. These batteries can be repurposed into battery banks for EV charging stations, depots, renewable energy systems, commercial buildings, and distribution-level grid support. This measure also improves the sustainability of the EV ecosystem by extending battery life before recycling. It reduces the lifecycle environmental burden of batteries, delays waste generation, and creates an additional value stream for retired EV batteries. However, implementation would require proper battery health assessment, safety standards, thermal management, battery management systems, and clear regulatory guidelines for second-life deployment.

4.4 Electricity Market, Regulatory And Policy Instruments

Power sector decarbonization measures need to be complemented by market, regulatory, and policy instruments that influence how electricity is priced, procured, and consumed. For EV charging, this is particularly important because charging decisions are highly sensitive to tariffs and operational signals. If market signals are based only on cost or grid congestion, charging may shift to low-price periods that are not necessarily low-emission. Therefore, electricity market design must evolve to reflect both system economics and carbon intensity, so that EV charging demand is encouraged to align with cleaner generation periods.

4.4.1 Emrp01: Introduce Time-Of-Day Tariffs

Time-of-day tariffs are an important market-based instrument for shaping electricity consumption patterns, particularly for flexible loads such as EV charging. Under a conventional flat tariff, consumers face the same electricity price regardless of when they charge, even though the

cost of supplying electricity varies significantly across the day. This can lead to clustering of EV charging during evening or night hours, depending on user behaviour, depot schedules, and residential charging habits. As EV adoption increases, such unmanaged charging can add to local distribution stress and system peak demand.

A time-of-day tariff addresses this issue by assigning different electricity prices to different time blocks. Higher tariffs during peak demand periods discourage charging when the grid is already stressed, while lower tariffs during off-peak periods encourage users to shift charging to hours when spare system capacity is available. This improves load factor, reduces peak demand, and can defer the need for costly grid upgrades. For EV users, the tariff provides a clear economic signal: charging during lower-priced periods reduces operating cost, while charging during peak periods becomes less attractive. However, as ToD tariff only depends on price signals, it may not definitively lead to lower emissions, and may vary from region to region.

4.4.2 EMRP02: Develop carbon-aware pricing mechanisms for wholesale electricity markets

At the wholesale market level, carbon-aware pricing mechanisms can help ensure that electricity dispatch and procurement decisions internalize the emissions impact of generation. In the absence of such mechanisms, market prices primarily reflect fuel costs, availability, demand, and network constraints, but may not adequately capture the environmental cost of carbon-intensive generation. This can result in situations where low-cost thermal generation continues to dominate dispatch, even when cleaner alternatives may be available.

Carbon-aware pricing can be implemented through several mechanisms. One approach is to incorporate carbon intensity signals directly into market clearing or scheduling frameworks, so that generation with lower emissions is preferentially dispatched when technically and economically feasible. Another approach is to introduce carbon adders, emission-linked penalties, or tradable carbon instruments that increase the effective cost of high-emission generation. Such measures can gradually shift market outcomes toward cleaner electricity without requiring every consumer to individually track grid emission factors.

4.4.3 EMRP03: Encourage favourable terms for green access power procurement for large EV charging customers.

Large EV charging customers, such as bus depots, commercial fleet operators, logistics hubs, public charging networks, and highway charging stations, can play an important role in driving renewable energy procurement. These consumers have large and relatively predictable electricity demand, making them suitable candidates for green open access, renewable power purchase agreements, and dedicated renewable energy contracts. Favourable procurement terms can help ensure that the electricity used for high-volume EV charging is increasingly sourced from renewable energy.

Green access mechanisms can allow large EV charging customers to procure electricity directly from renewable energy generators, either within the state or through inter-state arrangements, subject to regulatory approvals and network charges. This can reduce the effective carbon intensity of EV charging, especially in regions where the local grid remains thermal-dominated. For example, a bus depot or logistics charging hub located in a coal-heavy region could procure solar, wind, or hybrid renewable power from a renewable-rich region, thereby improving the emissions performance of its fleet operations.

Chapter 5 Comparative Assessment Of Countermeasures

While baseline emission estimation provides a realistic assessment of current outcomes, it does not answer a critical policy question: how much further can EV-related emissions be reduced through intelligent charging strategies? More specifically, can economic or carbon signals be used to reshape charging demand in a manner that aligns electricity consumption with lower-emission generation periods?

To address this question, an optimization-based analytical framework was developed to evaluate the emission reduction potential of three intervention mechanisms:

- Exposure of EV charging to wholesale electricity price signals from the wholesale electricity market
- Incorporation of time-resolved carbon price signals derived from generator dispatch and marginal emission intensity,
- A hybrid framework combining carbon pricing with an explicit aggregate emission constraint.

Unlike earlier Time-of-Day tariff analyses, which primarily reflect retail price structures, this framework operates at the system level and leverages wholesale and carbon-reflective signals that more closely mirror underlying grid conditions. The optimization is performed separately for:

- All India and each of the five regional grids,
- Five representative seasons,
- Weekday and weekend charging profiles,
- All major EV fleet categories.

The objective is to quantify the technically achievable emission reduction potential under realistic flexibility constraints, while also assessing trade-offs between charging cost and carbon abatement.

By systematically comparing these intervention strategies across regions and seasons, this chapter identifies the upper bound of emission reductions achievable through charging optimization alone, without altering fleet size or grid capacity.

The results provide critical insights for policymakers, regulators, and grid operators regarding the design of smart charging mandates, carbon pricing frameworks, and renewable-aligned EV charging programs in India.

5.1 INTERVENTIONS SCENARIOS

To quantify the emission reduction potential achievable through intelligent charging strategies, three intervention scenarios are evaluated within the developed optimization framework. Each scenario reshapes the temporal allocation of EV charging demand while preserving fleet-specific daily energy requirements and operational constraints. The scenarios differ in the signal used to guide charging decisions and, in the presence, or absence of explicit carbon control mechanisms.

5.1.1 Scenario 1: Wholesale Price Signal

In the first scenario, EV charging is optimized using time-resolved wholesale electricity prices obtained from the Day-Ahead Market. The objective function minimizes total charging cost over the day, subject to fleet energy requirements, charging power limits, and temporal feasibility constraints. No explicit emission objective or carbon constraint is imposed. Emission outcomes therefore emerge indirectly from the interaction between price signals and the underlying generation mix. This scenario represents a market-driven smart charging paradigm, where economic incentives alone shape charging behaviour. Its effectiveness depends on the degree to which low-price periods coincide with low-carbon generation.

5.1.2 Scenario 2: Carbon Price Signal (Marginal Emission Pricing)

The second scenario replaces wholesale electricity prices with a time-varying carbon price signal derived from generator dispatch and marginal emission intensity. The optimization objective minimizes total carbon cost, computed as the product of charging energy and time-specific carbon price. As in the first scenario, no explicit aggregate emission cap is imposed; rather, emissions are reduced through price-induced temporal shifting. This framework simulates an implicit carbon market that internalizes the environmental cost of electricity consumption. Charging is preferentially shifted toward periods with lower marginal emission factors, even if such periods are not the cheapest in purely economic terms.

5.1.3 Scenario 3: Carbon Price with Emission Constraint

In the third scenario, the carbon price signal remains similar to Scenario 2, where time-varying carbon costs are incorporated into the charging optimization. However, Scenario 3 introduces an explicit emission constraint which is imposed within the generator scheduling framework.

Unlike Scenario 2, where emission reductions emerge indirectly through price-based temporal shifting of charging demand, Scenario 3 explicitly constrains total emissions within the power system dispatch itself. In other words, generator commitment and dispatch decisions are no longer based solely on economic merit order, but must also satisfy a predefined upper bound on system-level emissions over the scheduling horizon⁴.

Together, these three scenarios provide a structured comparison between market-driven optimization, carbon-internalized pricing, and regulation-backed decarbonization. By applying them consistently across regions, seasons, and fleet categories, the framework identifies the relative effectiveness of price signals and emission constraints in reshaping EV charging demand and reducing system-wide emissions.

5.2 COMPARATIVE ASSESSMENT

⁴ Because the emission constraint may restrict the dispatch of lower-cost but higher-emission generators (for example, coal units during off-peak hours), the resulting generation schedule may deviate from the pure economic merit order. As a result, total system operating cost may increase relative to Scenario ². This cost increase reflects the trade-off between economic efficiency and guaranteed environmental performance.

5.2.1 Basis of Comparison

To evaluate the effectiveness of the proposed countermeasures, a comparative assessment is carried out based on two key performance indicators: emission reduction and marginal abatement cost (MAC). The emission reduction is calculated as the difference between the base-case emissions and the emissions after implementing the intervention:

$$\Delta E = E_{base} - E_{intervention}$$

where E_{base} and $E_{intervention}$ denote the emissions under the base-case and intervention scenarios, respectively. A positive value of ΔE indicates that the intervention successfully reduces emissions, whereas a negative value indicates an increase in emissions relative to the corresponding base case. The cost-effectiveness of each intervention is evaluated using the marginal abatement cost (MAC), defined as

$$MAC = \frac{C_{intervention} - C_{base}}{E_{base} - E_{intervention}}$$

Where C_{base} and $C_{intervention}$ represent the total system cost under the base-case and intervention scenarios, respectively. The MAC is expressed in Rs/tCO₂ and represents the incremental cost incurred for each tonne of CO₂ emissions avoided.

The sign of the MAC should not be interpreted in isolation, as its significance depends on the direction of the emission change. For example, a negative MAC may indicate a cost-saving emission reduction or a cost-saving increase in emissions, depending on the sign of ΔE . Similarly, a positive MAC may correspond to either a costlier emission reduction or a costlier

increase in emissions. Therefore, the MAC should always be interpreted jointly with the emission change. The interpretation of the different combinations of emission change and MAC is summarized in Table 1, where the green-shaded region identifies the desirable interventions that achieve emission reductions while remaining economically favourable or justifiable

Table 1 Interpretation of marginal abatement cost (MAC) signs based on the corresponding signs of cost change and emission change.

MAC	Numerator		Denominator	
Sign	Sign	Interpretation	Sign	Interpretation
+	+	Intervention costs higher	+	Emissions lower
+	-	Intervention costs lower	-	Emissions higher
-	+	Intervention costs higher	-	Emissions higher
-	-	Intervention costs lower	+	Emissions lower

5.2.2 All India

The All-India results provide a consolidated view of how the interventions perform when the regional effects are aggregated at the national level. Table 2 shows the combined seasonal impact of each intervention under the BAU and Stated Policies scenarios⁵. The results confirm that the effectiveness of each intervention depends not only on the control strategy but also on the

⁵ The BAU and State Policies Scenarios have been described in Report 1 of the study.

season in which it is applied.

Table 2 Pan-India seasonal comparison of demand flexibility and V2G interventions under BAU and Stated Policies scenarios, showing marginal abatement cost, daily cost impact, and emission change across representative seasons

Interventions	Scenario	MAC (Rs/tCO ₂)						Cost (Rs)	Emission (kt CO ₂)					
		Winter	Spring	Summer	Monsoon	Autumn	Avg		Winter	Spring	Summer	Monsoon	Autumn	Avg
Demand Flexibility (Market Prices)	BAU	-53.00	173.00	329.00	-58.00	106.33	99.47	-₹ 79,573.33	-4	1	1	-5	3	-0.80
Demand Flexibility (Carbon Prices)	BAU	465.00	-455.50	-454.50	300.33	-235.50	-76.03	-₹ 45,620.00	-2	2	2	-3	4	0.60
Demand Flexibility (Carbon Prices) + Emission Aware	BAU	25.00	18.33	46.93	61.60	26.20	35.61	₹ 4,77,205.90	6	12	14	20	15	13.40
V2G (Market Prices)	BAU	559.67	-1038.50	-2079.00	484.75	-462.00	-507.02	₹ 0.00	-3	2	1	-4	4	0.00
V2G (Carbon Prices)	BAU	759.67	-1326.50	-1481.50	713.25	-633.00	-393.62	-₹ 78,723.33	-3	2	2	-4	4	0.20
V2G (Carbon Prices) + Emission Aware	BAU	-202.50	-127.50	-97.29	-34.40	-83.80	-109.10	-₹ 14,61,901.71	6	12	14	20	15	13.40
Demand Flexibility (Market Prices)	Stated Policies	-415.67	-395.25	-2445.00	608.50	-841.33	-697.75	-₹ 13,95,500.00	6	4	1	-4	3	2.00
Demand Flexibility (Carbon Prices)	Stated Policies	-415.67	-395.25	-2445.00	608.50	-841.33	-697.75	-₹ 13,95,500.00	6	4	1	-4	3	2.00

Demand Flexibility (Carbon Prices) + Emission Aware	Stated Policies	-120.15	-64.80	-77.17	-108.12	-133.00	-100.65	-₹ 10,87,010.31	13	10	12	8	11	10.80
V2G (Market Prices)	Stated Policies	-1469.67	-	2773.50	807.71	-4996.00	-721.11	₹ 7,21,113.10	3	0	-2	-7	1	-1.00
V2G (Carbon Prices)	Stated Policies	-1213.60	-	-7980.00	1534.40	-2157.67	-2454.22	-₹ 19,63,373.33	5	0	1	-5	3	0.80
V2G (Carbon Prices) + Emission Aware	Stated Policies	-431.17	-534.13	-537.67	-758.75	-505.00	-553.34	-₹ 56,44,085.00	12	8	12	8	11	10.20

Under the BAU scenario, demand flexibility based on market prices produces mixed seasonal outcomes. Emissions increase in winter and monsoon, while reductions are observed in spring, summer, and autumn. On average, the intervention results in an emission change of -0.80 ktCO_2 , indicating a net increase in emissions at the national level, despite a daily cost reduction of ₹79,573.33⁶. This suggests that market-price-based flexibility can lower operating costs but may shift charging to periods with higher carbon intensity. Demand flexibility based on carbon prices performs slightly better under BAU, giving a small average emission reduction of 0.60 ktCO_2 along with a daily cost reduction of ₹45,620.00. However, the seasonal results remain inconsistent, with emission increases in winter and monsoon and reductions in the other seasons.

A much stronger improvement is observed when demand flexibility is combined with carbon prices and emission awareness. This intervention reduces emissions in all five seasons, with the largest reduction observed during the monsoon season at 20 ktCO_2 . The average emission reduction is 13.40 ktCO_2 , which is substantially higher than the market-price and carbon-price-only cases. However, this benefit is associated with an increase in daily cost of ₹4,77,205.90. Therefore, under BAU, emission-aware demand flexibility is environmentally effective but requires additional expenditure at the national level. The strongest BAU outcome is obtained for V2G with carbon prices and emission awareness. This intervention reduces emissions in all seasons and achieves an average reduction of 13.40 ktCO_2 , equal to the emission-aware demand flexibility case. However, unlike demand flexibility, it also reduces daily cost by ₹14,61,901.71. The average MAC of -109.10 Rs/tCO_2 indicates that, at the Pan-India level, this intervention achieves emission reduction together with cost savings. Thus, under BAU, emission-aware V2G emerges as the most favourable national intervention among the evaluated cases.

Similarly, under the Stated Policies Scenario, demand flexibility based on market prices and carbon prices shows identical results. The best Stated Policies outcome is obtained for V2G with carbon prices and emission awareness. This intervention reduces emissions in all five seasons, with an average emission reduction of 10.20 ktCO_2 . It also provides the largest daily cost saving among all Stated Policies interventions, at ₹56,44,085.00. The average MAC of -553.34 Rs/tCO_2 indicates that emission reduction is achieved along with significant cost savings. Thus, under the Stated Policies Scenario, emission-aware V2G is the strongest Pan-India intervention from both an emission and cost perspective.

Overall, the Pan-India results show that emission-aware interventions are more reliable than price-only interventions. Market-price and carbon-price strategies may reduce cost, but their emission impact varies across seasons and can become negative in specific periods. In contrast, emission-aware demand flexibility and emission-aware V2G consistently reduce emissions across all seasons under both scenarios. Among these, emission-aware V2G provides the most favourable combined outcome, especially under the Stated Policies Scenario, where it delivers both large emission reductions and substantial cost savings.

However, the Pan-India average should not be interpreted as a uniform national effect. It masks significant regional differences in grid carbon intensity, renewable availability, and charging behaviour. Therefore, while the national results indicate the broad potential of emission-aware flexibility and V2G, the regional results are necessary to identify where these interventions are most effective and where they may require additional design modifications.

⁶ Operational cost refers only to the cost associated with generator dispatch in the power system simulation. Additional costs, such as charger investment, battery degradation, communication infrastructure, control implementation, or transaction costs, are not included in this estimate.

5.2.3 Comparisons across India's Regional Grids

The results shown in Table 3 show a strong regional dependence. The Southern region consistently benefits the most from emission-aware interventions under both BAU and Stated Policies. This is likely because the region has a more favourable temporal alignment between renewable generation availability and flexible charging potential. As a result, shifting EV charging toward cleaner periods produces substantial emission reductions. The Northern region benefits from emission-aware scheduling, but price-only strategies can lead to emission increases under the Stated Policies Scenario. This suggests that the Northern grid has useful low-carbon windows, but these windows are not always aligned with market-price signals.

The Western region shows mixed behaviour. Under non-emission-aware interventions, emissions can increase, particularly in the BAU V2G cases. However, once emission awareness is included, the region shows positive emission reductions. This indicates that the Western region has emission reduction potential, but it requires careful scheduling. The Eastern region shows relatively small emission reductions in many cases. Given its coal-dominated generation mix, the scope for emission reduction through temporal shifting alone is limited. Emission-aware interventions improve outcomes, but the absolute reductions remain modest compared to the Southern and Northern regions.

The North-Eastern region behaves differently from the other regions. In several Stated Policies cases, emissions increase despite intervention. This does not necessarily imply poor intervention design; rather, it reflects the fact that the region already has a low-carbon grid. Since the baseline emission factor is low, there is limited additional carbon benefit from shifting charging demand. Therefore, interventions in this region may need to be evaluated more from the perspective of grid flexibility, reliability, and renewable balancing rather than only emission reduction.

Overall, the analysis shows that demand flexibility and V2G interventions are highly dependent on regional grid characteristics. No single intervention performs uniformly across all regions or scenarios. The same strategy can reduce emissions in one region, increase emissions in another, reduce cost in some cases, and increase cost in others. The key reason is that intervention performance depends on the temporal relationship between EV charging demand, electricity price, renewable availability, and grid emission intensity. Market-price-based strategies may be economically attractive, but they do not necessarily reduce emissions. Carbon-price-based strategies improve the signal but may still be insufficient unless the scheduling directly incorporates time-varying emission factors.

Emission-aware interventions provide the most consistent emission reductions across the analysed cases. However, even these interventions are not universally beneficial in every region. Their effectiveness depends on whether the regional grid has sufficient variation in carbon intensity and whether flexible charging can be shifted toward genuinely cleaner periods. For regions with high renewable variability, emission-aware flexibility can provide substantial carbon benefits. For coal-dominated regions, flexibility must be combined with grid decarbonisation or renewable-linked charging.

Table 3 Regional comparison of demand flexibility and V2G interventions under BAU and Stated Policies scenarios, showing marginal abatement cost and emission change across India's five regional grids

Interventions	Scenario	MAC (Rs/tCO ₂)					Emissions (kt CO ₂)				
		NR	WR	SR	ER	NER	NR	WR	SR	ER	NER
Demand Flexibility (Market Prices)	BAU	21.67	-19.94	-29.18	94.38	8.33	1.20	-1.60	0.20	-0.60	0.00
Demand Flexibility (Carbon Prices)	BAU	14.08	53.10	4.10	122.10	-16.17	1.20	-1.20	0.60	-0.20	0.00
Demand Flexibility (Carbon Prices) + Emission Aware	BAU	49.35	-610.23	218.57	177.60	-16.17	8.40	2.20	17.40	0.20	0.00
V2G (Market Prices)	BAU	75.40	76.71	136.46	-286.60	-7.17	0.60	-2.20	0.40	-0.20	0.00
V2G (Carbon Prices)	BAU	73.90	688.66	339.92	-294.10	-20.83	0.60	-2.40	0.40	-0.20	0.00
V2G (Carbon Prices) + Emission Aware	BAU	118.86	113.10	190.31	-1628.67	-21.50	7.80	2.40	17.40	0.40	0.00
Demand Flexibility (Market Prices)	Stated Policies	26.15	264.55	-57.85	1.23	61.08	-1.60	1.60	1.80	0.40	-1.40
Demand Flexibility (Carbon Prices)	Stated Policies	26.15	264.55	-57.85	1.23	61.08	-1.60	1.60	1.80	0.40	-1.40
Demand Flexibility (Carbon Prices) + Emission Aware	Stated Policies	163.87	46.27	198.07	-84.67	63.08	6.80	4.60	19.20	0.60	-1.40
V2G (Market Prices)	Stated Policies	8.92	-291.08	356.18	-89.38	68.21	-3.40	0.60	2.00	0.40	-1.40
V2G (Carbon Prices)	Stated Policies	7.25	-486.70	332.16	29.17	121.79	-3.40	0.80	2.00	0.60	-1.40
V2G (Carbon Prices) + Emission Aware	Stated Policies	43.82	59.97	122.83	86.38	123.62	4.40	3.60	21.00	0.60	-1.40

Chapter 6 Region Specific Countermeasures

6.1 METHODOLOGY FOR RANKING REGIONAL COUNTERMEASURES

This section presents the methodological framework used to rank EV related countermeasures across India's regional grids. The objective of the ranking exercise is not merely to list interventions, but to systematically prioritise them based on their relative contribution to emission reduction, feasibility of implementation, cost implications, and institutional readiness. Given the strong regional variation in grid carbon intensity, fleet composition, and charging load profiles established in the preceding sections, the ranking framework is designed to produce region specific priority lists for the Northern (NR), Western (WR), Southern (SR), Eastern (ER), and Northeastern (NER) grids. The same intervention may therefore receive different priority levels across regions, reflecting structural differences in grid characteristics and EV penetration.

The ranking methodology is implemented through a structured Multi Criteria Decision Making framework based on the Analytic Hierarchy Process (AHP), ensuring transparency, consistency, and traceability of judgments.

6.1.1 Definition of Alternatives: Countermeasure Set

The first step of the methodology is the formal definition of the set of countermeasures to be evaluated. These include interventions across multiple domains such as:

- Charging Behaviour and Demand side management
- Charging depot level interventions
- Power system decarbonization measures
- Electricity market, regulatory and policy instruments

The list of interventions are given Table 4 and the details of the interventions are given in Section 4.

Table 4 List of Interventions

Key	Category	Intervention
DSM01	Charging Behaviour and Demand-Side Measures	Mandate smart charging capability for all new public and private EV chargers
DSM02	Charging Behaviour and Demand-Side Measures	Enable and regulate aggregators to manage EV charging as a flexible resource
DSM03	Charging Behaviour and Demand-Side Measures	Emission-aware charging and discharging algorithms
DSM04	Charging Behaviour and Demand-Side Measures	Integrate EV charging into broader demand response programmes
DSM06	Charging Behaviour and Demand-Side Measures	Bidirectional EV Charging
DEP01	Charging Depot	Solar canopies over parking and charging areas
DEP02	Charging Depot	Dedicated renewable plus storage microgrids for high-capacity depots

DEP03	Charging Depot	Mandatory Energy Management Systems for large depots
DEP04	Charging Depot	Opportunity and flash charging for buses
PSDM01	Power Sector Decarbonization Measures	Strengthen transmission network
PSDM02	Power Sector Decarbonization Measures	Deploy utility-scale battery energy storage systems to absorb surplus renewable energy and serve peak demand
PSDM03	Power Sector Decarbonization Measures	Focus on more utility scale RE installation
PSDM04	Power Sector Decarbonization Measures	Second-life EV battery banks
PSDM05	Power Sector Decarbonization Measures	EVs as renewable integration assets in planning models
EMRP01	Electricity Market, Regulatory and Policy Instruments	Introduce time-of-day tariffs
EMRP02	Electricity Market, Regulatory and Policy Instruments	Develop carbon-aware pricing mechanisms for wholesale electricity markets
EMRP03	Electricity Market, Regulatory and Policy Instruments	Encourage favourable terms for green access power procurement for large EV charging customers

Each countermeasure is treated as an independent alternative in the ranking framework.

6.1.2 Selection of Evaluation Criteria

The ranking framework evaluates each countermeasure using four clearly defined criteria. These criteria are intentionally limited in number to ensure clarity and interpretability while still capturing the essential dimensions of policy decision making.

6.1.2.1 Emissions Impact

This criterion reflects the expected magnitude of reduction in EV related emissions attributable to the countermeasure. It is treated as a benefit criterion, meaning higher impact is preferred.

Importantly, emissions impact is assessed separately for each region. This is a critical feature of the methodology, because the emission reduction potential of a measure depends strongly on:

- The region's grid emission factor profile
- The temporal alignment between charging and low emission windows
- The dominant EV fleet categories in that region
- The seasonal variability of renewable generation

For example, measures that shift charging toward mid day solar hours may have very high emission impact in solar rich regions, but relatively lower impact in coal dominated grids where the diurnal emission dip is shallow. Thus, emissions impact ratings are region specific and form the primary driver of regional differentiation in rankings.

6.1.2.2 Implementation Time

This criterion captures the expected time required for implementation and scale up. It is treated as a burden criterion, meaning shorter implementation time is preferred.

Measures requiring major infrastructure expansion, regulatory overhaul, or long gestation investment cycles are rated less favourably under this criterion relative to those that can be implemented through existing institutional structures.

6.1.2.3 Cost of Implementation

This criterion reflects relative economic burden, including capital expenditure, operational cost implications, and systemic investment requirements. It is also treated as a burden criterion, meaning lower cost is preferred.

6.1.2.4 Technical Maturity

This criterion reflects technological readiness, regulatory clarity, availability of implementation models, and existing demonstration experience. It is treated as a benefit criterion, meaning higher maturity is preferred. Interventions with established pilots, operational experience, or clear regulatory pathways score higher than experimental or concept level approaches.

6.1.3 Pairwise Preference Conversion and Regional Ranking Synthesis

The ranking framework applies an Analytic Hierarchy Process based approach to prioritise countermeasures under multiple criteria. Instead of directly averaging qualitative VL to VH ratings, the method first expresses preferences through pairwise comparisons. Under each criterion, every countermeasure is compared against every other countermeasure, and the qualitative gap between their ratings is translated into preference intensity using the standard Saaty scale⁷. This ensures that a small difference in ratings leads to a modest preference, while larger differences lead to progressively stronger preference.

The framework distinguishes between benefit and burden criteria. For benefit criteria, such as emissions impact and maturity, higher ratings indicate stronger preference. For burden criteria, such as time and cost, lower ratings indicate stronger preference. This directional treatment ensures that the pairwise comparisons remain logically consistent across all criteria.

Once the pairwise comparison matrices are constructed, criterion level priority weights are derived using a normalization and averaging approach, which yields a consistent set of relative weights for the countermeasures under each criterion. Emissions impact is evaluated separately for each regional grid, reflecting differences in generation mix, diurnal emission profiles, and charging demand patterns. This produces a distinct emissions priority vector for NR, WR, SR, ER, and NER. In contrast, time, cost, and maturity are treated as region invariant characteristics, and therefore their priority vectors are common across regions.

To reflect policy priorities, the framework also derives the relative importance of the criteria themselves through a separate criteria level pairwise comparison. Emissions reduction is assigned the highest importance, while time, cost, and maturity act as secondary but meaningful considerations.

⁷ Saaty, Roseanna W. "The analytic hierarchy process—what it is and how it is used." *Mathematical modelling* ⁹, no. 3-5 (1987): 161-176.

The final score for each countermeasure in each region is then obtained by aggregating its criterion specific weights using these criteria importance weights, producing a composite priority score. Countermeasures are ranked within each regional grid by descending composite score to obtain region specific prioritised intervention lists.

The qualitative ratings used in the AHP framework for regional ranking of the interventions are given in Table 5

Figure 7 Overall methodology used for regional ranking of interventions

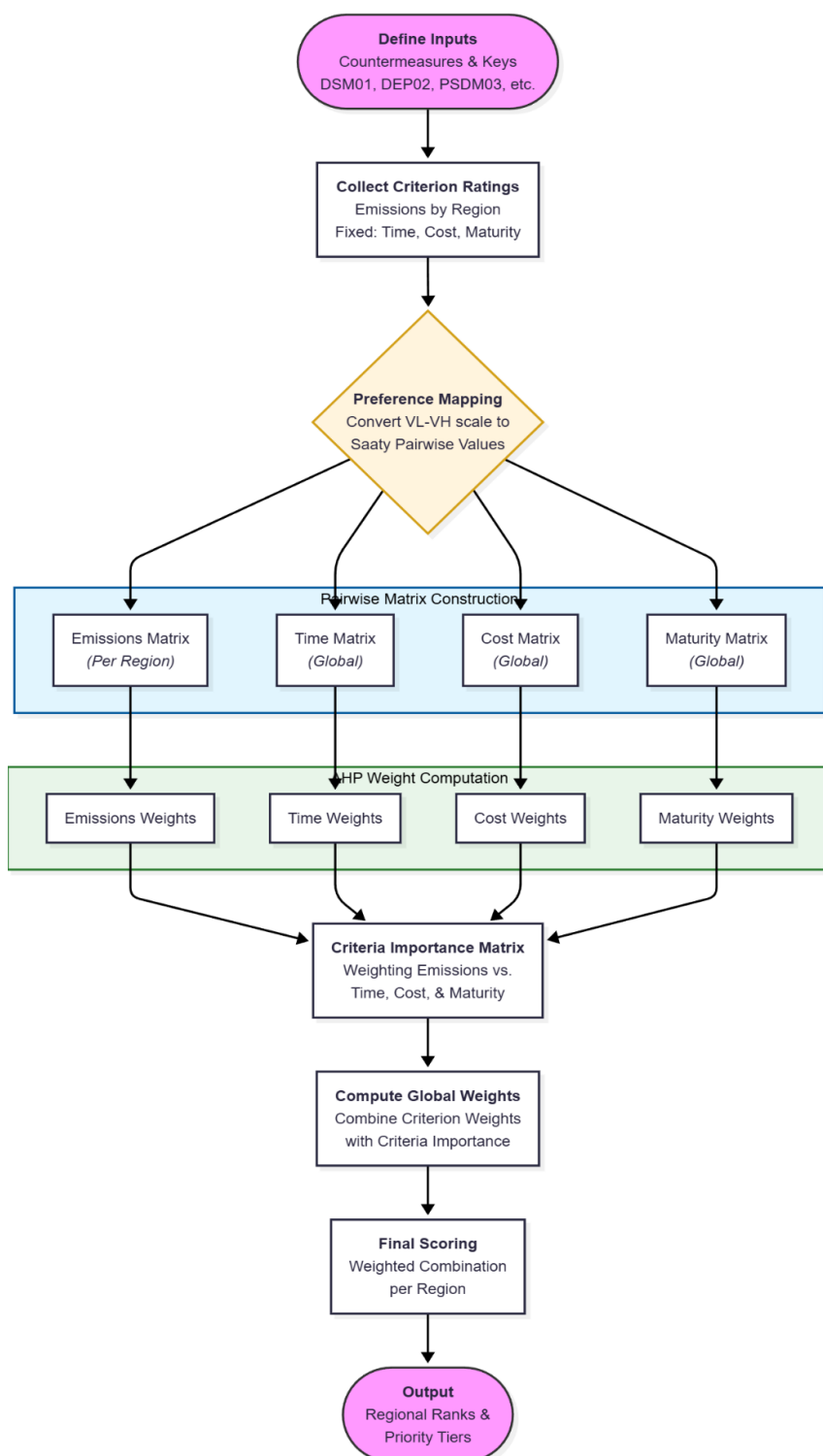


Table 5 Summary of Qualitative Ratings Used in the AHP Framework for regional ranking of the interventions

Key	Emissions Impact NR	Emissions Impact WR	Emissions Impact SR	Emissions Impact ER	Emissions Impact NER	Time	Cost	Maturity
DSM01	VH	VH	VH	H	H	VL	VL	M
DSM02	H	H	H	M	M	M	L	M
DSM03	VH	VH	VH	M	M	M	L	H
DSM04	H	L	H	M	M	M	L	M
DSM05	VH	VH	VH	VH	H	H	H	L
DEP01	H	VH	H	VH	H	L	H	VH
DEP02	VH	H	VH	VH	H	M	H	H
DEP03	H	H	H	H	M	M	M	M
DEP04	VH	VH	VH	H	M	M	VH	H
PSDM01	H	H	M	VH	H	VH	VH	H
PSDM02	VH	VH	VH	H	H	H	VH	H
PSDM03	H	H	H	H	H	M	L	H
PSDM04	H	H	H	H	H	H	H	H
PSDM05	M	H	M	H	H	L	VL	H
EMRP01	H	L	H	L	M	M	L	H
EMRP02	H	L	H	L	H	H	VL	H
EMRP03	VH	H	VH	VH	H	L	VL	H

Emissions ratings vary by region and reflect region specific decarbonisation leverage. Time and Cost are burden criteria, where lower values are preferred.

Maturity is a benefit criterion, where higher values are preferred.

VL = Very Low, L = Low, M = Medium, H = High, VH = Very High.

6.2 OVERVIEW OF REGIONAL RANKINGS

This section presents the results of the multi criteria ranking framework applied to the twenty one countermeasures across the five regional grids of India: Northern (NR), Southern (SR), Western (WR), Eastern (ER), and North Eastern (NER). The rankings reflect the composite priority scores derived from the AHP analysis.

The resulting heatmap of ranks shown in Figure 7 reveals clear regional differentiation in intervention priorities. While certain measures consistently rank high across most regions, others exhibit strong region specific variation driven primarily by differences in grid carbon intensity, renewable penetration, and structural network characteristics. Because emissions impact was assessed separately for each region, the final ranking captures the heterogeneous decarbonisation leverage of interventions under different system conditions.

Several broad patterns emerge from the results. Demand side management and charging behaviour interventions generally perform strongly in regions where shifting charging profiles can meaningfully align demand with lower emission windows. Charging depot level renewable integration measures also achieve high priority positions in multiple regions, particularly where heavy duty or fleet based charging is concentrated. In contrast, large scale transmission and distribution strengthening measures tend to rank higher in regions where structural grid constraints and coal intensive supply create systemic decarbonisation bottlenecks.

The Eastern region display particularly distinct ranking structures. In the Eastern grid, structural power sector and network strengthening interventions rise in priority relative to behavioural measures, reflecting the high coal dependence and the need for system level decarbonisation. In contrast, in regions with stronger renewable penetration, behavioural and market based interventions exhibit greater relative impact.

Overall, the results demonstrate that there is no single universally optimal intervention. Instead, effective emission reduction strategies require region specific prioritisation informed by grid characteristics, fleet composition, and implementation feasibility. The following subsections analyse each regional ranking in detail, interpret the dominant intervention categories, and extract policy relevant insights for targeted implementation

Figure 8 Summary of ranks achieved by the proposed interventions in each of the regional grids

DSM01	1	1	1	4	1
DSM02	13	12	10	16	14
DSM03	3	3	3	13	12
DSM04	14	11	17	15	15
DSM05	7	6	9	8	11
DEP01	8	7	2	2	4
DEP02	4	13	4	5	7
DEP03	15	14	11	9	16
DEP04	5	4	5	10	17
PSDM01	17	17	15	6	10
PSDM02	6	5	8	14	9
PSDM03	12	16	14	3	6
PSDM04	16	15	13	11	8
PSDM05	9	8	6	7	2
EMRP01	11	10	16	17	13
EMRP02	10	9	12	12	5
EMRP03	2	2	7	1	3
	NR	SR	WR	ER	NER

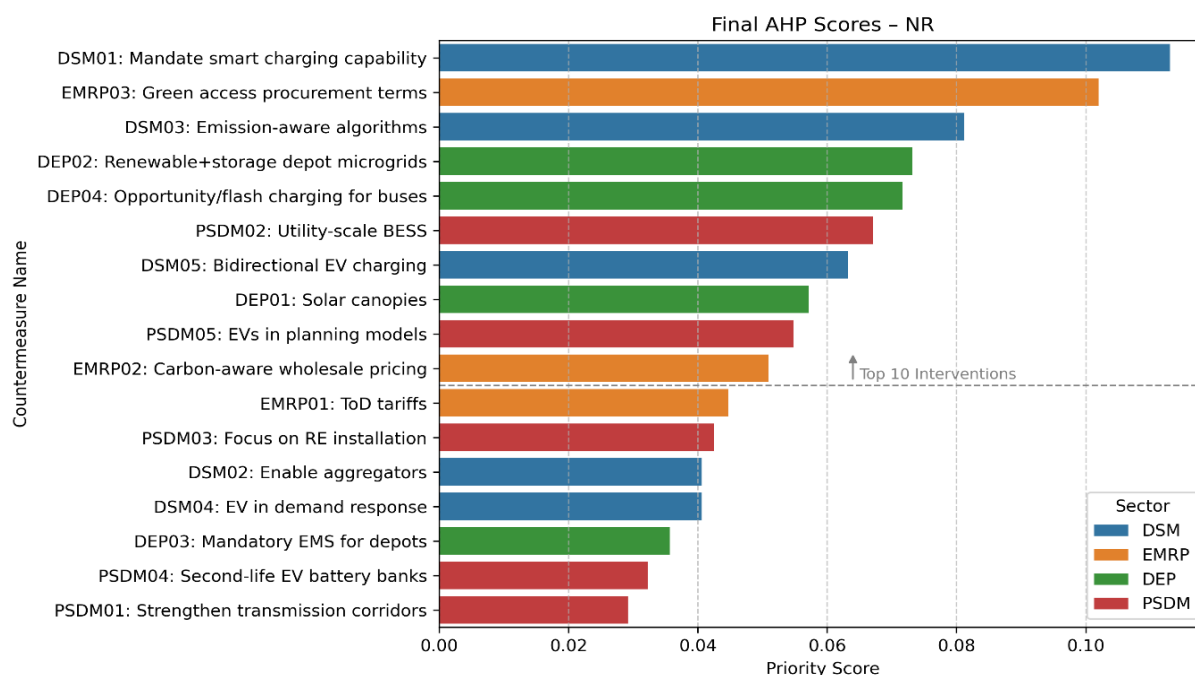
6.3 NORTHERN REGIONAL GRID

The Northern Regional Grid exhibits the highest electric vehicle related emissions among all Indian regions under present grid conditions. This outcome is driven by three structural characteristics.

First, the region has a high concentration of electric vehicles, particularly commercial three wheelers and heavy passenger vehicles. As shown in the emission assessment in Report 1, these segments dominate aggregate daily electricity demand and therefore determine the emission trajectory of the region. Second, the Northern grid displays one of the strongest intra day variations in carbon intensity. Emission factors decline substantially during mid day hours due to solar generation, reaching values close to 0.50 tCO₂ per MWh. However, emission intensity increases sharply during evening and night hours, rising to approximately 0.75 to 0.80 tCO₂ per MWh when coal-based generation dominates the margin. This implies that the timing of charging is a decisive determinant of total emissions. Third, electric bus fleets and commercial vehicles in the region rely heavily on overnight depot charging. Since night hours correspond to higher emission intensity, this charging pattern erodes the potential climate benefit of electrification, particularly for heavy duty segments where emission reductions are already marginal relative to internal combustion engine vehicles.

Given these characteristics, the Northern Region presents a high leverage opportunity for emission reduction through demand side flexibility, charging strategy reform, and coordinated grid interventions.

The highest-ranked countermeasure is DSM01: Mandate smart charging capability, indicating that controllability of EV charging is the most critical requirement in NR as shown in Figure 8. Since unmanaged charging can coincide with high-emission evening and night periods, smart charging provides the basic enabling layer for shifting demand toward lower-emission windows. This is followed by EMRP03: Green access procurement terms, which suggests that merely shifting charging may not be sufficient unless EV charging demand is also linked to cleaner electricity procurement. The third-ranked measure, DSM03: Emission-aware algorithms, further reinforces this point. In NR, price-based charging alone may not guarantee emission reduction because cheaper off-peak periods can still be coal dominated. Therefore, charging algorithms must explicitly consider marginal or time-varying emission factors rather than only electricity price. Among infrastructure-oriented options, DEP02: Renewable-plus-storage depot microgrids and DEP04: Opportunity/flash charging for buses rank highly. This is particularly important for bus and depot-based charging, where overnight charging can erode the emission benefits of electrification.

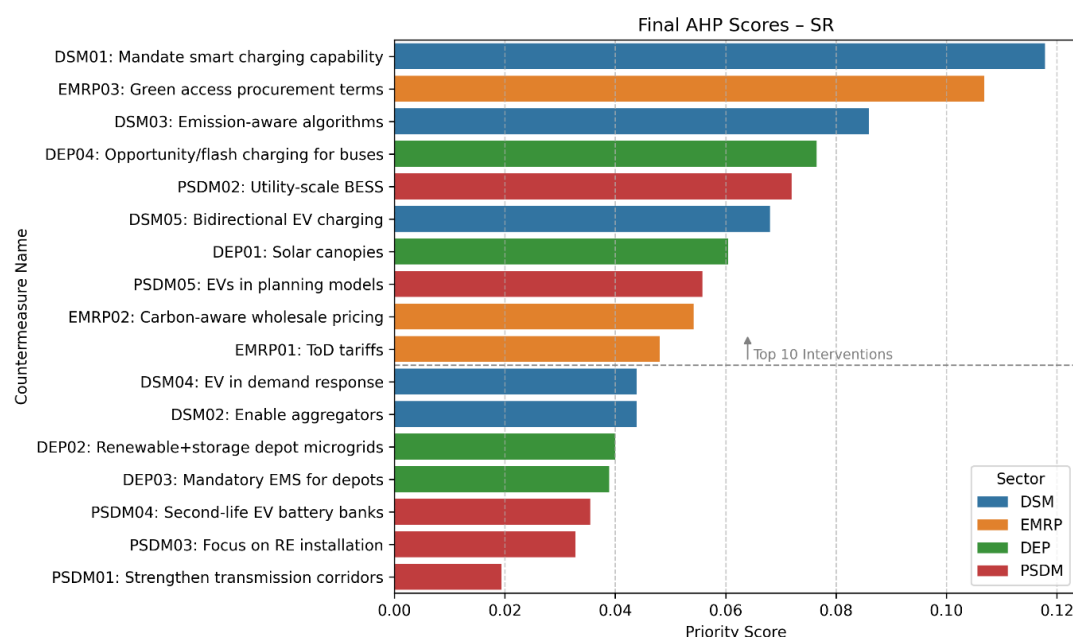
Figure 9 Ranking of countermeasures for the Northern Regional Grid

6.4 SOUTHERN REGIONAL GRID

For the Southern Region, the AHP ranking again places DSM01: Mandate smart charging capability as the highest-priority countermeasure. This indicates that even though the Southern grid has a comparatively cleaner and more renewable-rich generation mix, controllability of EV charging remains the most important enabling intervention. The second-ranked measure, **EMRP03: Green access procurement terms**, is also highly relevant for SR.

The high ranking of DSM03: Emission-aware algorithms shows that charging optimization should not be based only on cost or ToD tariffs. In the Southern grid, the emission factor varies meaningfully across the day because renewable generation reshapes the dispatch profile. Therefore, algorithms that explicitly account for time-varying grid emissions can further improve the carbon benefit of EV charging. A notable feature in SR is the high ranking of DEP04: Opportunity/flash charging for buses, which appears above renewable-plus-storage

depot microgrids. This suggests that, for the Southern grid, shifting some bus charging from overnight depot charging to daytime opportunity charging may be especially beneficial. Since midday periods often coincide with lower emission intensity due to solar generation, opportunity charging can directly improve the emission performance of electric bus fleets. PSDM02: Utility-scale BESS and DSM05: Bidirectional EV charging are also ranked within the top group. This reflects the importance of flexibility in a renewable-rich system.

Figure 10 Ranking of countermeasures for the Southern Regional Grid

6.5 EASTERN REGIONAL GRID

For the Eastern Region (ER), the AHP ranking is noticeably different from the Northern and Southern grids. Here, the top-ranked interventions are not only about shifting charging behaviour, but about ensuring access to cleaner electricity and building local renewable charging infrastructure. This is appropriate because the Eastern grid is one of the most coal-dominated regions, with relatively limited renewable penetration and persistently high emission intensity across the day.

The highest-ranked intervention is EMRP03: Green access procurement terms. This indicates that, for ER, the most important countermeasure is to ensure that EV charging demand is explicitly linked to renewable or low-carbon electricity procurement. Since the regional grid

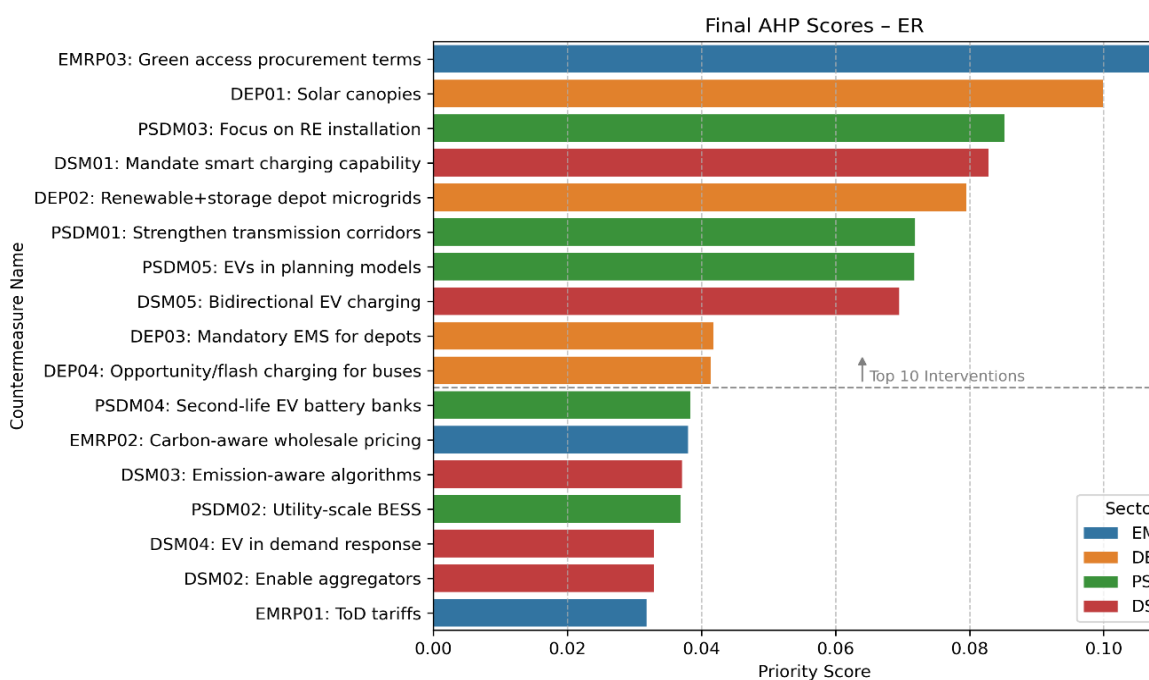
itself remains carbon intensive, simply electrifying vehicles or shifting charging time may not deliver strong emission benefits unless the electricity source is improved.

The second-ranked measure, DEP01: Solar canopies, is also highly significant. Unlike regions where solar canopies appear as a supporting intervention, in ER they become a core decarbonization measure. This suggests that site-level renewable generation at charging stations, depots, and public charging hubs can directly reduce dependence on the coal-heavy grid. Solar canopies are therefore especially relevant for daytime charging of 2Ws, 3Ws, LPVs, and depot-based fleets. The third-ranked measure, PSDM03: Focus on RE installation, reinforces the same theme at the system level. ER requires more renewable capacity addition before EV charging can deliver consistent emission reductions.

This ranking shows that grid decarbonization is not a background condition in ER; it is a direct EV emission mitigation requirement. DSM01: Mandate smart charging capability is ranked fourth, slightly below renewable procurement and installation measures. This is important because it suggests that smart charging alone has limited value in ER if the grid remains coal dominated across most hours. Smart charging is still necessary, but its effectiveness depends on whether there are genuinely cleaner time windows or locally available renewable energy to shift charging toward.

DEP02: Renewable-plus-storage depot microgrids ranks within the top five, showing the importance of local clean-energy systems for depot and fleet charging. In ER, depot microgrids can be particularly useful for buses and commercial fleets because they reduce exposure to high grid emission factors and can provide more predictable clean charging than the regional grid alone.

Figure 11 Ranking of countermeasures for the Eastern Regional Grid



6.6 WESTERN REGIONAL GRID

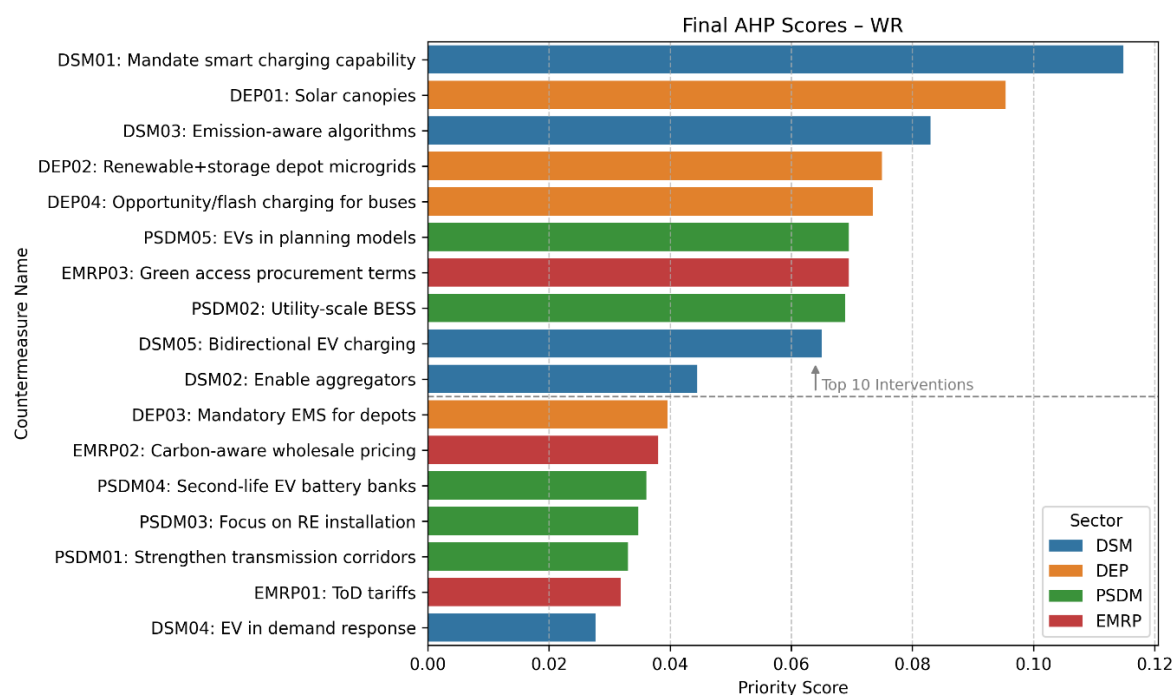
For the Western Region (WR), the AHP ranking suggests a balanced strategy combining smart charging, local renewable integration, depot-level interventions, and system flexibility. Unlike the Eastern grid, where clean electricity access dominates, and unlike the Southern grid, where renewable-aligned flexibility is especially attractive, WR requires both demand-side control and renewable-backed infrastructure because it has large EV demand as well as a sizeable thermal backbone.

The highest-ranked measure is DSM01: Mandate smart charging capability. This indicates that controllability of charging remains the most important intervention in WR. The Western grid has significant EV activity, especially from private 2Ws, 3Ws, LPVs, and depot-based fleets. The second-ranked measure is DEP01: Solar canopies, which is notably higher in WR than in SR and NR. This suggests that site-level solar integration at public chargers, workplaces, depots, and parking areas can play a major role in reducing EV charging emissions. Since WR has strong solar potential and substantial urban charging demand, solar canopies can directly offset grid draw during daytime charging windows.

The third-ranked measure, DSM03: Emission-aware algorithms, shows that charging optimization should explicitly account for the grid's time-varying carbon intensity. DEP02: Renewable-plus-storage depot microgrids and DEP04: Opportunity/flash charging for buses are also highly ranked.

This indicates that depot and bus-charging interventions are important in WR. Renewable-plus-storage microgrids can reduce dependence on grid electricity during high-emission hours, while opportunity charging can shift part of bus energy demand toward daytime periods, especially when paired with solar generation

Figure 12 Ranking of countermeasures for the Western Regional Grid



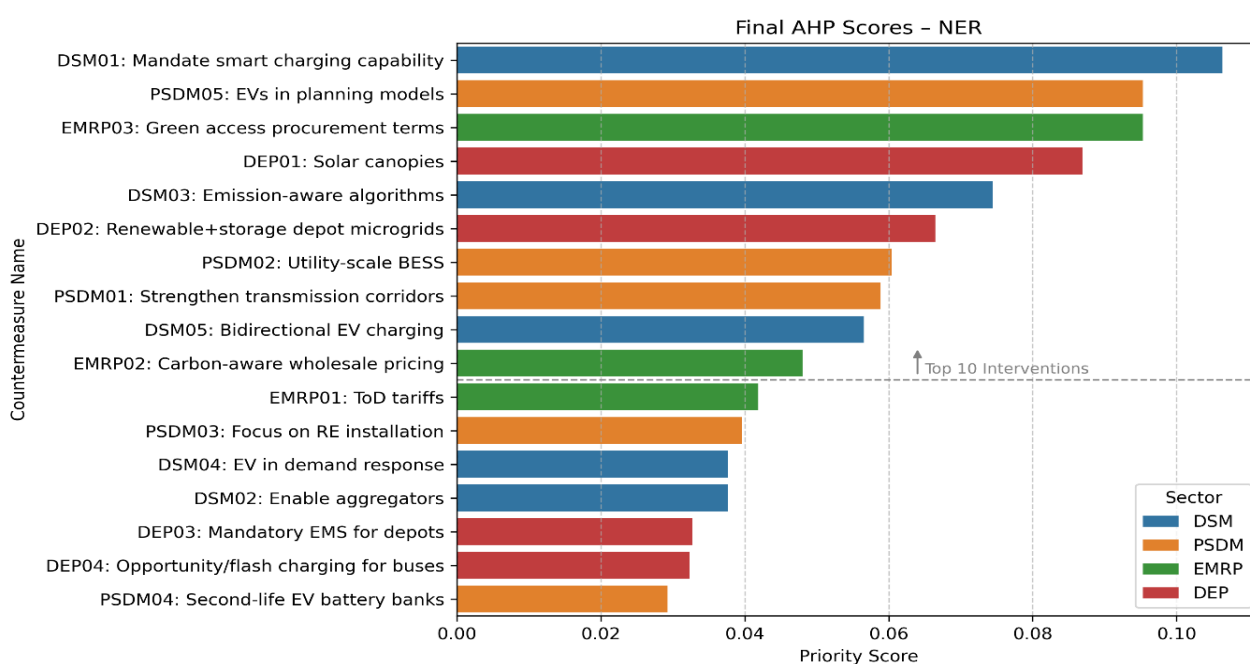
6.7 NORTH EASTERN REGIONAL GRID

For the North-Eastern Region (NER), the AHP ranking reflects a different policy priority compared with coal-heavy regions. Since NER already has the lowest grid emission factors nationally, largely due to hydro-dominated generation and limited coal dependence, the main challenge is not only reducing the carbon intensity of charging, but ensuring that future EV growth is planned, coordinated, and grid-compatible.

The highest-ranked measure is DSM01: Mandate smart charging capability. In NER, the purpose of smart charging is less about avoiding highly coal-intensive hours and more about managing future charging demand, preventing local feeder stress, and aligning EV load with hydro availability and system operating conditions. The second-ranked measure, PSDM05: EVs in planning models, is especially important. Unlike NR or WR, where immediate emission mitigation dominates, NER requires proactive planning because present EV demand is still relatively low. Including EVs in distribution and resource planning can help avoid uncoordinated infrastructure growth, particularly as 3W, public charging, and fleet electrification expand in urban and semi-urban centres.

EMRP03: Green access procurement terms remain highly ranked, showing that the clean-grid advantage of NER should be formalized through procurement mechanisms. Even though present emissions are low, future EV demand could increase reliance on gas-based or imported fossil-based power during stress periods. Green procurement can help ensure that EV charging remains tied to low-carbon supply. DEP01: Solar canopies also appear among the top-ranked interventions. DSM03: Emission-aware algorithms appear within the top five, indicating that operational control remains relevant even in a low-carbon grid. Such algorithms can help preserve the emissions advantage of NER by aligning charging with cleaner or less constrained system periods. This is especially important as EV penetration grows and charging demand becomes more visible in local distribution networks.

Figure 13 Ranking of countermeasures for the North Eastern Regional Grid



Chapter 7 Conclusion And Way Forward

7.1 CONCLUSION

This report presented a comprehensive assessment of technological, operational, market, and policy interventions for reducing EV charging-related emissions in India. The interventions were evaluated considering regional and seasonal electricity dispatch modelling, marginal abatement cost (MAC) analysis, and a multi-criteria decision-making (AHP) framework to evaluate and prioritize interventions across India's five synchronous grid regions. The assessment demonstrates that reducing EV charging emissions requires coordinated action across four complementary domains: charging behaviour and demand-side management, charging depot and fleet-level infrastructure, power sector decarbonisation, and electricity market and regulatory reforms. No single intervention is capable of delivering sustained emission reductions in isolation. Instead, the greatest benefits are achieved through coordinated implementation of operational, infrastructural, and policy measures.

Among all interventions, mandatory smart charging capability (DSM01) consistently ranks as the highest-priority intervention across all regional grids. This indicates that enabling intelligent charging control should form the foundation of India's low-carbon EV charging strategy. Smart charging provides immediate emission reduction opportunities without requiring major changes to the existing electricity infrastructure while simultaneously improving grid flexibility.

The assessment also identifies emission-aware charging algorithms (DSM03) and green electricity procurement (EMRP03) as high-priority interventions. These measures directly align EV charging with cleaner electricity supply and significantly improve emission outcomes compared with conventional price-based charging strategies. Renewable-powered charging depots, including solar canopies (DEP01) and renewable-storage microgrids (DEP02), further strengthen charging infrastructure by increasing the utilisation of clean electricity at the point of charging. From the power system perspective, utility-scale battery energy storage (PSDM02) and continued renewable energy deployment provide important enabling infrastructure that increases renewable energy utilisation and supports low-carbon charging over the longer term. Market and regulatory interventions, particularly carbon-aware electricity markets and green power procurement mechanisms, complement these technical measures by creating economic incentives for cleaner charging practices.

The regional assessment further demonstrates that intervention priorities vary across India's regional grids. The Northern and Southern Regions show the greatest benefits from intelligent charging strategies and emission-aware operation, while the Western Region requires careful implementation of demand flexibility measures to avoid unintended emission increases during coal-dominated periods. In the Eastern Region, where thermal generation continues to dominate the electricity mix, charging interventions alone cannot fully realise the environmental benefits of transport electrification without parallel power sector decarbonisation. The Northeastern Region, characterised by a relatively cleaner generation mix, should prioritise charging infrastructure expansion while preserving its low-carbon electricity advantage.

Overall, the findings indicate that India's EV transition should be accompanied by an equally coordinated transition in charging practices, electricity markets, and power system operation to maximise emission reductions.

7.2 WAY FORWARD

Based on the assessment presented in this report, the following implementation roadmap is recommended to systematically reduce EV charging-related emissions in India. The interventions should not be viewed as standalone measures but as complementary actions spanning charging infrastructure, power system operation, electricity markets, and regulatory frameworks.

In the near term, priority should be given to interventions that are technologically mature, economically viable, and capable of delivering immediate emission reductions. These include mandating smart charging capability for all new public and private charging infrastructure, enabling EV charging aggregators, deploying emission-aware charging algorithms, and promoting green electricity procurement for large charging consumers. Simultaneously, the deployment of solar-powered charging stations and renewable-powered charging depots should be accelerated to reduce dependence on grid-supplied carbon-intensive electricity.

In the medium term, charging infrastructure should evolve into an active grid resource. Renewable-storage microgrids, energy management systems for charging depots, and utility-scale battery energy storage systems should be expanded to improve renewable energy utilisation and provide greater operational flexibility. EV charging should also be integrated into broader demand response programmes, allowing charging demand to support grid balancing while reducing charging emissions during periods of high carbon intensity.

In the long term, EVs should become an integral component of a decarbonized and flexible power system. This requires the large-scale deployment of bidirectional charging (Vehicle-to-Grid), utilisation of second-life EV batteries for stationary storage applications, continued expansion of renewable energy and transmission infrastructure, and the development of carbon-aware electricity market mechanisms that explicitly value emission reductions alongside economic efficiency.

The regional assessment presented in this report also highlights that implementation priorities should reflect the characteristics of the regional power system rather than follow a uniform national strategy. Regions with higher renewable penetration should prioritise emission-aware charging and renewable-integrated charging infrastructure, whereas regions with carbon-intensive electricity mixes should combine charging interventions with accelerated power sector decarbonisation and market reforms. Accordingly, national policy should establish common technical standards and regulatory frameworks, while allowing state governments, utilities, and system operators to tailor implementation pathways based on regional electricity generation, network characteristics, and charging demand.

Overall, the successful implementation of these interventions will require coordinated action among central and state governments, electricity regulators, system operators, utilities, charging service providers, vehicle manufacturers, and fleet operators. Such a coordinated approach will ensure that India's rapid transition towards electric mobility is accompanied by a corresponding reduction in charging-related emissions, thereby maximizing the environmental benefits of transport electrification while supporting the country's broader clean energy and net-zero ambitions.

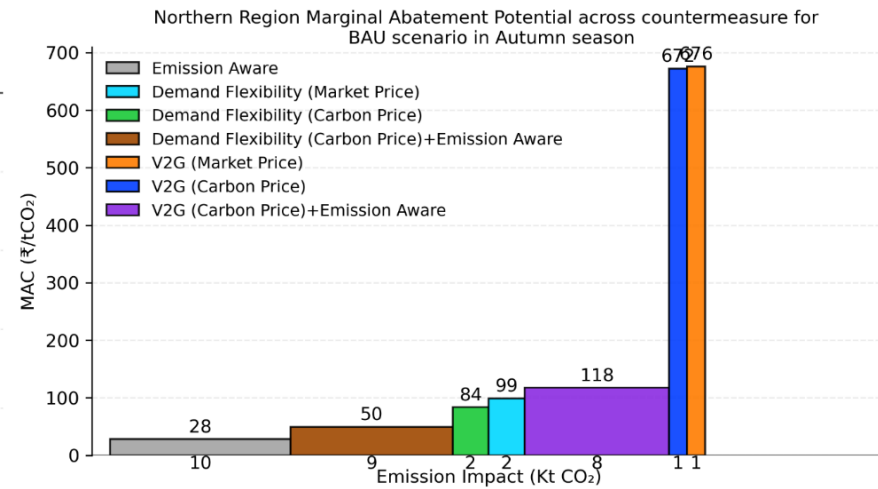
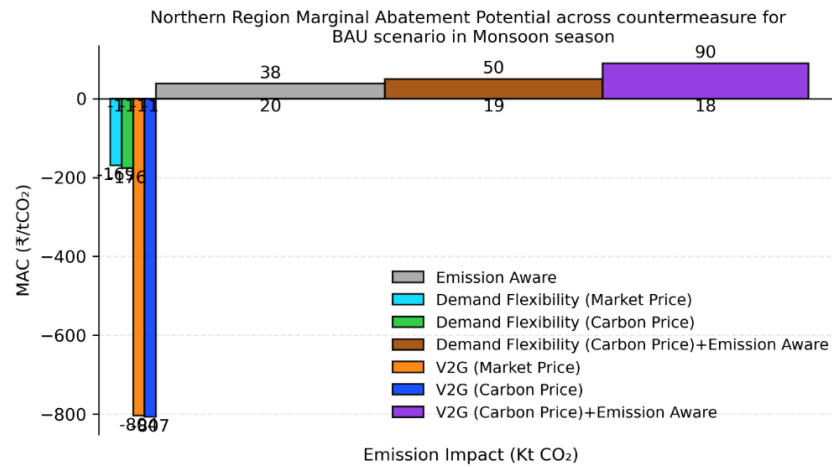
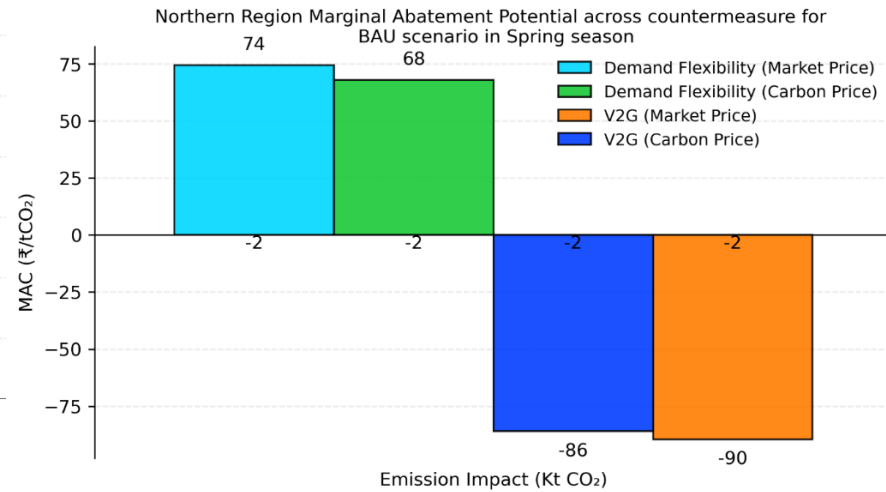
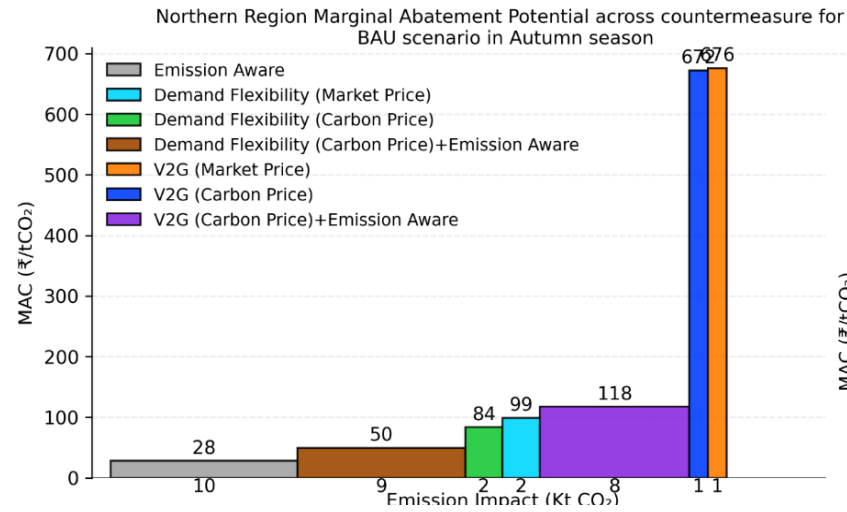
8. ANNEXURES

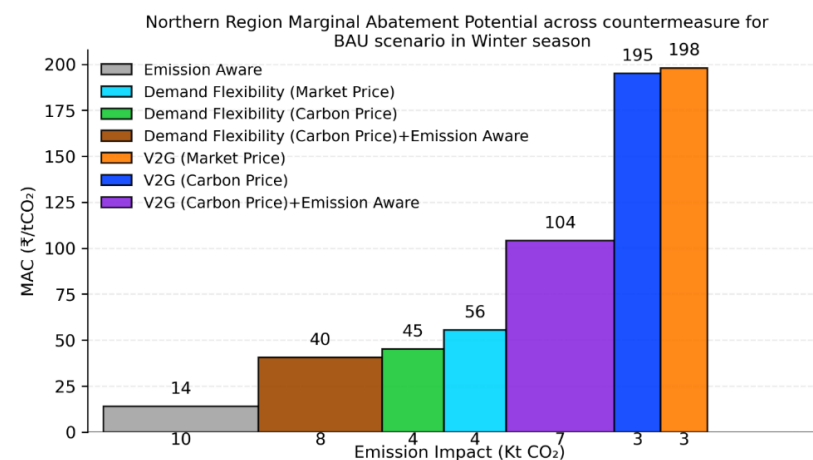
8.1 MARGINAL ABATEMENT COST AND EMISSION CHANGE ACROSS INDIA'S FIVE REGIONAL GRIDS

8.1.1 Northern Grid

Interventions	Scenario	MAC (Rs/tCO ₂)						Cost (Rs)	Emission (kt CO ₂)					
		Winter	Spring	Summer	Monsoon	Autumn	Avg		Winter	Spring	Summer	Monsoon	Autumn	Avg
Demand Flexibility (Market Prices)	BAU	55.50	74.50	48.33	-169.00	99.00	21.67	₹ 26,000.00	4	-2	3	-1	2	1.20
Demand Flexibility (Carbon Prices)	BAU	45.25	68.00	49.67	-176.00	83.50	14.08	₹ 16,900.00	4	-2	3	-1	2	1.20
Demand Flexibility (Carbon Prices) + Emission Aware	BAU	40.50	-	57.17	50.16	49.56	49.35	₹ 4,14,498.25	8	0	6	19	9	8.40
V2G (Market Prices)	BAU	198.00	-89.50	396.50	-804.00	676.00	75.40	₹ 45,240.00	3	-2	2	-1	1	0.60
V2G (Carbon Prices)	BAU	195.00	-86.00	395.50	-807.00	672.00	73.90	₹ 44,340.00	3	-2	2	-1	1	0.60
V2G (Carbon Prices) + Emission Aware	BAU	104.00	-	164.00	89.94	117.50	118.86	₹ 9,27,116.67	7	0	6	18	8	7.80
Demand Flexibility (Market Prices)	Stated Policies	120.75	-29.60	-103.00	235.00	-92.40	26.15	-₹ 41,840.00	4	-5	-4	2	-5	-1.60
Demand Flexibility (Carbon Prices)	Stated Policies	120.75	-29.60	-103.00	235.00	-92.40	26.15	-₹ 41,840.00	4	-5	-4	2	-5	-1.60

Demand Flexibility (Carbon Prices) + Emission Aware	Stated Policies	79.75	-137.50	155.50	55.61	666.00	163.87	₹ 11,14,327.83	8	-2	4	23	1	6.80
V2G (Market Prices)	Stated Policies	815.00	-213.33	-330.83	-	-235.14	8.92	-₹ 30,336.90	2	-6	-6	0	-7	-3.40
V2G (Carbon Prices)	Stated Policies	808.50	-213.00	-332.50	-	-234.00	7.25	-₹ 24,650.00	2	-6	-6	0	-7	-3.40
V2G (Carbon Prices) + Emission Aware	Stated Policies	354.20	-472.00	1107.00	141.90	-912.00	43.82	₹ 1,92,808.00	5	-3	2	20	-2	4.40

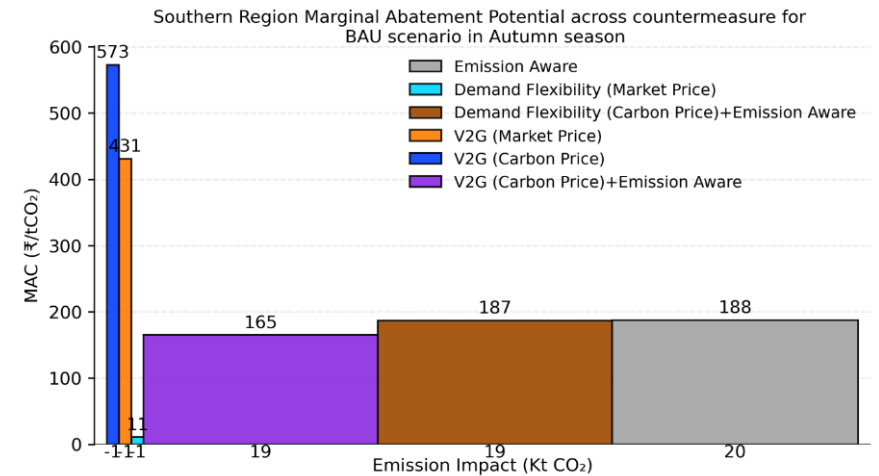
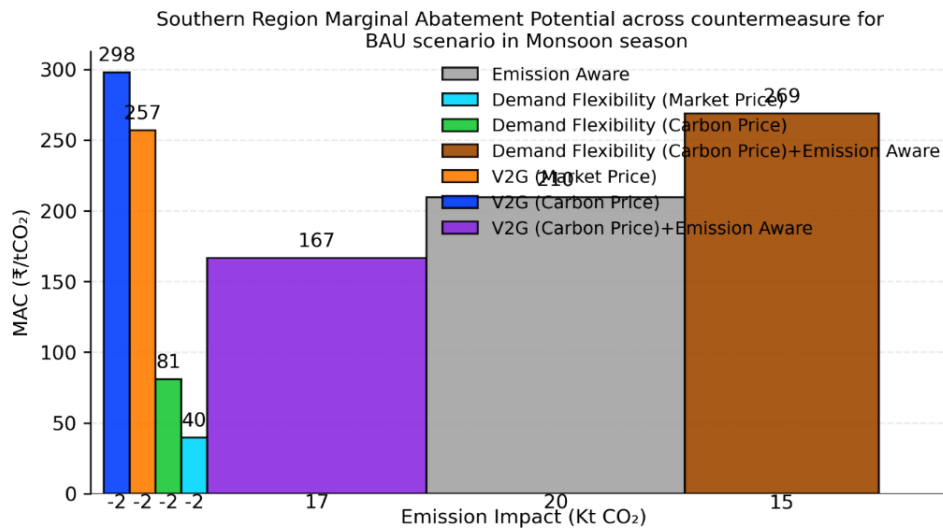
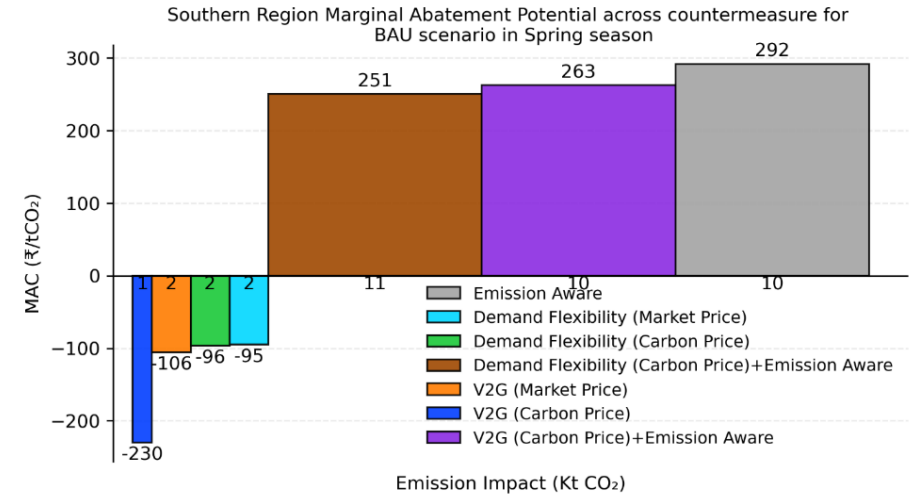
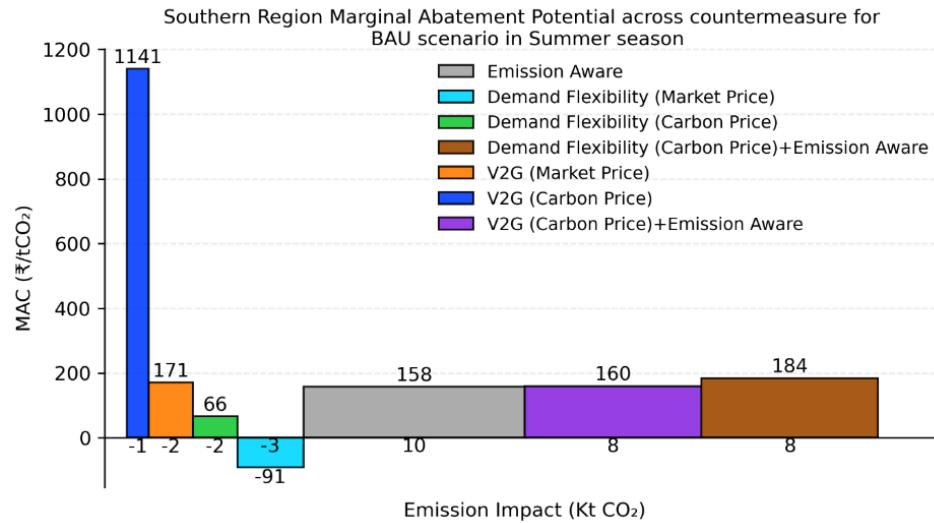


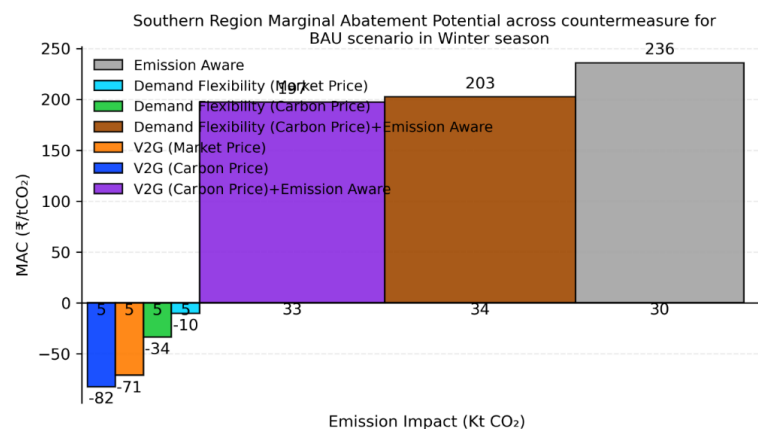


8.1.2 Southern Grid

Interventions	Scenario	MAC (Rs/tCO ₂)						Cost (Rs)	Emission (kt CO ₂)					
		Winter	Spring	Summer	Monsoon	Autumn	Avg		Winter	Spring	Summer	Monsoon	Autumn	Avg
Demand Flexibility (Market Prices)	BAU	-10.40	-95.00	-91.00	39.50	11.00	-29.18	₹ 5,836.00	5	2	-3	-2	-1	0.20
Demand Flexibility (Carbon Prices)	BAU	-33.60	-96.50	65.50	81.00	-	4.10	₹ 2,460.00	5	2	-2	-2	0	0.60
Demand Flexibility (Carbon Prices) + Emission Aware	BAU	202.56	250.55	184.25	268.80	186.68	218.57	₹ 38,03,077.94	34	11	8	15	19	17.40
V2G (Market Prices)	BAU	-71.20	-105.50	171.00	257.00	431.00	136.46	₹ 54,584.00	5	2	-2	-2	-1	0.40

V2G (Carbon Prices)	BAU	-82.40	-230.00	1141.00	298.00	573.00	339.92	₹ 1,35,968.00	5	1	-1	-2	-1	0.40
V2G (Carbon Prices) + Emission Aware	BAU	197.27	262.70	160.00	166.65	164.95	190.31	₹ 33,11,453.70	33	10	8	17	19	17.40
Demand Flexibility (Market Prices)	Stated Policies	-251.50	234.50	-122.00	-92.40	-	-57.85	-₹ 1,04,130.00	2	-2	4	5	0	1.80
Demand Flexibility (Carbon Prices)	Stated Policies	-251.50	234.50	-122.00	-92.40	-	-57.85	-₹ 1,04,130.00	2	-2	4	5	0	1.80
Demand Flexibility (Carbon Prices) + Emission Aware	Stated Policies	244.39	319.50	49.83	188.29	188.33	198.07	₹ 38,02,926.45	31	8	18	24	15	19.20
V2G (Market Prices)	Stated Policies	-535.00	2680.00	-316.50	-403.80	-	356.18	₹ 7,12,350.00	2	-1	4	5	0	2.00
V2G (Carbon Prices)	Stated Policies	-619.00	2752.00	-391.75	-412.60	-	332.16	₹ 6,64,325.00	2	-1	4	5	0	2.00
V2G (Carbon Prices) + Emission Aware	Stated Policies	209.90	17.73	75.00	123.83	187.67	122.83	₹ 25,79,348.09	31	11	21	24	18	21.00

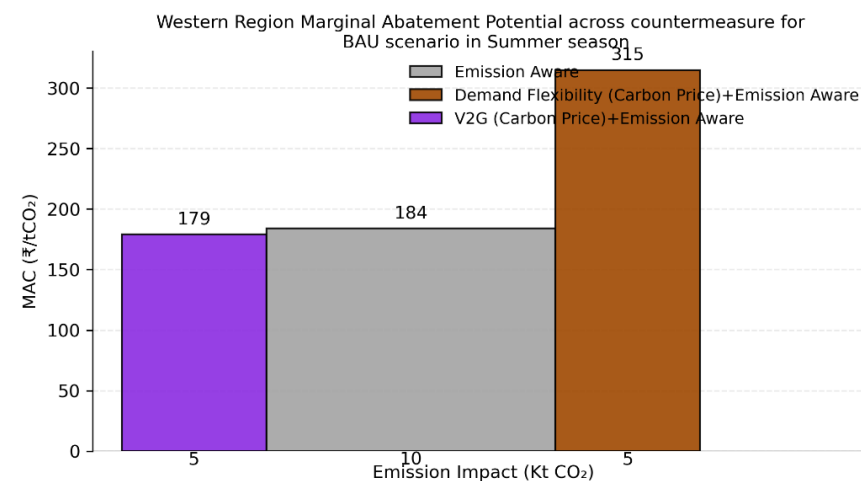
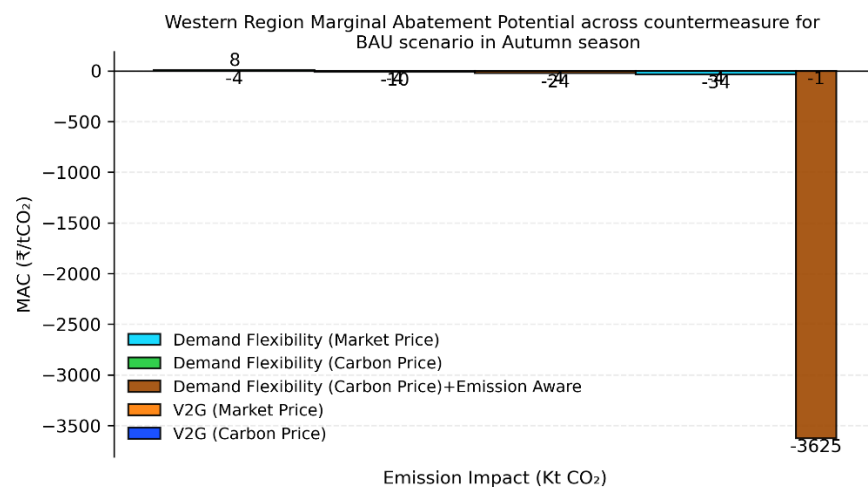
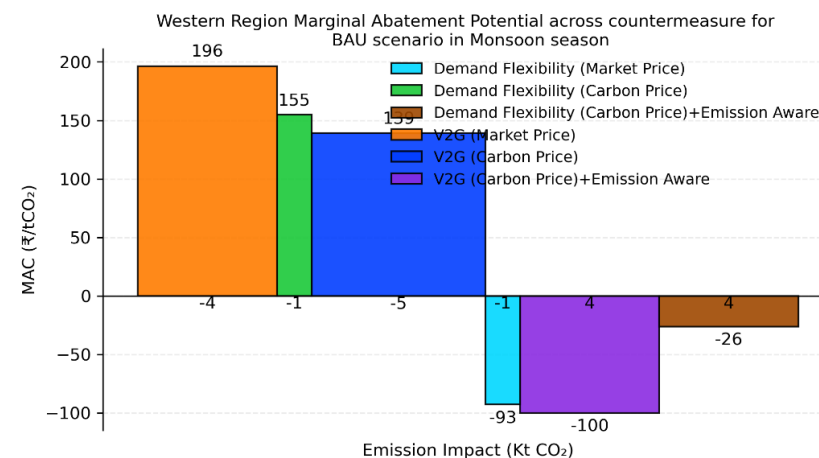
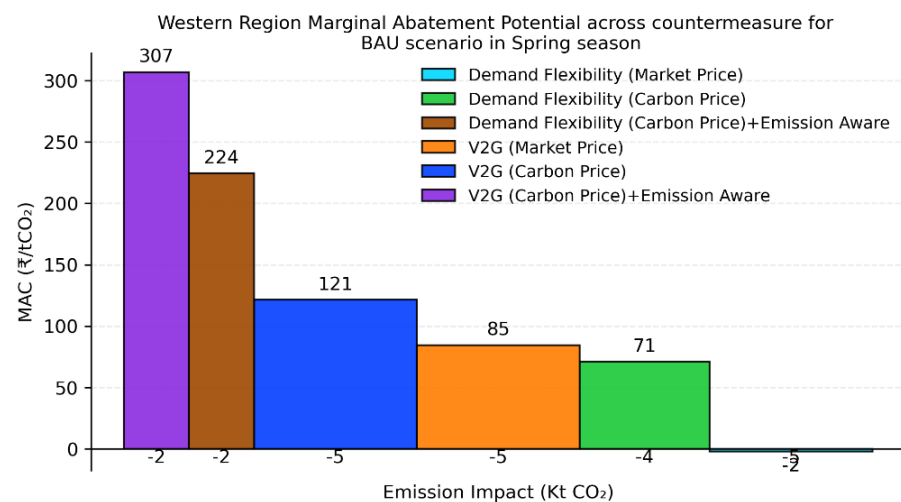


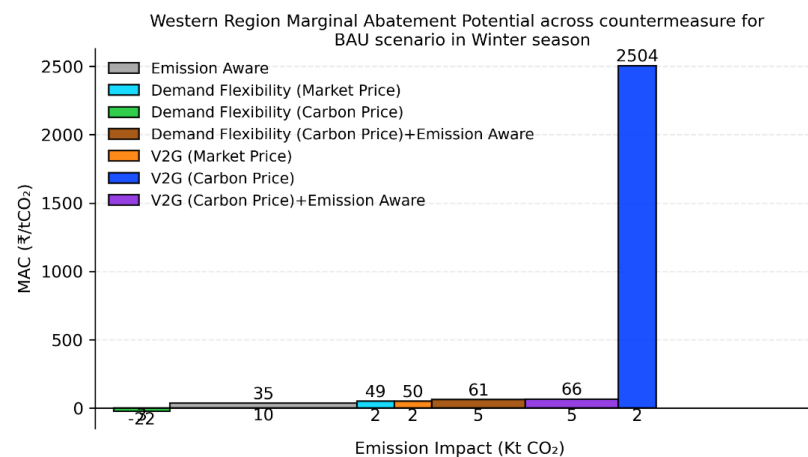


8.1.3 Western Grid

Interventions	Scenario	MAC (Rs/tCO ₂)						Cost (Rs)	Emission (kt CO ₂)					
		Winter	Spring	Summer	Monsoon	Autumn	Avg		Winter	Spring	Summer	Monsoon	Autumn	Avg
Demand Flexibility (Market Prices)	BAU	49.00	-2.00	-	-93.00	-33.75	-19.94	₹ 31,900.00	2	-5	0	-1	-4	-1.60
Demand Flexibility (Carbon Prices)	BAU	-22.33	71.25	-	155.00	8.50	53.10	-₹ 63,725.00	3	-4	0	-1	-4	-1.20
Demand Flexibility (Carbon Prices) + Emission Aware	BAU	60.80	224.50	314.80	-26.25	-3625.00	-610.23	-₹ 13,42,506.00	5	-2	5	4	-1	2.20
V2G (Market Prices)	BAU	50.00	84.60	-	196.50	-24.25	76.71	-₹ 1,68,767.50	2	-5	0	-4	-4	-2.20
V2G (Carbon Prices)	BAU	2504.50	121.40	-	139.00	-10.25	688.66	-₹ 16,52,790.00	2	-5	0	-5	-4	-2.40

V2G (Carbon Prices) + Emission Aware	BAU	66.20	307.00	179.20	-100.00	-	113.10	₹ 2,71,440.00	5	-2	5	4	0	2.40
Demand Flexibility (Market Prices)	Stated Policies	1695.00	-60.75	-141.00	146.00	-316.50	264.55	₹ 4,23,280.00	1	4	3	-2	2	1.60
Demand Flexibility (Carbon Prices)	Stated Policies	1695.00	-60.75	-141.00	146.00	-316.50	264.55	₹ 4,23,280.00	1	4	3	-2	2	1.60
Demand Flexibility (Carbon Prices) + Emission Aware	Stated Policies	388.67	18.86	-1.67	-105.50	-69.00	46.27	₹ 2,12,848.57	3	7	6	2	5	4.60
V2G (Market Prices)	Stated Policies	-	15.67	-200.00	239.00	-1219.00	-291.08	-₹ 1,74,650.00	0	3	2	-3	1	0.60
V2G (Carbon Prices)	Stated Policies	396.00	-43.50	-1203.00	378.00	-1961.00	-486.70	-₹ 3,89,360.00	1	4	1	-3	1	0.80
V2G (Carbon Prices) + Emission Aware	Stated Policies	-44.67	31.67	-154.50	1052.00	-584.67	59.97	₹ 2,15,880.00	3	6	4	2	3	3.60

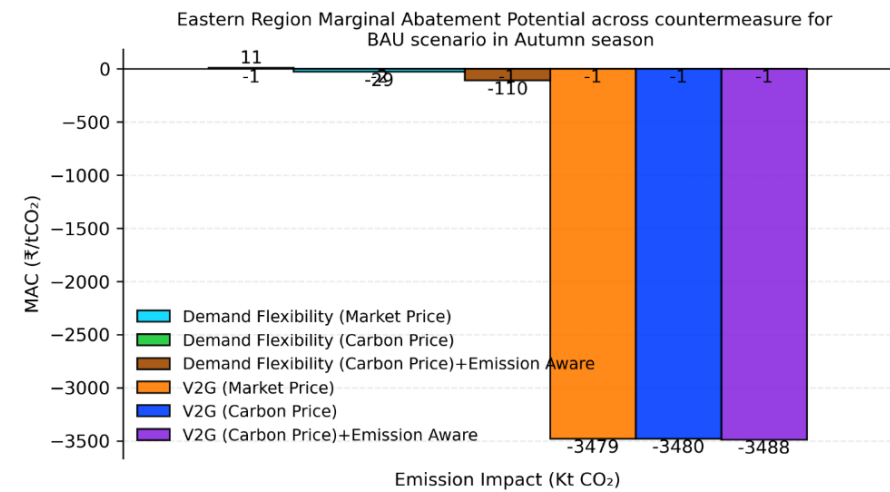
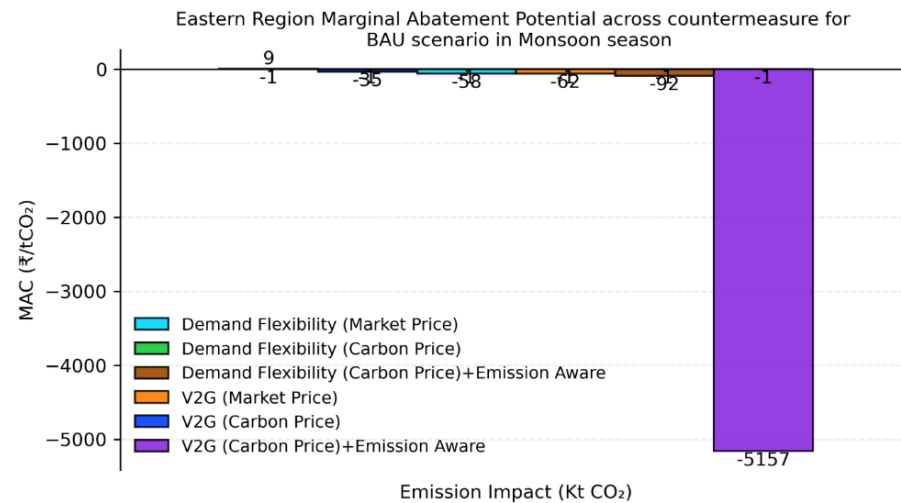
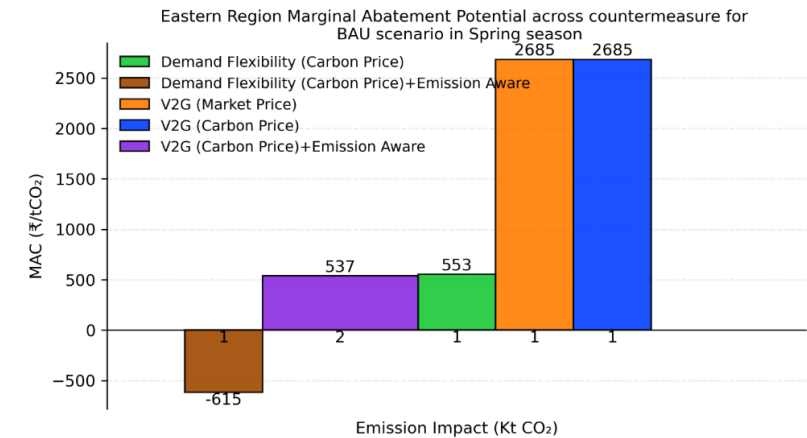
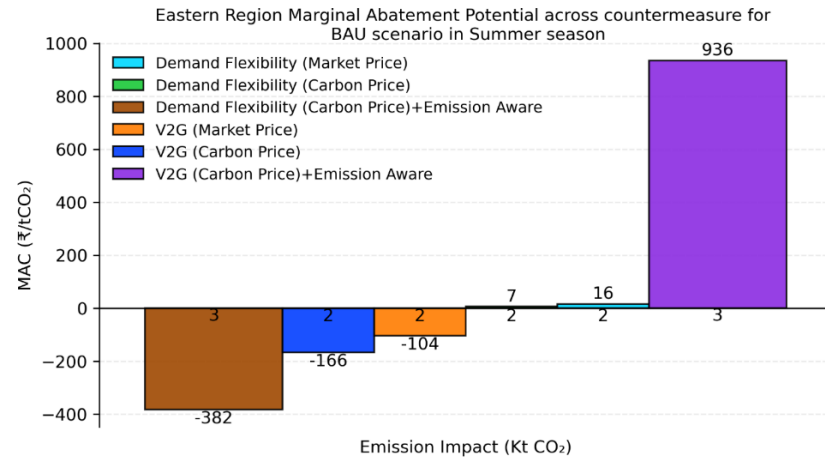


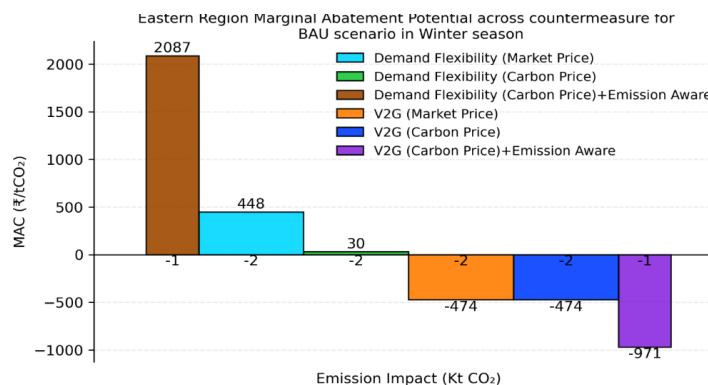


8.1.4 Eastern Grid

Interventions	Scenario	MAC (Rs/tCO ₂)						Cost (Rs)	Emission (kt CO ₂)					
		Winter	Spring	Summer	Monsoon	Autumn	Avg		Winter	Spring	Summer	Monsoon	Autumn	Avg
Demand Flexibility (Market Prices)	BAU	448	-	16.5	-58	-29	94.38	-₹ 56,625.00	-2	0	2	-1	-2	-0.60
Demand Flexibility (Carbon Prices)	BAU	30.5	553	7	9	11	122.10	-₹ 24,420.00	-2	1	2	-1	-1	-0.20
Demand Flexibility (Carbon Prices) + Emission Aware	BAU	2087	-615	-382	-92	-110	177.60	₹ 35,520.00	-1	1	3	-1	-1	0.20
V2G (Market Prices)	BAU	-473.5	2685	-103.5	-62	-3479	-286.60	₹ 57,320.00	-2	1	2	-1	-1	-0.20
V2G (Carbon Prices)	BAU	-474	2685	-166.5	-35	-3480	-294.10	₹ 58,820.00	-2	1	2	-1	-1	-0.20

V2G (Carbon Prices) + Emission Aware	BAU	-971	537	935.667	-5157	-3488	-1628.67	-₹ 6,51,466.67	-1	2	3	-1	-1	0.40
Demand Flexibility (Market Prices)	Stated Policies	-43.667	11.5	3.667	38.667	-4	1.23	₹ 493.33	3	-4	-3	3	3	0.40
Demand Flexibility (Carbon Prices)	Stated Policies	-43.667	11.5	3.667	38.667	-4	1.23	₹ 493.33	3	-4	-3	3	3	0.40
Demand Flexibility (Carbon Prices) + Emission Aware	Stated Policies	-208.33	-3	-17	-204	9	-84.67	-₹ 50,800.00	3	-4	-3	4	3	0.60
V2G (Market Prices)	Stated Policies	642.667	-724.25	-1171.67	-204.667	1011	-89.38	-₹ 35,753.33	3	-4	-3	3	3	0.40
V2G (Carbon Prices)	Stated Policies	643	-724.5	-611.333	-173	1011.667	29.17	₹ 17,500.00	3	-4	-3	4	3	0.60
V2G (Carbon Prices) + Emission Aware	Stated Policies	-176	-729	-623.667	943.25	1017.333	86.38	₹ 51,830.00	3	-4	-3	4	3	0.60

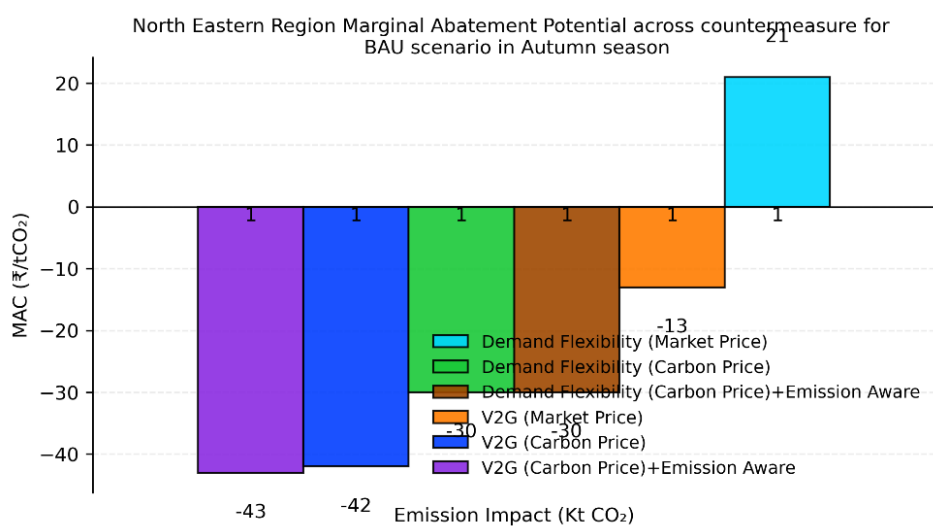
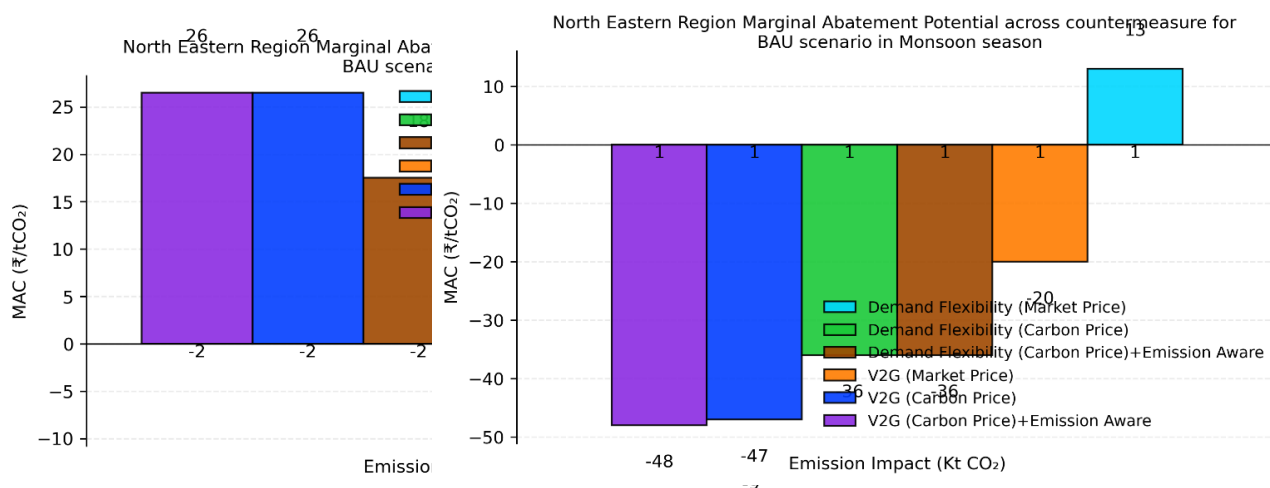




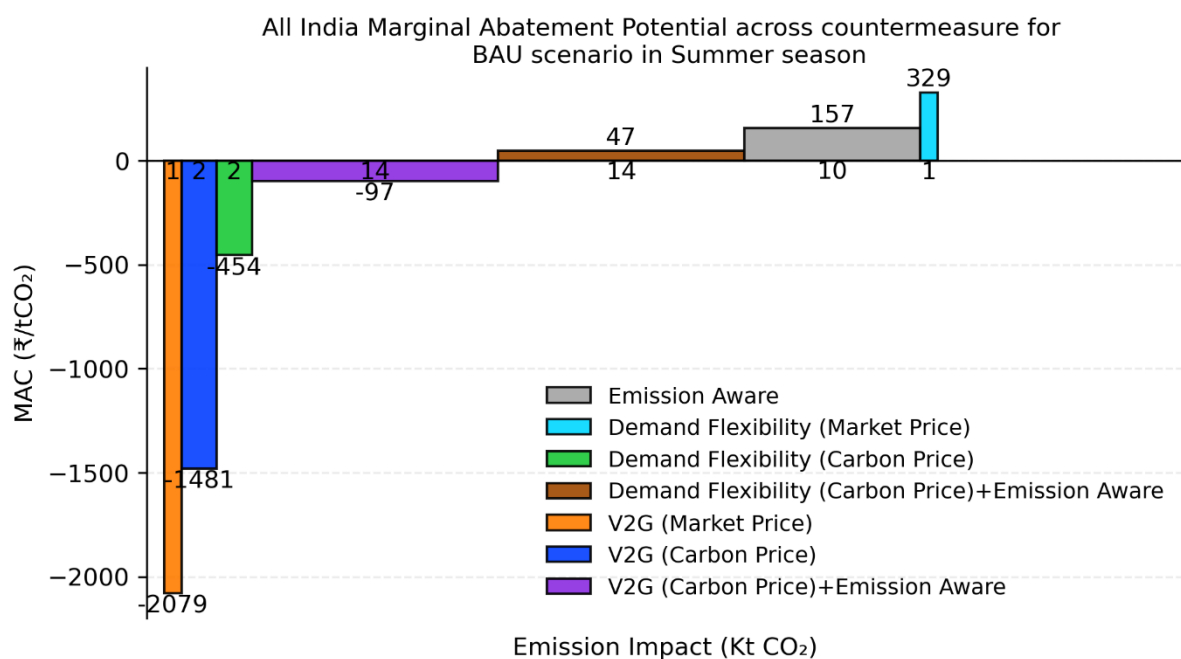
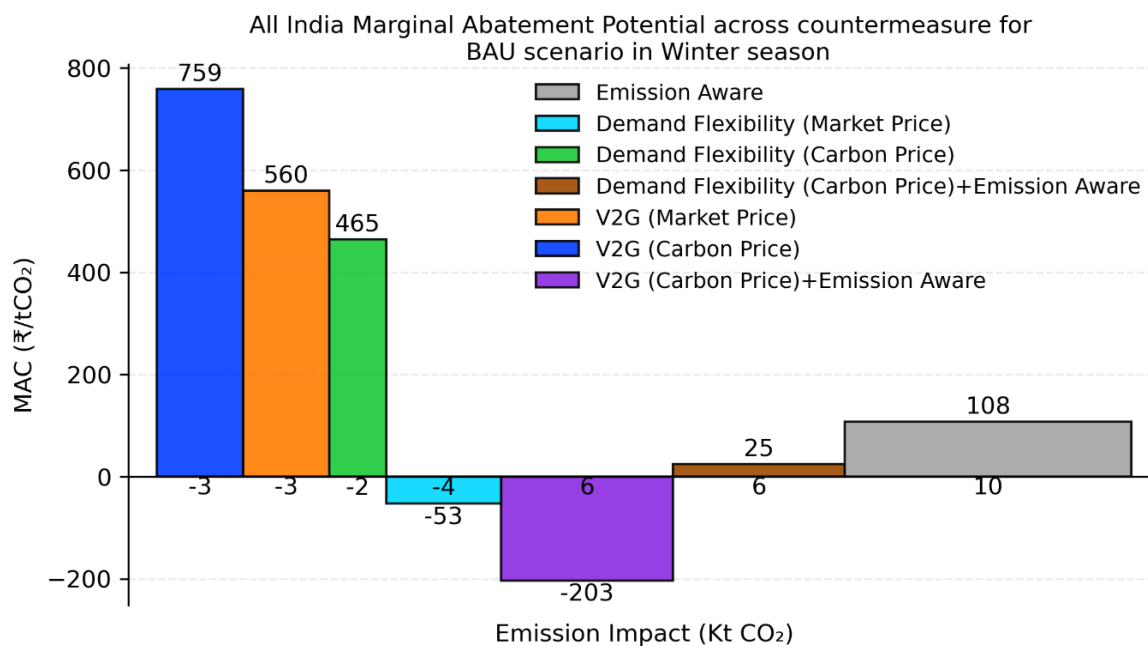
8.1.5 North-Eastern Grid

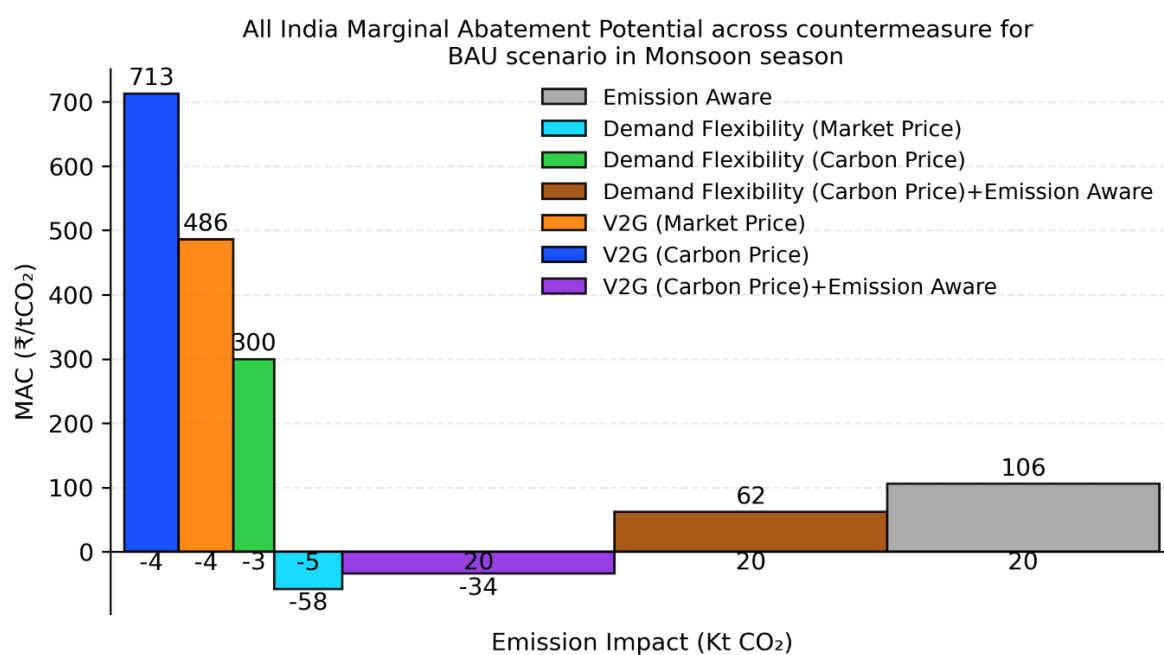
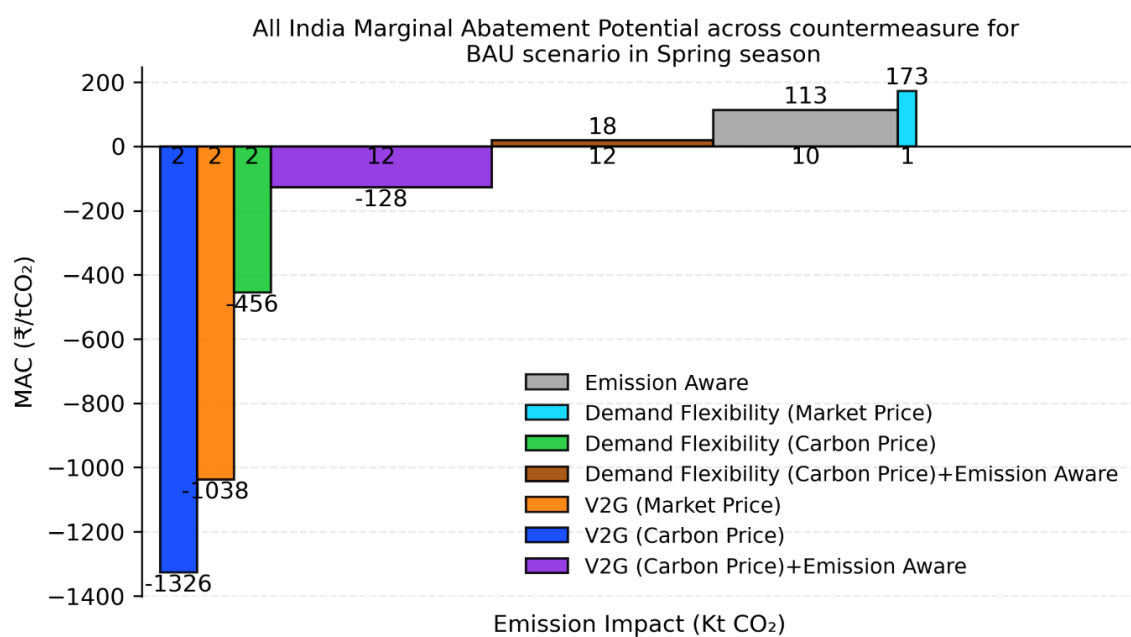
Interventions	Scenario	MAC (Rs/tCO ₂)						Cost (Rs)	Emission (kt CO ₂)					
		Winter	Spring	Summer	Monsoon	Autumn	Avg		Winter	Spring	Summer	Monsoon	Autumn	Avg
Demand Flexibility (Market Prices)	BAU	-	-9	-	13	21	8.33	₹ 0.00	0	-2	0	1	1	0.00
Demand Flexibility (Carbon Prices)	BAU	-	17.5	-	-36	-30	-16.17	₹ 0.00	0	-2	0	1	1	0.00
Demand Flexibility (Carbon Prices) + Emission Aware	BAU	-	17.5	-	-36	-30	-16.17	₹ 0.00	0	-2	0	1	1	0.00
V2G (Market Prices)	BAU	-	11.5	-	-20	-13	-7.17	₹ 0.00	0	-2	0	1	1	0.00
V2G (Carbon Prices)	BAU	-	26.5	-	-47	-42	-20.83	₹ 0.00	0	-2	0	1	1	0.00

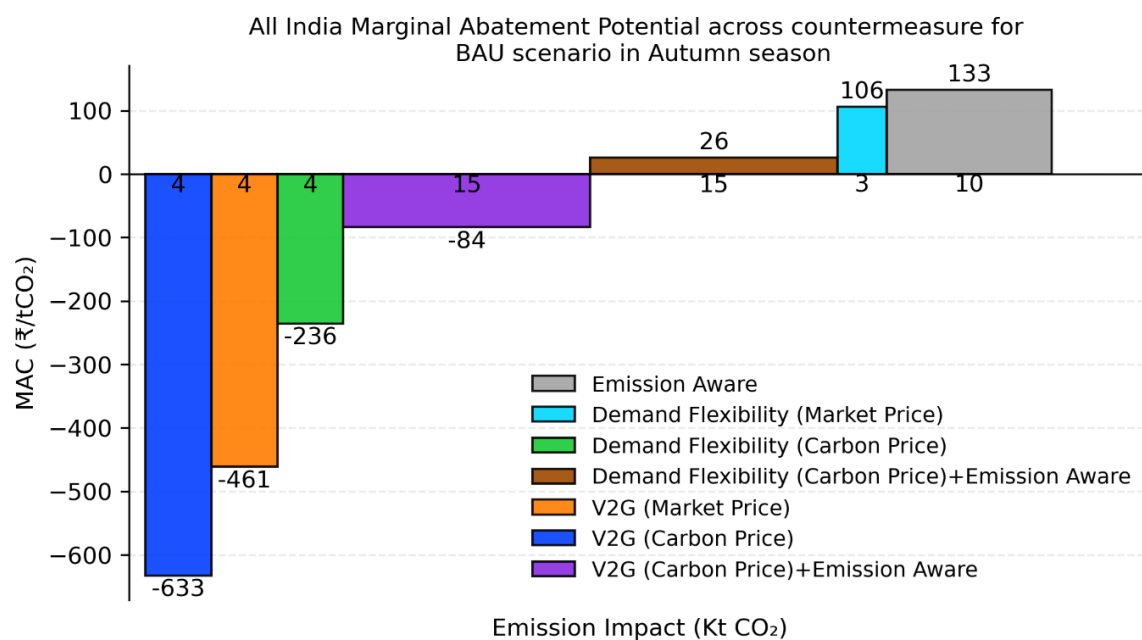
V2G (Carbon Prices) + Emission Aware	BAU	-	26.5	-	-48	-43	-21.50	₹ 0.00	0	-2	0	1	1	0.00
Demand Flexibility (Market Prices)	Stated Policies	42	26.33333	86	-	90	61.08	-₹ 85,516.67	-2	-3	-1	0	-1	-1.40
Demand Flexibility (Carbon Prices)	Stated Policies	42	26.33333	86	-	90	61.08	-₹ 85,516.67	-2	-3	-1	0	-1	-1.40
Demand Flexibility (Carbon Prices) + Emission Aware	Stated Policies	46	30.33333	86	-	90	63.08	-₹ 88,316.67	-2	-3	-1	0	-1	-1.40
V2G (Market Prices)	Stated Policies	56.5	42.33333	92	-	82	68.21	-₹ 95,491.67	-2	-3	-1	0	-1	-1.40
V2G (Carbon Prices)	Stated Policies	81.5	58.66667	179	-	168	121.79	-₹ 1,70,508.33	-2	-3	-1	0	-1	-1.40
V2G (Carbon Prices) + Emission Aware	Stated Policies	84.5	61	180	-	169	123.62	-₹ 1,73,075.00	-2	-3	-1	0	-1	-1.40



8.1.6 All India









Published by:
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September 2026

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