



भारत सरकार के प्रधान वैज्ञानिक सलाहकार का कार्यालय
Office of the Principal Scientific Adviser
to the Government of India

RE-Charge Ready Reckoner

A Handbook on Renewable Energy (RE) Integration for
Zero Emission Truck (ZET) Charge Parks

October 2026



अजय के. सूद

भारत सरकार के प्रमुख वैज्ञानिक सलाहकार

Ajay K. Sood

Principal Scientific Adviser to the Govt. of India

कर्तव्य भवन 3, जनपथ, नई दिल्ली - 110001
Kartavya Bhavan 3, Janpath, New Delhi-110001
Tel. : +91-11-24011867, 24011868
E-mail : sood.ajay@gov.in, office-psa@nic.in
Website : www.psa.gov.in

FOREWORD

India's rapid economic growth and increasing freight movement are driving significant growth in road transportation. As the country advances towards its climate and energy security goals, the transition to Zero Emission Trucks (ZETs) can help reduce emissions, improve energy efficiency, and lower dependence on fossil fuels. These benefits can be further enhanced by powering ZET charging infrastructure with renewable energy, supporting a cleaner and more sustainable freight transport system.

The integration of Renewable Energy (RE) with ZET charging infrastructure entails several considerations related to renewable energy potential, charging demand, grid connectivity, investment requirements, energy storage, tariffs, financing and regulatory compliance. To facilitate RE integration with ZET charge parks in India, I am pleased to present the **"RE-Charge Ready Reckoner – A Handbook on Renewable Energy (RE) Integration for Zero Emission Truck (ZET) Charge Parks."** This handbook provides a practical framework for assessing the integration of renewable energy with ZET charge parks. It brings together approaches for estimating renewable energy generation potential, determining charging and grid requirements, evaluating costs and returns, managing demand charges, selecting appropriate power conversion systems, and addressing operation and maintenance considerations. It also provides an overview of relevant national and state-level policies, regulations, and financial enablers. Overall, the handbook serves as a practical reckoner for understanding and optimising costs and developing technically feasible and commercially viable RE-integrated charge parks, supported by illustrative case studies and techno-economic analyses.

I am confident that this handbook will serve as a valuable reference for charge park developers, fleet operators, DISCOMs, renewable energy developers, policymakers, investors and other stakeholders involved in developing ZET charging infrastructure. By supporting informed planning and investment decisions, it can contribute to the deployment of renewable energy-powered charging infrastructure and accelerate India's transition towards sustainable, efficient and energy-secure freight transportation.

I sincerely appreciate the contributions of all experts, institutions and stakeholders whose knowledge, insights and dedicated efforts have helped shape this handbook.



[Ajay Kumar Sood]

New Delhi
5th October 2026

डॉ. (श्रीमती) परविन्दर मैनी
वैज्ञानिक सचिव
Dr. (Mrs) Parvinder Maini
Scientific Secretary



भारत सरकार के
प्रमुख वैज्ञानिक सलाहकार के कार्यालय
कर्तव्य भवन 3, जनपथ, नई दिल्ली - 110001
Office of the Principal Scientific Adviser
to the Government of India
Kartavya Bhavan 3, Janpath, New Delhi-110001



MESSAGE

The transition to Zero Emission Trucking (ZET) presents an opportunity to simultaneously address freight sector decarbonisation, energy security, and sustainable economic growth. While significant efforts are being undertaken to develop charging infrastructure for electric trucks, the long-term environmental and economic benefits of such infrastructure depend on its integration with clean energy sources.

As part of the ongoing work of the Consultative Group on e-Mobility (CGeM) and the Centre of Excellence for Zero Emission Trucking (CoEZET), several studies have been undertaken to support the development of a robust ZET ecosystem in India. Building on these efforts, the present report, "RE-Charge Ready Reckoner: A Handbook on Renewable Energy Integration for Zero Emission Truck Charge Parks," examines practical pathways for integrating renewable energy into charging infrastructure for medium- and heavy-duty electric trucks.

The report provides guidance on renewable energy resource assessment, charging demand estimation, system sizing, financial viability, regulatory considerations, and implementation models. By bringing together technical, economic, and policy perspectives, it offers stakeholders a practical framework for planning renewable-energy-powered charging facilities that can improve project viability while reducing emissions.

I extend my appreciation to CoEZET, IIT Madras, the members of the Consultative Group on e-Mobility, and all contributors and stakeholders whose efforts have made this handbook a reality. I trust that this document will serve as a valuable reference for all those engaged in planning, financing, and deploying renewable-energy-integrated charging infrastructure for Zero Emission Trucks in India.


(Parvinder Maini)

Date: 05th Oct 2026

Executive Summary

India is one of the fastest growing economies in the world, witnessing growth at an unprecedented scale owing to its perpetually expanding domestic demands and well-intentioned ambition to become a *Viksit Bharat* by 2047. Given the rising demand particularly around manufacturing and services, the logistics sector, reportedly, represents almost five percent of India's Gross Domestic Product (GDP)¹. About 65% of freight movement today is handled by road transport primarily through trucks². With the accelerated economic growth, road freight sector alone is expected to grow fourfold by 2050 in comparison to other modes of transport to meet rising demands. This exponential increase will also lead to a proportional increase in fossil fuel consumption to power these trucks. In India, using conventional trucks to meet the growing demand would require spending over US\$1 trillion cumulatively on crude oil imports for diesel production by 2050³. These fuel powered vehicles will only further pollute air, exacerbate public health hazards and increase energy cost⁴. Although trucks represent just 3% of the total vehicle fleet (including both passenger and freight) they are responsible for a staggering 53% of total Particulate Matter (PM) emissions. Hence electrifying this segment through battery powered Zero Emission Trucks (ZETs) will play a crucial role in meeting national decarbonization and energy security targets.

However, the climate benefits of ZETs are diminished if the vehicles are once again powered by carbon-intensive grid electricity. To that end, this handbook aims to demystify the concerns over Renewable Energy (RE), particularly around its high upfront costs and uncertainty around long-term returns. A simplified technoeconomic model tailored to demand patterns, geographic conditions, and investment appetite is highlighted to present a simple use case to decision makers.

This document on Renewable Energy (RE) Integration for Zero Emission Truck (ZET) Charge Parks, highlights the clear investment costs, returns, energy mix options and payback period for two case studies that reveals the advantages of shifting to renewables for Zero Emission Trucking. A comparative analysis of the business models indicates the mechanism through which charge park owners can achieve financial break-even within one year, compared with approximately 5-6 years under a complete upfront CAPEX investment model which requires nearly 13 times higher upfront investment for the same capacity. There would be a stark 95% reduction in CO₂ emissions when charge parks are powered by RE completely as opposed to grid electricity.

A thorough policy analysis attempts to review relevant national schemes detailing out the fiscal and financial enablers such as reduced GST on EV infrastructure, viability gap funding, green bonds, and public private partnership (PPP) models. Particular emphasis is placed on regulatory convergence between the transport and energy sectors, particularly with regard to licensing, tariff design, and interoperability standards, for providing a clear roadmap for renewable energy integration for DISCOMs, policymakers and state transport departments.

This handbook presents a roadmap to provide requisite support for planning, developing, and implementing renewable energy integration with the charging infrastructure for Zero Emission Trucks (ZETs) and offers practical guidance for decision-makers and investors, including charge park owners and operators. This is prepared as ready reckoner with requisite calculations for model case studies and can be used as a quick reference book for RE integration with charge parks.

¹ [Fast Tracking Freight in India, Niti Aayog, RMI, and RMI India | June 2021](#)

² [Trucking is the backbone of India's economy, DAT Freight and Analytics](#)

³ [Transforming Trucking in India – Niti Aayog, RMI](#)

⁴ [Transforming Trucking in India – Niti Aayog, RMI](#)



Table of Contents

Executive Summary	iv
List of Tables	vii
List of Figures	viii
Chapter 1.....	1
Introduction to ZET Charging Parks and Renewable Energy Integration.....	1
1.1 The Need for Zero Emission Trucking in India	1
1.2 The Promise of Zero Emission Trucking	2
1.3 Bridging the Gap: Powering Zero-Emission Trucking with Renewable Energy	2
Chapter 2.....	4
Renewable Energy Generation Potential.....	4
2.1 State wise Assessment of RE Generation	4
2.2 Site Assessment of RE Estimation	8
Chapter 3.....	11
Charging Park Capacity and Grid Connection Requirements.....	11
3.1 Estimating Charging Demand.....	11
3.2 Sizing Charging Infrastructure.....	13
3.3 Grid Connection and Utility Requirements.....	17
CHAPTER 4	18
Cost Estimation for Renewable Energy Generation and Integration.....	18
4.1 Solar Photovoltaic (PV) System Costs	18
4.2 Wind Energy System Costs.....	19
4.3 Integration and Balance of System Costs.....	20
CHAPTER 5	27
Returns Maximisation and Demand Charges Management.....	27
5.1 Demand Charge Management Strategies.....	27
5.2 Energy Arbitrage and Time-of-Use Rates.....	29
5.3 Incentives and Financing Options	32
CHAPTER 6	34
Power Converter Specification for RE Integration.....	34
6.1. Power Converter Specifications for RE Integration	34
6.2. Converter Topologies and Ratings	36
6.3. Grid Integration and Compliance.....	37
Chapter 7.....	40
Maintenance Considerations for Solar and Wind.....	40
7.1. Maintenance Considerations for Solar PV Systems	40



7.2. Operation and Maintenance Best Practices for Solar	41
7.3. Performance Monitoring and Troubleshooting for Solar	41
7.4. Maintenance Considerations for Wind Power Plants	42
7.5. Operation and Maintenance Best Practices for Wind	43
7.6. Performance Monitoring and Troubleshooting for Wind.....	43
Chapter 8.....	44
Policies and Regulatory Compliances	44
8.1 EV Policies in India	46
8.2 EV State Policies in India	50
8.3 EV Regulations in India.....	53
8.4 EV Regulations in Indian States.....	60
8.5 National Level Renewable Energy Policies for EV Charge Parks	62
8.6 EV Policies of States related to Charging infrastructure & Renewable Energy (RE) Integration	64
8.7 Guide for ZET Stakeholders for Harnessing RE Policies	66
8.8 Environmental Regulations for EV Charge Parks	67
Chapter 9.....	70
Conclusion.....	70
ANNEXURES	71
A.1 Cost-Benefit Analysis of Captive and Group Captive Renewable Energy Models for ZET Charging Parks and CO ₂ Emissions	71
A.2 Fundamentals of Power Converter Technology	76
A.3 Power Converter Types and their Functions in ZET Charging Infrastructure	77
A.4 Key Performance Metrics	78
A.5 Key Technologies, Efficiency Considerations and Power Density in Power Converters.....	80
A.6 Key Institutions Supporting E-Mobility in India	81
Government Ministries and Departments.....	81
Regulatory Bodies	82
Industry Associations and Collaborative Platforms	82
References	83
Glossary.....	84
Acknowledgements.....	87



List of Tables

Table 1 Top 10 States with Highest Wind Power Potential and Actual capacity as of 2024	6
Table 2 Top 10 States with Highest Solar Power Potential and Actual capacity as of 2024	7
Table 3 Details and assumptions of Case Studies	122
Table 4 Demand Estimation of Chennai – Bangalore Corridor	12
Table 5 Demand Estimation of Solapur – Vijayapura Corridor	13
Table 6 Truck Dimensions	14
Table 7 Cost Estimation Breakup of Solar PV Captive Plant without Trackers	19
Table 8 Cost Estimation Breakup of Wind Captive Plant	19
Table 9 Difference between Captive and Group Captive	20
Table 10 Group Captive power plant cost of Solar PV and Wind	21
Table 11 Land Area required per MW of solar and wind as per Captive investment model	21
Table 12 RE Capacity Estimation for Chennai – Bangalore Corridor	21
Table 13 RE Capacity Estimation for Solapur - Vijayapura Corridor	22
Table 14 Case Study 1 - Captive Power Plant Cost Estimations per Charging Station	22
Table 15 Case Study 1 - Group Captive Power Plant Cost Estimations per Charging Station	22
Table 16 Case Study 2 - Captive Power Plant Cost Estimations per Charging Station	23
Table 17 Case Study 2 – Group Captive Power Plant Cost Estimations per Charging Station	23
Table 18 Captive Power Plant Average Savings and RoI	24
Table 19 Group Captive Power Plant Average Savings and RoI	25
Table 20 Summary of Captive and Group Captive plants	26
Table 21 State-wise Demand Charges for EV Charging Stations (2024)	28
Table 22 Tamil Nadu Tariff rate for High Tension EV Charging Station (2024)	29
Table 23 Maharashtra DISCOM Tariff rate for High Tension EV Charging Station (2024)	29
Table 24 Storage Sizing for a solar plant	31
Table 25 Storage and RE Sizing based on charging guns	31
Table 26 Li-ion NMC Battery Cost computation per MWh	32
Table 27 Key Specifications of PCS and Chargers	35
Table 28 Converter and subsystem costs	36
Table 29 Power Converter Topologies and Their Characteristics	37
Table 30 Standards for Bi-Directional PCS and DC Chargers Aligning National and Global Protocols	38
Table 31 Evolution of E-mobility Policies and Initiatives in India: A Timeline	45
Table 32 Summary of FAME I and FAME II Schemes	47
Table 33 PM E-Drive Key Components	48
Table 34 Building Bye-Laws and Policies in States	49
Table 35 State-wise EV-sales penetration targets (all vehicle segments)	51
Table 36 100 % electrification targets for specific vehicle segments	51
Table 37 Charging-infrastructure deployment targets of Key States	52
Table 38 Other Policy Enablers and Opportunities	64
Table 39 Stakeholder-wise Environmental Compliance Responsibilities	69
Table 40 Benefits of Grid vs RE Scenario	70



List of Figures

Figure 1 Power Sources Mix- Generation	2
Figure 2 Wind Power Potential of India	5
Figure 3 Solar Power Potential of India	5
Figure 4 Potential Cumulative Energy Output from Solar and Wind Energy	6
Figure 5 Charging Bay layout considering a minimum of 5 chargers	16
Figure 6 Year wise installed capacity of Renewable Energy	18
Figure 7 Bangalore- Chennai Corridor Cost Estimations per Charging Station (Rs.)	23
Figure 8 Solapur – Vijayapura Corridor Cost Estimations per Charging Station (Rs.)	24
Figure 9 Chennai - Bangalore Corridor Emissions Comparison (tonnes of CO ₂)	25
Figure 10 Solapur - Vijayapura Corridor Emissions Comparison (tonnes of CO ₂)	26
Figure 11 Demand vs RE Generation pattern for 100%	30
Figure 12. Demand vs RE Generation pattern for 100% Wind	30
Figure 13 The integration of various power converters at sources placed in ZET charging parks	34
Figure 14 Cross Comparison of State EV Policies	53
Figure 15 Standards Specific for Charging stations	57

Chapter 1

Introduction to ZET Charging Parks and Renewable Energy Integration

1.1 The Need for Zero Emission Trucking in India

As the world's largest democracy, most populous country, and fifth-largest economy, India plays a pivotal role in the global effort to build a decarbonized economy. India's position as the world's third-largest net importer of crude oil and petroleum products further complicates this scenario. With over 80% of its crude oil consumption relying on imports, the country faces not only environmental challenges but also significant economic and energy security concerns⁵. India has made a bold commitment in its updated Nationally Determined Contribution to reduce the emissions intensity of its GDP by 45% by 2030 from its 2005 levels⁶. In line with this goal, India has set a target of achieving a 30% Electric Vehicle market share by 2030⁷ under the EV30@30 Campaign.

As the share of EVs grows in the coming years, greening the grid becomes equally important. Powering EVs with renewable energy offers the most effective solution for reducing emissions, lowering costs, improving air quality, and strengthening energy security. The transition will not only decrease reliance on petroleum-based fuels used in road transportation but also shift consumer demand from internal combustion engine vehicles to EVs, necessitating an expanded electricity supply and a well-developed charging infrastructure to support widespread adoption. As of 2023 the total electric vehicle registrations in India has increased to around 11 Lakhs from around 2,000 in FY 2014-15⁸. Given this exponential growth of EVs, around 4.44 lakhs public EV chargers would be required by year 2030⁹. As of 2024, India has around 12,146 public EV charging stations operational across the country¹⁰. Only 2% of the target has been achieved so far signifying a rapid deployment rate of EV Chargers in the next few years.

India's freight transportation sector is expanding to meet the demands of an increasing number of consumers. Road transport, particularly trucking, carries the significant share of India's goods, accounting for 70% of today's domestic freight demand¹¹. However, this economic growth and increased transportation activity have come at a significant environmental cost. Between 1990 and 2019, India's total CO₂ emissions from fuel combustion grew by a staggering 330%. Even more concerning, transport-sector emissions surged by 375% over the same period, now contributing 14.2% of the country's total CO₂ emissions from fuel combustion¹² of which the trucking sector is responsible for one-third of transport-related CO₂ emissions in India. It represents just 3% of the total vehicle fleet (including both passenger and freight) yet is responsible for a staggering 53% of total on road PM emissions. The confluence of rapid

⁵ [India - Country Commercial Guide](#) (International Trade Administration)

⁶ [India's Updated First Nationally Determined Contribution Under Paris Agreement 2021-2030](#) (August 2022 Submission to UNFCCC)

⁷ [NITI Aayog convenes India's Electric Mobility Enablers under G20 Presidency](#)

⁸ [India EV Digest 2023](#)

⁹ [Note on 'India EV Digest – 2023'](#)

¹⁰ [MHI Press Release, 2024](#)

¹¹ [Transforming Trucking in India](#) (niti.gov.in)

¹² [Towards Decarbonising Transport 2023](#) (niti.gov.in)

economic growth, increasing freight demand, rising emissions presents both a challenge and an opportunity for transformative change in India's transportation sector, particularly in trucking. Zero Emission Trucking (ZET) and deployment of charging stations for these ZETs emerge as a critical solution to address these interconnected issues.

1.2 The Promise of Zero Emission Trucking

Zero Emission Trucking through Battery Electric Trucks (BETs) and Fuel Cell Electric Trucks (FCETs) offer a promising solution to rising emissions of the rapidly growing freight transportation sector. In 2021 alone, Medium Duty Trucks (MDTs) and High Duty Trucks (HDTs) were responsible for emitting around 1.6 million tonnes of NO_x and 53,000 tonnes of Particulate Matter (PM) emissions. When operated at scale and powered by electricity generated from renewable resources, BETs and FCETs can significantly contribute to India's decarbonization efforts while simultaneously reducing the country's reliance on imported fuels.

By transitioning to zero-emission vehicles like BETs and FCETs, India can simultaneously:

- Reduce transport-sector emissions, contributing to national and global climate goals
- Decrease dependence on imported fossil fuels, enhancing energy security
- Improve air quality in urban and rural areas, benefiting public health
- Drive innovation in the automotive and energy sectors, potentially creating new economic opportunities

1.3 Bridging the Gap: Powering Zero-Emission Trucking with Renewable Energy

While zero-emission vehicles offer a promising solution for reducing transport-sector emissions, their environmental benefits are only fully realized when powered by clean energy sources. Currently, the charging infrastructure is powered by the grid which is 75% from fossil fuels and 25% from renewable energy sources¹³.

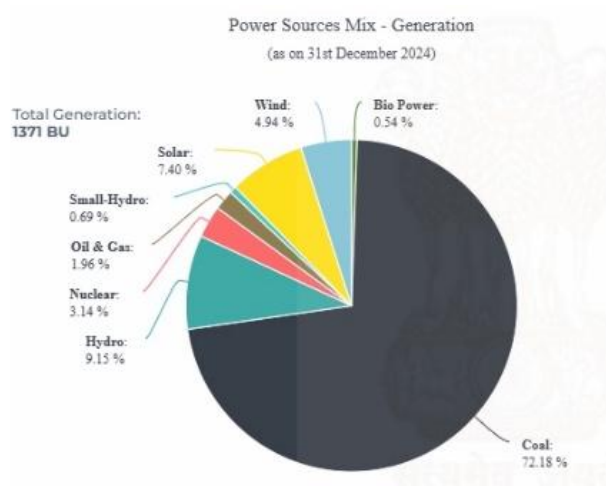


Figure 1. Power Sources Mix- Generation

Battery-electric trucks (BETs) operating on India's current electricity grid can achieve greenhouse gas (GHG) emission reductions of 9% to 35% compared to conventional diesel trucks¹⁴. When

¹³ [India Climate and Energy Dashboard](#)

¹⁴ [Freight Trucks in India are Primed for Electrification](#)

powered entirely by renewable energy sources, the reductions can be as high as 83%¹⁵. The extent of emissions savings depends on factors such as the energy mix of the grid, charging infrastructure availability, and economic feasibility. Charge Park Operators must evaluate these parameters to determine the most sustainable and cost-effective energy procurement strategy for BET deployment.

The government of India has come up with strategies to incentivise renewable energy usage for EVs by setting a ceiling of Rs 2.50 per unit and Rs 3.50 per unit for slow AC chargers during the solar and non-solar hours respectively. Additionally, a ceiling limit of Rs. 10/- per unit and Rs. 12/- per unit has been set for DC Fast chargers during the solar and non-solar hours respectively¹⁶. The generation of energy from sustainable, renewable sources therefore emerges as a crucial link in the chain of decarbonizing India's transportation sector. By ensuring that the electricity used to charge Battery Electric Trucks (BETs) and produce hydrogen for Fuel Cell Electric Trucks (FCETs) comes from renewable sources such as solar and wind, India can create a truly sustainable transportation ecosystem. This approach not only maximizes the emission reduction potential of zero-emission vehicles but also accelerates the country's transition away from fossil fuels. Moreover, investing in renewable energy infrastructure for the transportation sector can have spillover benefits, contributing to the overall greening of India's electricity grid and supporting the country's broader climate goals.

Inference:

India's estimated potential for renewable energy as of 2023 is substantial: namely Wind Power Potential: 11,63,856 MW and Solar Power Potential: 7,48,200 MW¹⁷

This enormous potential underscores the viability of powering zero-emission trucking with clean, renewable energy. Please refer Chapter 2 for more information on State wise renewable energy potential. To realize the vision of zero-emission trucking powered by renewable energy, the development of robust charging infrastructure is crucial. ZET (Zero Emission Trucking) Charge Parks represent a key component of this infrastructure. These facilities are designed to provide efficient, high-capacity charging for electric trucks, integrating renewable energy sources to ensure a truly sustainable transportation ecosystem.

¹⁵ [A comparison of the life-cycle greenhouse gas emissions from combustion and electric heavy-duty vehicles in India](#)

¹⁶ [MHI Press Release, 2024](#)

¹⁷ [EnergyStatistics India publication 2024N.pdf \(mospi.gov.in\)](#)

Chapter 2

Renewable Energy Generation Potential

2.1 State wise Assessment of RE Generation

India is endowed with vast renewable energy potential, particularly in wind and solar energy, which are key pillars of the nation's energy transition strategy. With an estimated wind energy potential of over 1163 GW and solar potential exceeding 750 GW¹⁸, the country has the capacity to meet a significant portion of its energy demand through renewables. Wind energy resources are concentrated in states like Rajasthan, Gujarat, Tamil Nadu, Maharashtra, and Karnataka, while high solar insolation levels make states such as Rajasthan, Gujarat, and Karnataka ideal for large-scale solar installations. While some states possess a natural advantage in renewable energy resources, others are making considerable progress through focused efforts and policy interventions. Andhra Pradesh, with its substantial wind energy potential, has been actively developing wind farms and Telangana has prioritized solar power development, commissioning several large-scale projects. Even states with less ideal conditions are advancing; Uttar Pradesh, despite lower solar insolation, has increased its solar power capacity through various initiatives, and Madhya Pradesh has been actively promoting solar energy with a growing project portfolio.

Site assessments, including wind speed mapping and solar irradiance analysis, play a critical role in identifying high-potential locations for renewable energy projects. Moreover, the integration of renewable energy generation requires addressing challenges like land acquisition, grid stability, and energy storage solutions. With innovative policies, technological advancements, and hybrid systems that combine wind and solar, India is poised to achieve its ambitious target of 500 GW of non-fossil fuel energy capacity by 2030¹⁹, paving the way for a sustainable energy future. The wind and solar potential map of India is depicted in Fig1 and Fig 2 highlighting the states with the highest capacity.

¹⁸ [MNRE Report 2023 - 2024](#)

¹⁹ [Invest India](#)

State wise Wind Energy Potential (MW)

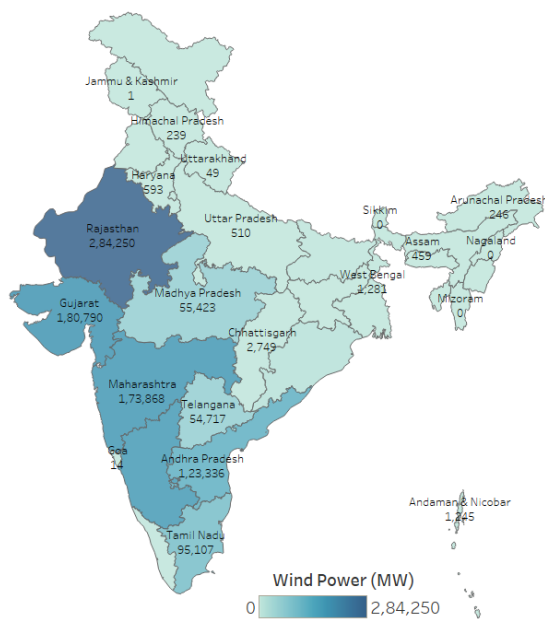


Figure 2. Wind Power Potential of India

State wise Solar Energy Potential (MW)

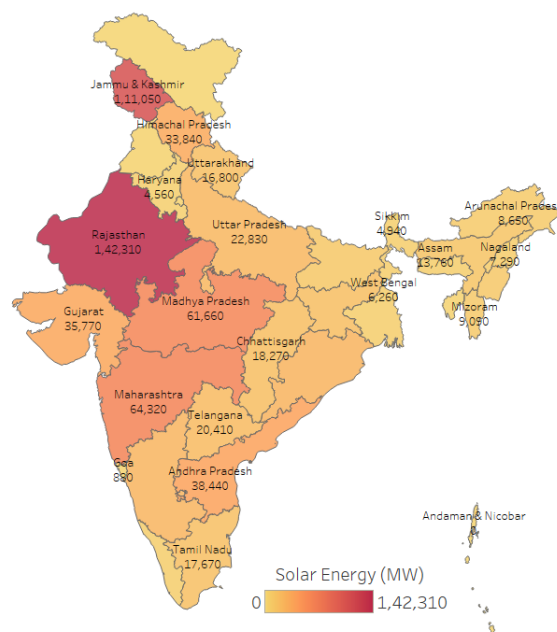


Figure 3. Solar Power Potential of India

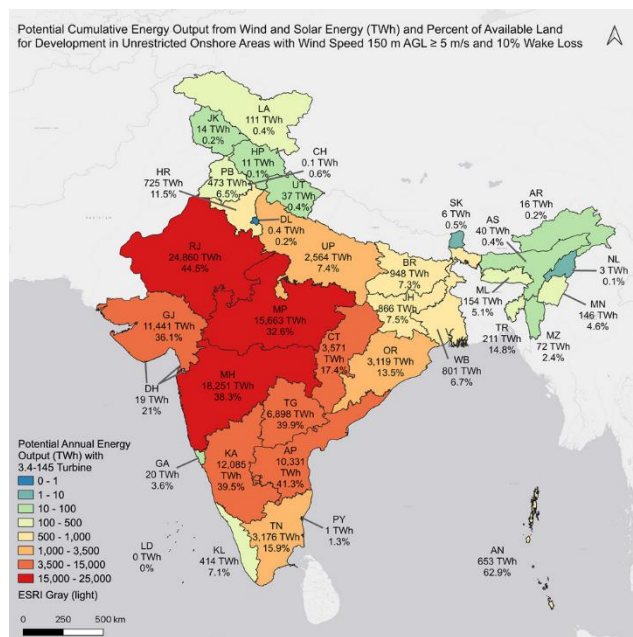


Figure 4. Potential Cumulative Energy Output from Solar and Wind Energy

The top 10 states with the highest estimated Wind power potential and their actual capacities as of 2024 are listed below:

Table 1. Top 10 States with Highest Wind Power Potential and Actual capacity as of 2024

SN	States/ UTs	Estimated Wind Potential (MW)	Actual Wind Capacity as of 2024 (MW)	Percentage achieved (%)
1.	Rajasthan	284250	5195	2%
2.	Gujarat	180790	11783	7%
3.	Maharashtra	173868	5212	3%
4.	Karnataka	169251	6225	4%
5.	Andhra Pradesh	123336	4096	3%
6.	Tamil Nadu	95107	10608	11%
7.	Madhya Pradesh	55423	2844	5%
8.	Telangana	54717	128	0%
9.	Odisha	12129	0	0%
10.	Bihar	4023	0	0%

The top 10 states with the highest estimated Solar power potential and their actual capacities as of 2024 are listed below:


Table 2. Top 10 States with Highest Solar Power Potential and Actual capacity as of 2024

SN	States/ UTs	Estimated Solar Potential (MW)	Actual Solar Capacity as of 2024 (MW)	Percentage achieved (%)
1.	Rajasthan	142310	21469	15%
2.	Jammu & Kashmir	111050	65	0%
3.	Maharashtra	64320	6308	10%
4.	Madhya Pradesh	61660	4050	7%
5.	Andhra Pradesh	38440	4590	12%
6.	Gujarat	35770	13797	39%
7.	Himachal Pradesh	33840	96	0%
8.	Odisha	25780	495	2%
9.	Karnataka	24700	8718	35%
10.	Uttar Pradesh	22830	2930	13%
14.	Tamil Nadu	17670	8332	47%

Tamil Nadu has one of the highest installed capacities for wind energy in India, with over **10,608 MW** of wind power, contributing to about **20% of India's total wind energy capacity**. It also has around **8000 MW** of solar capacity, reflecting its strong renewable energy potential. Solar and wind combined reached almost 10% in 2023. Maharashtra leads in solar and wind capacity in western India, with **6308 MW** of solar and over **5,000 MW** of wind capacity. The state's ambitious renewable energy targets align well with the goals of powering ZET with clean energy sources.

In 2024, Rajasthan emerged as the leading state in solar capacity additions, installing **7.09 GW** of new solar power. Gujarat followed with **4.32 GW**, while Tamil Nadu secured the third position with **1.73 GW**. Collectively, these three states accounted for **71% of India's total utility-scale solar installations** for the year, reflecting their strong policy frameworks and favourable geographical conditions for solar energy expansion.

India's wind sector witnessed **3.4 GW** of new capacity additions in 2024, marking a **21% increase** compared to 2023. Gujarat, Karnataka, and Tamil Nadu were the key contributors, adding **1,250 MW**, **1,135 MW**, and **980 MW**, respectively which together accounted for **98% of the total wind capacity additions**, demonstrating a concentrated growth pattern in India's wind energy sector. Currently, India has utilized only 1% of its solar energy and 10% of its wind energy capacity on average at the state level. High trucking traffic areas concentrated along critical freight corridors like the **Golden Quadrilateral** which connects Delhi, Mumbai, Chennai, and Kolkata and account for nearly 50% of India's freight traffic²⁰. However, these states have tapped just **20% of their solar potential and 3% of their wind potential**, leaving a substantial opportunity for strategic RE integration. Through the development of RE corridors, India can create closed-loop systems to decarbonize freight transport charging and enable widespread adoption of EV trucks, aligning with the nation's net-zero goals.

²⁰ [ZETReport.pdf](#)

2.2 Site Assessment of RE Estimation

Deploying renewable energy (RE)-powered EV charging parks for trucks requires detailed site assessment to ensure optimal energy generation, reliability, and cost-effectiveness. Given the high energy demand of electric heavy-duty trucks, integrating RE sources like solar and wind necessitates careful planning for maximum efficiency, grid stability, and long-term sustainability. The charging park owner can choose to deploy their own solar/wind farm or invest in one via a group captive mechanism based on the local RE potential. For a self-owned plant, the following areas must be considered:

Renewable Energy Resource Analysis:

- **Solar irradiance data:** Solar irradiance indicates the amount of solar energy available. A minimum of 4-5 kWh/m²/day is generally desirable for viable solar power generation. Higher values translate to greater energy production and reduced land requirements. Understanding the peak sun hours and the annual average helps determine the optimal size of the solar array.
- **Wind speed data:** For wind energy, consistent and adequate wind speeds are crucial. Average annual wind speeds of at least 5-6 m/s are often considered necessary for efficient wind turbine operation. Wind resource maps and historical data should be analysed to assess the wind potential at the site. Diurnal and seasonal variations in wind speed must be considered.
- **Hybrid potential:** Combining solar and wind can offer a more consistent energy supply, mitigating the intermittency of individual resources. Analysing the correlation between solar and wind availability is essential. For example, if solar is strongest in summer and wind in winter, a hybrid system can provide a more balanced output. The optimal ratio of solar to wind capacity needs to be determined.
- **Seasonal variability:** Energy generation from solar and wind varies seasonally. Understanding these variations is important for ensuring a reliable energy supply throughout the year. For example, solar output may be lower during monsoon seasons, while wind speeds might be higher in certain months. This information is used to design appropriate energy storage solutions or backup systems.

Space Availability:

- **Area for RE installations:** Solar panel arrays and wind turbines require sizeable amount of land. The required area depends on the desired capacity and the technology used. For solar, an estimated 10-15 acres per MW might be required. For wind, the spacing between turbines can be substantial. A detailed layout plan should be developed considering future expansion.
- **Shading analysis:** For hybrid or solar-only installations, shading from nearby buildings, trees, or other structures can significantly impact energy production. A shading analysis is crucial to optimize the placement of solar panels and minimize losses especially in densely populated areas.
- **Charging Park space:** The charging park needs sufficient space for charging bays, truck parking, queuing areas, and movement. Consider the turning radius of large trucks and the layout for efficient traffic flow within the park. Adequate space is also needed for driver rest areas and other amenities.
- **Equipment space:** Space is required for electrical and power electronics equipment (inverters, transformers), energy storage (batteries), and office facilities. Proper

ventilation and safety considerations should be incorporated into the design of these spaces.

Grid Connection:

- **Grid availability and reliability:** A reliable grid connection is essential for integrating RE generation and supplying power to EV chargers. The grid's capacity and stability are critical factors. Assessment of the frequency and duration of grid outages in the area is necessary; a weak grid might necessitate larger energy storage or backup generation.
- **Proximity to RE-fed grids:** Connecting to a grid already receiving RE generation can simplify integration as it reduces transmission losses and can potentially leverage existing infrastructure. Identify nearby substations or transmission lines connected to RE sources.
- **V2G/V2B compatibility:** If V2G or V2B functionality is planned, the grid connection must be compatible which requires careful planning and coordination with the grid operator. The grid needs to be able to handle bidirectional power flow.
- **Backup systems:** In areas with grid instability or limited RE availability, backup systems like diesel generators might be necessary. The size and type of backup generation should be determined based on the site's reliability requirements. Environmental regulations regarding generator emissions must be adhered to.
- **Proximity and capacity of substation:** The distance to the nearest substation and its available capacity are paramount. Longer distances increase transmission losses and costs. The substation must have sufficient capacity to handle the charging load and the RE generation.
- **Right of way:** If a dedicated transmission line is required, obtaining right-of-way approvals can be a lengthy process that has to be factored into the project timeline. The cost of acquiring right-of-way should also be considered.
- **Energy storage alternatives:** Various energy storage technologies are available, including batteries, pumped hydro, and others. The choice of storage depends on factors like cost, lifespan, and discharge rate. A detailed analysis should be conducted to determine the optimal storage solution.

Energy Demand Assessment:

- **Peak demand:** Determine the peak power demand of the EV chargers, considering the number and type of chargers as this will influence the size of the RE system and the grid connection requirements. Future expansion of the charging park should be factored into the peak demand calculation.
- **Consumption patterns:** Analyse daily, weekly, and monthly energy consumption patterns to understand variations in demand for optimizing the RE system and energy storage. Traffic patterns and truck schedules can influence consumption.
- **BESS requirements:** Battery Energy Storage Systems (BESS) can be used for peak shaving, load levelling, and backup power. The size and type of BESS depend on the energy demand profile and the desired level of grid independence. The lifecycle and cost of the BESS should be considered.
- **Scalability:** The infrastructure should be designed for future scalability with minimal changes. Consider the potential increase in the number of EVs and the charging capacity required in the future. Modular design can facilitate scalability.

Policy Adherence:

- **Local regulations:** Compliance with local regulations regarding RE installations, emissions, safety standards, and licensing is mandatory. Obtaining necessary permits and approvals and familiarising with local building codes and environmental regulations are essential.
- **Permits:** Obtain all necessary permits for solar or wind installations, grid connection, and construction. The permitting process can vary depending on the location. Engage with local authorities early in the planning process.
- **Government schemes:** Utilize available government schemes and incentives for RE integration. This can significantly reduce project costs. Research available subsidies, tax credits, and other financial incentives.

Inference:

India's vast potential in solar and wind energy provides a ready means to decarbonize its energy sector and increase the share of renewable energy in its power mix. Over the past decade, technological advancements and declining costs have led to massive deployments of renewable capacity across the country. The growth in Solar and Wind-based power generation has been remarkable, with a 300% increase in the last 10 years. There exists immense opportunity to integrate RE with high power charge parks. However, the high energy demand of electric heavy-duty trucks, integrating RE sources like solar and wind necessitates careful planning for maximum efficiency, grid stability, and long-term sustainability.

Chapter 3

Charging Park Capacity and Grid Connection Requirements

Nearly 50% of India's vehicle freight traffic is concentrated along seven major corridors²¹ such as the Golden Quadrilateral, which connects Delhi, Mumbai, Chennai, and Kolkata, North-South Corridor, East-West Corridor, Delhi-Mumbai Industrial Corridor (DMIC), Bangalore-Chennai Corridor, Chennai-Kolkata Corridor, Mumbai-Kolkata Corridor. These corridors account for a significant share of trucking activity due to their role in connecting industrial hubs and ports²². Focusing on these highways in this region, the following two corridors have been chosen as case studies for the report:

1. The Chennai to Bangalore highway
2. The Solapur to Vijayapura highway

3.1 Estimating Charging Demand

The Chennai-Bengaluru (348 km) and Solapur-Vijayapura (98 km) corridors have been selected for case studies due to their high freight volume and strategic industrial importance. To estimate charging demand, factors such as charger capacity, truck battery size, dwell times, truck traffic, and demand of the corridor must be considered.

Based on prevailing industry standards and market adoption the assumptions taken into consideration are as follows:

1. *Maximum Charger capacity: 360 kW rating based on current charger rating available in the market.*
2. *Minimum charging time: 45 minutes*
3. *Maximum charging time: 150 minutes*
4. *Percentage of Charge available in the truck: 50%*
5. *Distance between each station: 20km²³*
6. *Truck Gross Vehicle Weight (GVW) Capacities considered:*
 - a. *14 - 18 Ton trucks (kWh) with battery capacity of 100 - 240 kWh*
 - b. *28 - 40 Ton trucks (kWh) with battery capacity of 160 - 300 kWh*
 - c. *55 Ton trucks (kWh) with battery capacity of 300 kWh*
7. *Percentage of Traffic from the following Capacities:*
 - a. *14 - 18 Ton trucks contribute 40% of the traffic*
 - b. *28 - 40 Ton trucks contribute 40% of the traffic*
 - c. *55 Ton trucks (kWh) contribute 20% of the traffic.*

3.1.1 Case Study: Estimating Demand for an Urban Charge Park

Based on Toll data from IHMCL for the periods from 2022 and 2023 the following numbers were obtained

²¹ [Transforming Trucking in India](#)

²² [ZETReport09092022.pdf](#)

²³ [Ministry of Power – Guidelines for Charging Station Infrastructure](#)

Table 3. Details and assumptions of Case Studies

Details	Case Study 1	Case Study 2
States	Tamil Nadu / Karnataka	Maharashtra / Karnataka
Corridor Name	Chennai -Bengaluru	Solapur –Vijayapura
Maximum Truck Traffic in the corridor (average nos. per month)	310984	137724
Minimum Truck traffic in the corridor (average nos. per month)	124281	132935
Length of the corridor (km)	348	98

To determine the optimal traffic level for estimating renewable energy potential, it is advisable to use the average projected upper and lower traffic numbers. Based on which the following have been calculated:

Table 4. Demand Estimation of Chennai – Bangalore Corridor

Case Study 1: Chennai - Bangalore Corridor			
	Considering 100% of the traffic are from EVs	Considering 50% of the traffic are from EVs	Considering 25% of the traffic are from EVs
Energy Required in an hour (kWh)	78603	39302	19651
No of stations required (no)	17	17	17
Distance between each station (km)	20	20	20
Total Energy required in a day (kWh)	1,886,481	943,240	471,620
Energy Required per station per day (kWh)	108,418	54,209	27,105
Energy Required per station per hour (kWh)	4,517	2,259	1,129
No of 360kW Chargers required (minimum of 5 considered)	13	6	5
Capacity per station (kW)	5,000	2,500	2,000

Table 5. Demand Estimation of Solapur – Vijayapura Corridor

Case Study 2: Solapur –Vijayapura Corridor			
	Considering 100% of the traffic are from EVs	Considering 50% of the traffic are from EVs	Considering 25% of the traffic are from EVs
Energy Required in an hour (kWh)	9793	4897	2448
No of stations required (no)	5	5	5
Distance between each station	20	20	20
Total Energy required in a day (kWh)	235,041	117,520	58,760
Energy Required per station per day (kWh)	47,968	23,984	11,992
Energy Required per station per hour (kWh)	1,999	999	500
No of 360kW Chargers required (minimum of 5 considered)	6	5	5
Capacity per station (kW)	2,000	2,000	2,000

Key Insights from the Case Studies

- High energy demand: A single station on the Chennai-Bangalore route at 100% EV adoption needs 108 MWh/ per station /day, highlighting the need for robust grid connections.
- Scalability matters: Even at 50% EV adoption, each station requires at least 5 chargers and 2 MW capacity, which is a significant investment.
- Site viability: Investing in high-traffic corridors (like Chennai-Bangalore) ensures better charger utilization and profitability compared to lower-traffic routes.
- Energy cost planning: At 100% electrification, the entire Chennai-Bangalore corridor demands 1.8 GWh daily, necessitating the need for significant Renewable Energy investments.
- Higher truck volumes on Chennai-Bangalore make it more profitable but capital-intensive, whereas Solapur-Vijayapura may have lower investment but also lower utilization rates.

3.2 Sizing Charging Infrastructure

The Government of India has taken steps to reduce the cost of setting up EV charging stations to promote the adoption of EVs. However, designing an efficient charging station requires careful planning based on several technical and operational factors.

3.2.1 Truck Specifications

The truck's weight, length, and battery capacity directly influence the layout design, charger placement, and energy requirements. The charging infrastructure is calculated based on the following truck capacities available in India:

Table 6. Truck Dimensions

Truck Type	Reference Model	Dimensions	Source
12-Ton Truck	Ashok Leyland Boss 1219 EV	- Length: 9480 mm - Wheelbase: 5200 mm	ashokleyland.com
14-Ton Truck	Ashok Leyland Boss 14 HB EV	- Length: 9480 mm - Wheelbase: 5200 mm	ashokleyland.com
14-Ton Truck	Tata ULTRA T.7 Electric	- Length: 6400 mm - Wheelbase: 3550 mm	tatamotors.com
28 Ton Truck	Tata Prima E.28K Electric truck	- Length: 8110 mm - Wheelbase: 3800 mm	tatamotors.com
28-Ton Truck	Olectra Meghaetron 28T	- Length: 8770 mm - Wheelbase: 4975 mm	olectra.com
55-Ton Truck	IPLTech Electric Rhino 5536	- Tractor Length: 8,500 mm - With Trailer Length : 18750 mm - Wheelbase: 3850 mm	montraelectrictruck.com

3.2.2 Design Considerations Based on Truck Specifications

- Larger trucks require more powerful chargers (≥ 360 kW) to reduce downtime and improve turnaround efficiency owing to a higher payload.
- The length and wheelbase influence parking bay size, ensuring that trucks can align correctly with the charging point without obstructing other vehicles.
- Battery capacity impacts power demand, meaning high-capacity batteries require more energy per charge, affecting substation and grid requirements.

3.2.3 Charging Bay Dimensions

The size of a charging bay must be carefully planned to accommodate trucks of different sizes while allowing for safe movement and operation of charging equipment.

Ministry of Road Transport and Highways for Heavy-Duty Vehicles⁴³

- Length: 18.75 meters
- Width: 4.5 meters

The prescribed dimensions ensure that all truck sizes can be accommodated without congestion. For instance, if a station has five charging bays, it requires a minimum width of 22.5 meters (5 bays × 4.5m) and a length of at least 18.75 meters, excluding additional manoeuvring space.

Proper space allocation also allows for:

- **Ease of Entry and Exit:** Charging bays should be designed to ensure smooth entry and exit for large vehicles fulfilling the Turning Circle Diameter (TCD) requirements specified in Indian standard IS 12222:2011.
- **Safe Clearance for Charging Equipment:** Adequate spacing prevents overheating risks, facilitates maintenance, and ensures compliance with safety regulations.

3.2.4 Layout Configuration

Charging station layout affects efficiency, accessibility, and scalability. A poorly designed layout can lead to long queues, inefficient vehicle movement, and underutilization of chargers. A linear arrangement is a commonly recommended design, where trucks park parallel to each other with designated charging points.

Optimal Layout for a 5-Charger Station in a Linear Arrangement setting-

- **Total Width:** 5 charging bays × 4.5 meters = 22.5 meters
- **Total Length:** 18.75 meters (Truck parking area)
- **Driveway Space:** An additional 17 meters in front of the bays for manoeuvring

The charging park design should prioritize scalability, allowing for the addition of charging bays as demand increases. Alternative layouts, such as angled or pull-through designs, can be explored to optimize space utilization based on the available land area and any site-specific constraints.

3.2.5 Infrastructure Requirements

A well-planned electrical infrastructure is crucial for supporting high-power EV charging, ensuring a stable and efficient energy supply for heavy-duty electric trucks. The setup must include essential components such as transformers, substations, and power distribution networks capable of handling peak demand, particularly in high-traffic corridors.

Key Components include:

- Transformers and Substations
- Compliance with Indian Standards
- Safety and Accessibility Considerations

3.2.6 Total Area Estimation

Once all design parameters are finalized, the total area requirement for the charging station can be calculated considering the largest truck dimensions and additional space for manoeuvring and equipment:

Linear Layout (No. of Charging bays considered: 5)

- Charging Bay Area: $22.5\text{m} \times 18.75\text{m} = 421.88\text{ sq. meters}$
- Driveway and Manoeuvring Space: $34\text{ m} \times 34\text{ m} = 1156\text{ sq. meters}$
- Converters and Transformer Space: $18.75\text{m} \times 4.5\text{m} = 84.38\text{ sq. meters.}$

The total area of 2,910 sq. meters inclusive of pathway, is required for a charging station with 5 charging bays to facilitate the easy entry and exit of trucks.

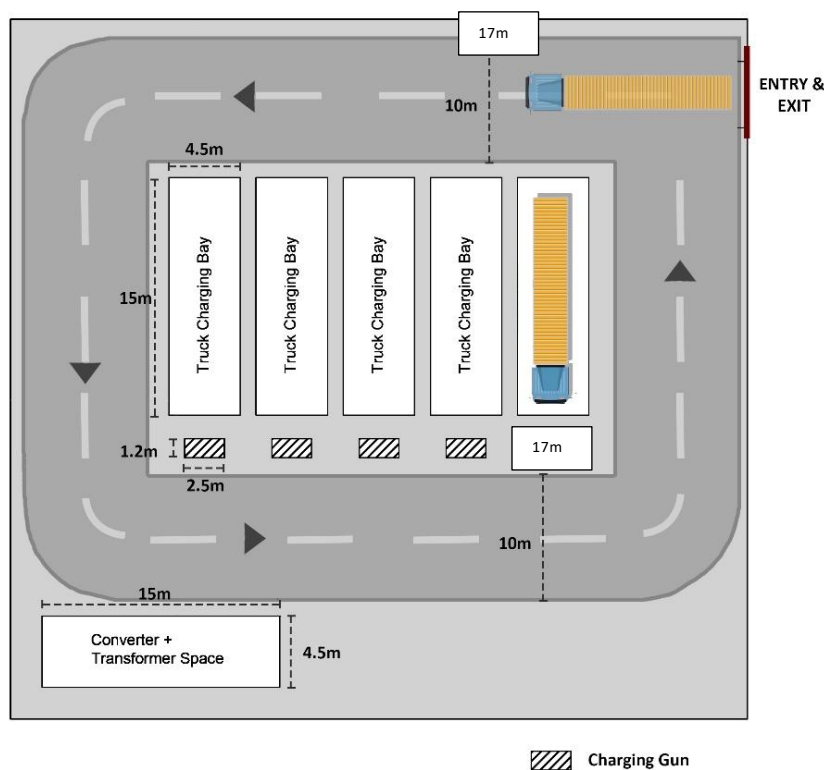


Figure 5. Charging Bay layout considering a minimum of 5 chargers

The proposed charging station layout and its dimensions are designed to accommodate the diverse needs of electric trucks operating in India, including 14-ton, 28-ton, and 55-ton models. If on-site renewable energy generation, such as solar panels, or battery storage is incorporated, additional space might be required. The layout's design should also consider future expansion, enabling the seamless addition of more chargers as demand for electric truck charging grows.

3.3 Grid Connection and Utility Requirements

Electricity supply in India is regulated at both central and state levels, with the CEA setting standards for grid connectivity for EV charging infrastructure such as:

- a. **Technical Standards for Connectivity of “The Distributed Generation Resources (Amendment) Regulations, 2019”**- Introduces standards for charging stations connected or seeking connectivity to the electricity supply system
- b. **Measures Relating to Safety and Electric Supply (Amendment) Regulations, 2019**- Specifies safety requirements for charging infrastructure including general safety for EV charging stations, earth protection system, fire safety, testing of charging stations, inspection and periodic assessment, maintenance of records, and safety provisions as per international standards that need to be followed.

State regulations, such as the State Electricity Supply Code, govern electricity connections and supply by DISCOMs, with rules varying by state. The type of connection (single-phase, three-phase, HT) affects the cost, time, tariffs, and infrastructure needed. Connections from existing networks are more economical than those requiring system expansion, and system upgrades are needed when a new connection exceeds the feeder's capacity utilization threshold of 70%.

Inference:

Electricity tariffs significantly impact the business case for public EV charging, and a separate tariff for EVs would help encourage adoption through incentives like reduced charges. DISCOMs should streamline electricity connection processes for Charge Park Operators (CPO) by establishing clear guidelines, providing a single-window system for applications, and fast-tracking approvals. CPOs should assess site viability for charging facilities, potentially using captive renewable energy systems like solar photovoltaic (PV) or hybrid solutions, supported by energy storage. Feasibility studies should evaluate power generation potential, and CPOs must balance captive generation with grid connections if necessary. Energy management and distributed charging can optimize grid use, reduce costs, and improve grid reliability, while DISCOMs must assess EV charging impacts and develop readiness plans for infrastructure preparedness. The energy requirement for EV charging can be met partly or fully through Renewable Energy generation which must be assessed on a case to case basis. This is typically enabled through solar photovoltaic (PV) or solar-wind hybrid systems, supported by stationary energy storage for reliable power supply. The surface area available for installing the generation system, and the site characteristics in terms of solar insolation and wind profile, are critical parameters in assessing feasibility which are discussed in the following chapter.

CHAPTER 4

Cost Estimation for Renewable Energy Generation and Integration

India's vast potential in Solar and Wind energy generation offers a ready means to decarbonize and increase the share of renewable energy. Over the recent past, technology advancement and declining costs have led to massive deployments of renewable capacity across the country, with a 300% growth in Solar and Wind based power generation in the last 10 years (Figure 6).

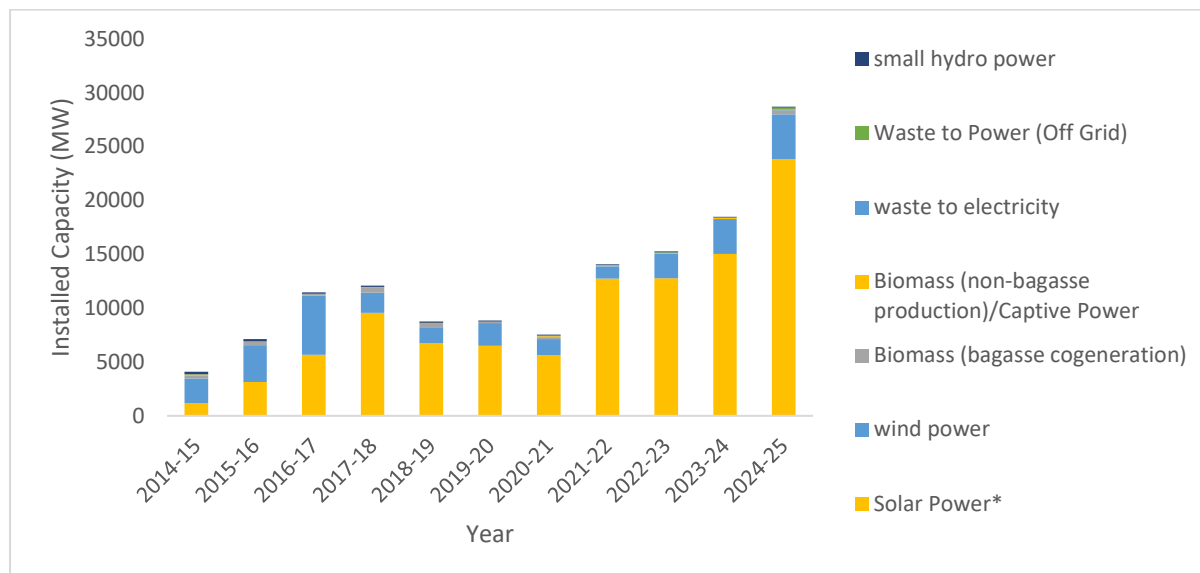


Figure 6. Year wise installed capacity of Renewable Energy

Source: MNRE²⁴

Adopting renewable energy has not only played a pivotal role in helping India's effort towards addressing climate change but also brings with it a massive economic opportunity for large-scale cost-savings. Solar and Wind based energy in India is among the cheapest forms of energy generation available anywhere in the world, the costs have reached such an inflection point that both developing and developed countries have a compelling reason to phase out fossil fuels, meet their growing energy demands, and save on costs in the process.²⁵

4.1 Solar Photovoltaic (PV) System Costs

Solar modules make up about 50% of the total capital cost, with inverters contributing 5%-10%. The systems offer long-term savings due to low operational costs. Solar PVs typically last over 25 years, requiring only occasional maintenance. Land costs for solar projects vary by region, but solar panel costs have decreased due to technological advancements and economies of scale.

²⁴ MNRE (<https://mnre.gov.in/en/year-wise-achievement/>)

²⁵ Zero to Green Report, IITM Research Park

Table 7. Cost Estimation Breakup of Solar PV Captive Plant without Trackers

Component	Cost (Rs per MWp)
Land	2,400,000
Approvals	2,300,000
Power Evacuation infrastructure	2,600,000
Modules	17,000,000
Inverters	1,500,000
Structures	2,500,000
AC Cables	1,500,000
DC Cables	300,000
Transformers, HT panels	2,000,000
SCADA	300,000
I&C	2,000,000
Total	34,400,000

The total estimated cost of ₹34.4 million (₹3.44 crore) per MWp highlights the capital-intensive nature of solar PV projects. However, these costs are offset by long-term benefits such as minimal operational expenses, and savings on per-unit electricity costs. Captive solar power plants, in particular, help industries and businesses reduce dependency on grid power, hedge against electricity price fluctuations, and meet sustainability targets.

4.2 Wind Energy System Costs

Wind energy costs appear to be declining, likely due to advancements in turbine technology, which seem to be making it more competitive, particularly in regions with strong wind like Tamil Nadu and Maharashtra. While the initial capital investment for wind energy systems tends to be higher than that for solar PV, operational costs may be lower. Capacity Utilization Factor (CUF) measures the efficiency of a power plant by comparing its actual energy output to its maximum possible output over a given period. High-capacity utilization factor (CUF) regions such as Andhra Pradesh, Gujarat, Karnataka, Maharashtra, and Tamil Nadu seem to offer significant potential. Turbine supply is estimated to account for nearly 70% of total expenditure, while additional costs are associated with land acquisition, transportation, foundation works, permits, and power evacuation infrastructure. Wind turbines are typically installed on elevated terrains to maximize efficiency.

Table 8. Cost Estimation Breakup for Wind Captive Plant

Wind components	Cost per MW
Turbine Supply	57500000
Turbine Transport	3000000
Land	4000000
Foundation Works	3000000
Permits and Approvals	3000000
Power Evacuation Infrastructure	10000000
Total	80,500,000

The total capital expenditure per MW for wind energy projects in India is around ₹8.05 crore, making it a higher upfront investment compared to solar PV systems. However, wind farms have lower operational costs and higher capacity utilization factors (CUF) in high-wind regions, making them economically viable in the long run.

4.3 Integration and Balance of System Costs

To ensure a stable and cost-effective power supply, industries and CPOs can opt for either Captive Power Plants (CPPs) or Group Captive Power Plants (GCPPs).

Captive Power Plants (CPPs) are owned by a single entity and allows an exemption from cross-subsidy surcharges if at least 51% of power is consumed in-house. Large industrial units like steel plants and refineries benefit most from CPPs.

Group Captive Power Plants (GCPPs), allow multiple entities to co-own a plant, with participants owning at least 26% and consuming 51% of the generated power. GCPPs are ideal for industrial parks, IT hubs, and MSME clusters, offering shared renewable energy infrastructure and reduced capital investment.

Table 9. Difference between Captive and Group Captive

Feature	Captive Power Plant	Group Captive Power Plant
CAPEX and OPEX	Higher CAPEX Lower OPEX	Lower CAPEX Higher OPEX
Ownership	Owned by a single entity (e.g., a factory, company, or industrial unit) for its own use.	Owned collectively by multiple consumers (industries or commercial entities).
Minimum Consumption Requirement	At least 51% of the power generated must be consumed by the owner.	At least 51% of the power generated must be consumed by participating consumers who collectively own at least 26% of the plant.
Participants	A single industrial or commercial entity.	Multiple entities pool resources.
Investment Type	Entirely funded by the company setting it up.	Shared investment among participating consumers.
Regulatory Benefits	Exempt from cross-subsidy surcharge (CSS) and additional open-access charges.	Also exempt from CSS, provided ownership and consumption criteria are met.
Flexibility	Less flexible since it serves a single company's needs.	More flexible, allowing multiple users to benefit.
Common Use Cases	Large manufacturing units, refineries, steel plants, and cement factories.	Industrial parks, IT parks, and clusters of MSMEs.

For ZET charging infrastructure, group captive models present a cost-efficient approach to renewable energy adoption based on the cost detailed below.

Captive Power is best suited for large industries that want full control over power generation. Group Captive is a cost-effective option for multiple businesses looking to share power generation benefits without full ownership responsibility.

The Group Captive costs are tabulated below in Table 10. These costs are based on actual investment figures for solar PV and wind projects obtained from Independent Power Producers (IPP) partnered with IIT Madras Research Park. These benchmark costs are used as the basis for estimating the group captive renewable energy investment requirements for the two case studies.

Table 10. Group Captive power plant cost of Solar PV and Wind

Investment Mechanism	1 MW Solar	1 MW Wind
Investment through Group Captive Mechanism (Rs.)	32,00,000	1,50,00,000

Based on the above the total land area required per MW of Solar and Wind are estimates as follows:

Table 11. Land Area required per MW of solar and wind as per Captive investment model

Source	1 MW Solar	1 MW Wind
Land Required	3.5 acres	1.5 acres

Cost Estimation for selected Case Studies:

For the two case studies namely “Solapur – Vijayapura Corridor” and “Chennai – Bangalore Corridor” data was collected from Maharashtra and Tamil Nadu. Calculations based on 3 possible EV percentage scenarios (100%, 50% and 25%) is given in the following section:

Data collected:

- Output per kW capacity (kWh) for solar in Tamil Nadu is considered as 4.5 kWh a day based on actual energy output.
- Output per kW capacity (kWh) for solar in Maharashtra is considered as 4 kWh a day.
- Output per kW capacity (kWh) for wind in Tamil Nadu and Maharashtra is computed as 7.2 and 6 kWh based on CUFs of 30% and 25% respectively²⁶

Formula:

- Total capacity required (kW) = Total Energy required in a day (kWh) / Average daily operational hours of the RE plants (hours)
- RE Required per station (MW) = Total capacity required (MW) / Number of stations required

The following capacities for RE were estimated for both corridors based on the energy estimated per day and as given in Table 4 and Table 5 of Chapter 3:

Table 12. RE Capacity Estimation for Chennai – Bangalore Corridor

Case Study 1: Chennai - Bangalore Corridor				
Capacity of RE required per station based on estimated daily demand (MW)				
Scenarios	100% solar	100% wind	Hybrid	
			50% Solar	50% Wind
100% of traffic from EVs	24.09	15.06	12.05	7.53
50% of traffic from EVs	12.05	7.53	6.02	3.76
25% of traffic from EVs	6.02	3.76	3.01	1.88

²⁶ [NIWE Report](#)

Table 13. RE Capacity Estimation for Solapur - Vijayapura Corridor

Case Study 2: Solapur –Vijayapura Corridor				
Capacity of RE required per station based on estimated daily demand (MW)				
Scenarios	100% solar	100% wind	Hybrid	
			50% Solar	50% Wind
100% of the traffic are from EVs	11.99	7.99	6.00	4.00
50% of the traffic are from EVs	6.00	4.00	3.00	2.00
25% of the traffic are from EVs	3.00	2.00	1.50	1.00

Based on all of the above capacity and cost estimations we have computed the overall integration costs for two scenarios for both Captive and Group captive mechanism as required per station. Actual costs per MW for group captive plants implemented in IIT Madras Research Park as per their agreements with Independent Power Producers were used for these cost estimations in this chapter.

Table 14. Case Study 1 - Captive Power Plant Cost Estimations per Charging Station

Case Study 1: Chennai - Bangalore Corridor			
Captive Power Plant Cost Estimations per Charging Station (Rs.)			
Scenarios	Charging station powered by 100% solar	Charging station powered by 100% wind	Charging station powered by 50:50 solar and wind
Considering 100% of the traffic are from EVs	828,798,614	1,212,178,205	1,020,488,410
Considering 50% of the traffic are from EVs	414,399,307	606,089,103	510,244,205
Considering 25% of the traffic are from EVs	207,199,653	303,044,551	255,122,102

Table 15. Case Study 1 - Group Captive Power Plant Cost Estimations per Charging Station

Case Study 1: Chennai - Bangalore Corridor			
Group Captive Power Plant Cost Estimations per Charging Station (Rs.)			
Scenarios	Charging station powered by 100% solar	Charging station powered by 100% wind	Charging station powered by 50:50 solar and wind
Considering 100% of the traffic are from EVs	77,097,545	105,406,800	91,252,173
Considering 50% of the traffic are from EVs	38,548,773	52,703,400	45,626,086
Considering 25% of the traffic are from EVs	19,274,386	26,351,700	22,813,043

Table 16. Case Study 2 - Captive Power Plant Cost Estimations per Charging Station

Case Study 2: Solapur –Vijayapura Corridor			
Captive Power Plant Cost Estimations per Charging Station (Rs.)			
Scenarios	Charging station powered by 100% solar	Charging station powered by 100% wind	Charging station powered by 50:50 solar and wind
Considering 100% of the traffic are from EVs	41,25,20,852	64,35,64,507	52,80,42,680
Considering 50% of the traffic are from EVs	20,62,60,426	32,17,82,254	26,40,21,340
Considering 25% of the traffic are from EVs	10,31,30,213	16,08,91,127	13,20,10,670

Table 17. Case Study 2 – Group Captive Power Plant Cost Estimations per Charging Station

Case Study 2: Solapur –Vijayapura Corridor			
Group Captive Power Plant Cost Estimations per Charging Station (Rs.)			
Scenarios	Charging station powered by 100% solar	Charging station powered by 100% wind	Charging station powered by 50:50 solar and wind
Considering 100% of the traffic are from EVs	3,83,74,033	5,59,62,131	4,71,68,082
Considering 50% of the traffic are from EVs	1,91,87,016	2,79,81,066	2,35,84,041
Considering 25% of the traffic are from EVs	95,93,508	1,39,90,533	1,17,92,020

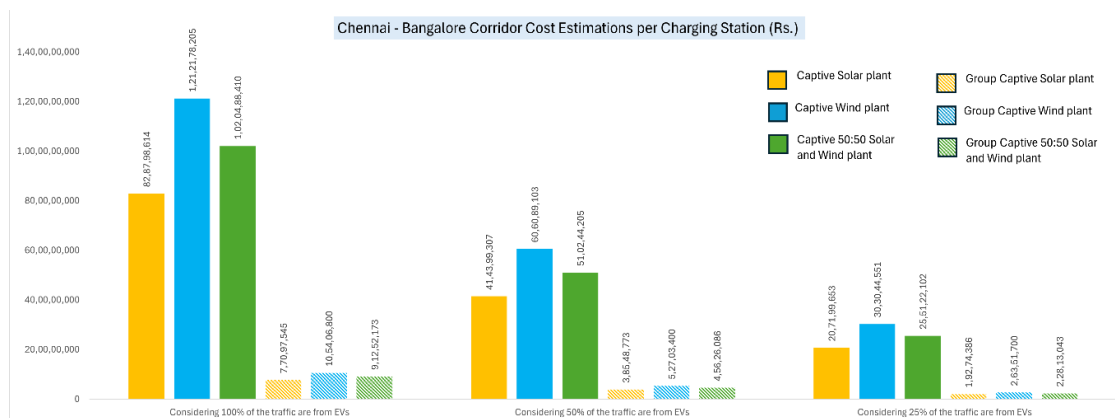


Figure 7. Bangalore- Chennai Corridor Cost Estimations per Charging Station (Rs.)

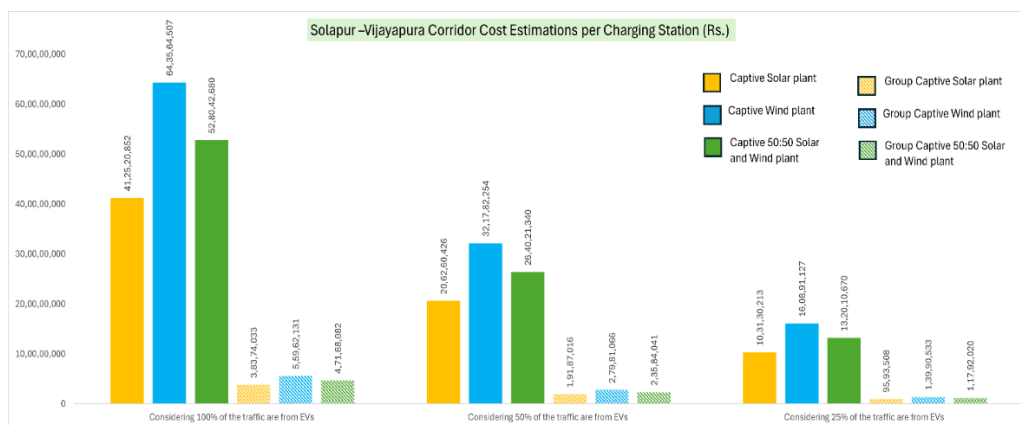


Figure 8. Solapur – Vijayapura Corridor Cost Estimations per Charging Station (Rs.)

Key Insights from the Case Studies

- For Chennai-Bangalore (100% EV adoption), captive power (₹82 Cr for solar, ₹121 Cr for wind) is ~12 times costlier than group captive power (₹7 Cr for solar, ₹10 Cr for wind) per charging station.
- For Solapur-Vijayapura (100% EV adoption), captive power (₹41 Cr for solar, ₹64 Cr for wind) is ~13 times higher than group captive (₹3 Cr for solar, ₹5 Cr for wind).
- Using a 50:50 solar-wind mix reduces costs compared to full wind power while ensuring stability. In Chennai-Bangalore (100% EVs), a mixed approach saves ₹19 Cr compared to wind-only captive power. In Solapur-Vijayapura (100% EVs), a mixed approach saves ₹11 Cr compared to wind-only captive power.
- Group Captive Power is the most viable model for charging park owners due to lower upfront investment.
- Captive power may be feasible for large-scale operators or industrial hubs but comes with high capital expenditure.

By choosing renewables instead of conventional energy source such as coal or thermal for EV Charging stations our two case studies show an average savings and RoI as detailed below from varying combinations of EV adoption and a mix of solar, wind and the two combined to meet the corresponding energy requirements:

Table 18. Captive Power Plant Average Savings and RoI

Captive Power Plant		
Particulars per station	Case Study 1: Chennai - Bangalore Corridor	Case Study 2: Solapur – Vijayapura Corridor
Average Savings per Charging Station (Rs.)	156,193,273	6,06,93,449
Average Payback period per Charging Station (Years)	4.03	5.49

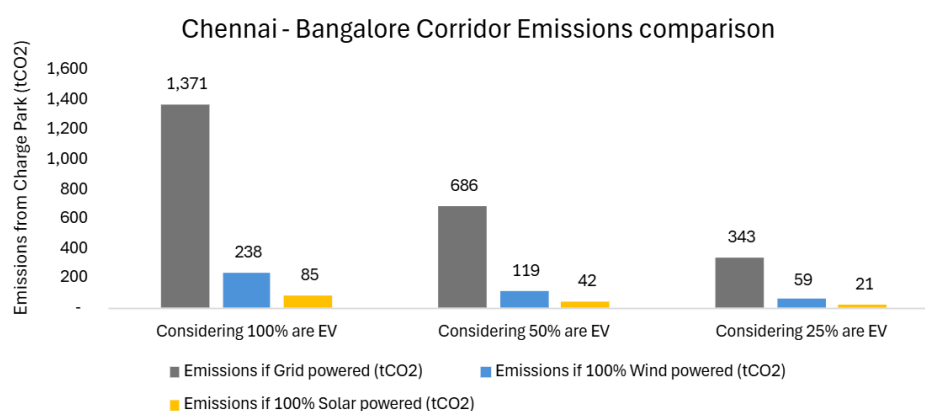
Table 19. Group Captive Power Plant Average Savings and RoI

Group Captive Power Plant		
Particulars per station	Case Study 1: Chennai - Bangalore Corridor	Case Study 2: Solapur – Vijayapura Corridor
Average Savings per Charging Station (Rs.)	88,060,425	3,19,09,327
Average Payback period per Charging Station (Years)	0.90	1.49

These numbers include converter and transformer cost of Rs. 3700 per kW and maintenance cost of 1.4% mandated by TNEB²⁷ which are considered for various scenarios detailed in the Annexure.

[Link to the RE \(Renewable Energy\) Sizing Online Calculator for ZET Charge Parks](#)

In addition to the quick payback period and savings in terms of cost, an analysis on the CO₂ emissions indicated almost a 95% reduction in emissions if powered by solar and an 83% reduction in emissions if powered by wind plants for the same scenario. The emissions avoided by switching to renewables is almost equal to 700 acres of forest²⁸

Figure 9. Chennai - Bangalore Corridor Emissions Comparison (tonnes of CO₂)

²⁷ [Comprehensive Tariff Order on Solar Power](#)

²⁸ [EPA Emissions Calculator](#)

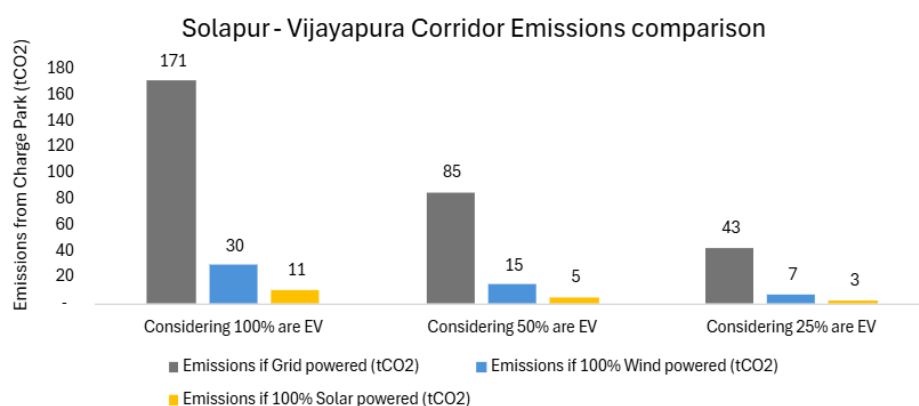


Figure 10. Solapur - Vijayapura Corridor Emissions Comparison (tonnes of CO₂)

Inference:

The summary table below highlights the most optimal use case by comparing key parameters such as CAPEX, savings, payback period, technology options, and use case scenarios across both captive and group captive investment models.

Table 20. Summary of Captive and Group Captive plants

Feature	Captive Power Plant	Group Captive Power Plant
Capex	Higher (₹10–121 Cr)	Significantly lower (₹1–10 Cr)
Savings	Low	High
Payback Period	~.3–6.9 years	~ 0.76–2.1 years
Best performer (average)	Hybrid (50:50)	100% Solar

CHAPTER 5

Returns Maximisation and Demand Charges Management

5.1 Demand Charge Management Strategies

Nature-based solar and wind plants are inherently variable across hours, seasons and based on geographic locations. The only way to overcome the hourly/ seasonal deficit of renewable energy is by adding flexibility to it through energy storage systems. Energy Storage systems are essential to balance intermittency of the renewable energy sources and to optimize energy by load shifting based on energy arbitrage and peak demand. Battery storage systems are most widely used energy storage due to its technological advancement and cost effectiveness. A battery storage system can be used in following ways to maximize returns and manage demand charges:

Peak Shaving: Discharging energy from the storage whenever there is an increase in demand above the limit will reduce dependency on the grid and thereby reduce the excess cost incurred due to demand charges.

Load Shifting: Renewable energy can be used to charge EVs during off-peak hours, lowering electricity costs under time-of-use (TOU) rates.

Grid Export and Net Metering: Some states allow net metering, enabling EV charging stations to sell excess solar energy back to the grid, further reducing electricity expenses.

Excess Energy: As solar and wind are variable sources, there might be times during which there is an excess or deficit of supply. In order to balance this, a storage system can be utilized to charge whenever there is an excess and discharge whenever there is a deficit of renewable energy.

Sanctioned Demand: refers to the amount of power (kVA) that can be drawn by a consumer from the grid at any instant. 'Demand Charges' stands for the cost paid per kVA of sanctioned demand. The cost per unit is fixed by the local electricity board. If the sanctioned demand limit is breached for 3 times within a month the consumer will be penalised. Each month the charge park owner will be charged for either the 90% of the sanctioned demand, irrespective of the consumption, or maximum load drawn at an instant whichever is higher. Hence, it is important to maintain and manage the demand charges within the sanctioned limit. The sanctioned demand for High Tension EV Charger category as per tariff book charges 2024 to Tamil Nadu DISCOM is Rs.145/kVA and is around Rs. 80/kVA according to the Maharashtra DISCOM. The Demand charges for EVs for all states are tabulated below²⁹:

²⁹ [CEA, Tariff Book 2024](#)

Table 21. State-wise Demand Charges for EV Charging Stations (2023)

Sl. No.	State/Utility	Fixed/Demand Charge
1	Andaman & Nicobar Islands	Nil
2	Andhra Pradesh	Nil
3	Assam	Nil
4	Bihar	180 Rs/kVA/Month
5	Chandigarh	Nil
6	Chhattisgarh	Nil
7	Dadra & Nagar Haveli and Daman & Diu	Nil
8	Delhi (BRPL/BYPL/TPDDL)	Nil
9	Goa	25 Rs/Installation/Month
10	Gujarat	25-50 Rs/kVA/Month (based on usage type)
11	Himachal Pradesh	Nil
12	Jammu & Kashmir	Nil
13	Jharkhand	120 Rs/kVA/Month
14	Karnataka	70 Rs/kVA/Month (plus extra above 50 kW)
15	Kerala	290 Rs/kVA/Month of billing demand
16	Ladakh	Nil
17	Lakshadweep	Nil
18	Madhya Pradesh	75 Rs/kVA/Month
19	Maharashtra (MSEDCL)	80 Rs/kVA/Month
20	Mizoram	75 Rs/kVA/Month
21	Odisha	Nil
22	Puducherry	Nil
23	Punjab	40 Rs/HP/Month of sanctioned load
24	Rajasthan	135 Rs/kVA/Month
25	Sikkim	150/500 Rs/Month (above/below 45kW load)
26	Tamil Nadu	145 Rs/kW/Month
27	Telangana	50 Rs/kW/Month

Sl. No.	State/Utility	Fixed/Demand Charge
28	Tripura	50 Rs/kW/Month
29	Uttarakhand	Nil
30	Uttar Pradesh	Nil
31	West Bengal (WBSEDCL)	Nil

Note: Nil data represents an absence of an EV Specific tariff rate

Source: BEE³⁰

5.2 Energy Arbitrage and Time-of-Use Rates

Energy arbitrage involves capitalizing on fluctuations in electricity prices by storing energy during periods of low demand (off-peak) and utilizing it during high-demand (peak) times. This strategy is particularly relevant in regions with Time-of-Day (ToD) tariff structures, where electricity rates vary based on the time of consumption. Time-of-Day (ToD) tariffs adjust electricity rates based on consumption periods, encouraging users to shift usage to off-peak times for cost savings and grid efficiency. Here's an overview of ToD tariffs for EV charging in Delhi and Karnataka:

Delhi: The Delhi Electricity Regulatory Commission (DERC) has implemented ToD tariffs for EV charging stations. During peak hours (2 PM to 5 PM and 10 PM to 1 AM), higher tariffs apply, while off-peak hours offer reduced rates.

Karnataka: Karnataka has introduced ToD tariffs for EV charging, with higher rates during peak periods (6 AM to 10 AM and 6 PM to 10 PM) and lower rates during off-peak times

State-wise electricity boards have time of day usage defined which gives different per unit tariff rates for different hours of energy usage. According to the TNEB (Tamil Nadu Electricity Board) Tariff Order of 2024, the per unit rates of High-Tension EV Charger is defined as:

Table 22. Tamil Nadu Tariff rate for High Tension EV Charging Station (2024)

Time	6am - 9 am 6 pm - 10 pm	9 am - 4 pm	4 pm - 6pm 10 pm - 6am
Tariff rates (Rs. /kWh)	9.45	6.3	7.85
Demand Charges (Rs. / kVA)	145		

Source: TNEB³¹

Whereas for the MSEDCL there are no time-of-day tariffs for High Tension EV's:

Table 23. Maharashtra DISCOM Tariff rate for High Tension EV Charging Station (2024)

Particulars	Cost
Tariff rates (Rs. /kWh)	7.40
Demand Charges (Rs. / kVA)	80

Source: Maharashtra DISCOM³²

³⁰ [BEE India EV Digest 2023](#)

³¹ [TNEB Tariff Order](#)

³² [Maharashtra Electricity Regulatory Commission \(MERC\)](#)

By utilizing a storage system to balance the time-of-day usage cost. The size of the storage system will depend upon multiple factors such as:

1. Demand pattern of the site
2. Type of renewable energy source selected
3. Location of the offsite RE plant
4. Investment appetite of the CPO or DISCOM.

Based on the above factors, a flat load or demand pattern against the intermittent generation pattern of RE sources on a 24-hour scale indicated gaps showing a pattern of excess and deficit across the day.

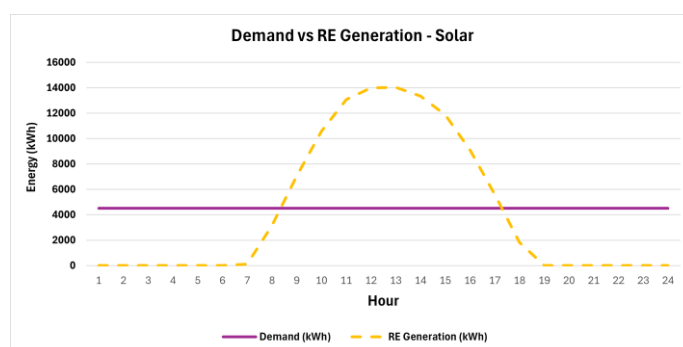


Figure 11. Demand vs RE Generation pattern for 100%

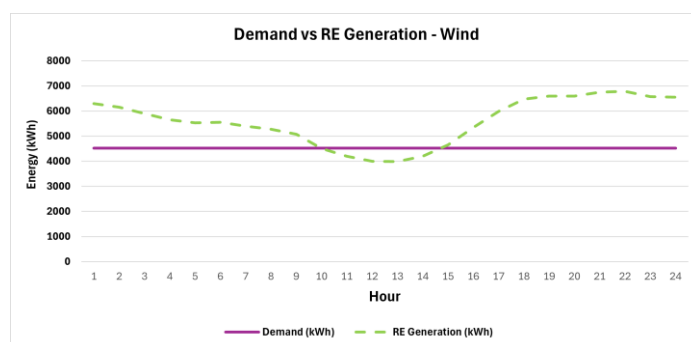


Figure 12. Demand vs RE Generation pattern for 100% Wind

5.2.1 Sizing the battery storage

Plotting the **excess and deficit** across the hours of energy consumption and load patterns for the two case studies under the **three scenarios of energy mix** helps determine the required **storage size as a percentage of the average daily demand**.

For an accurate estimation of storage requirements, an important factor to consider is the **pattern of consumption**, also known as the **load curve**. A load curve represents the variation of electricity demand over a 24-hour period. The typical patterns of consumption include:

- **Flat demand curve** – where the load remains relatively constant throughout the day.

- **Morning peak curve** – where demand increases significantly in the daytime hours³³.
- **Evening peak curve** – where demand rises from evening hours until daytime³⁴.

It is to be noted that sizing storage for wind power plants would vary drastically based on the location of the plant, consumption patterns and the settlement mechanism rules of the particular state. Hence estimating storage for wind plants would be subject to variation as it needs to be evaluated on a case by case basis.

The storage sizing for the two case studies will **differ across these load conditions**, as summarized in **Table 24** below.

Table 24. Storage Sizing for a solar plant

Storage Sizing for Solar as a percentage of Daily Energy Consumption			
Demand Pattern	Flat Demand	Morning Peak	Evening Peak
Corridor			
Chennai - Bangalore	23%	16%	29%
Solapur - Vijayapura	24%	17%	31%
Average	23%	16%	30%

This analysis results in an **average storage requirement of 23%** of daily energy consumption, which is considered the **ideal case scenario** for estimating storage sizing across varying demand profiles.

Taking an alternate approach to determine renewable energy (RE) and storage capacities, based on the **number of charging guns** a **Charge Point Operator (CPO)** intends to install, the following assumptions have been applied to estimate the sizing requirements:

1. **Battery storage capacity** equivalent to **23% of the daily demand**.
2. **Average solar generation** of **4 kWh per kW of installed capacity per day**.
3. **Average wind generation** of **6 kWh per kW of installed capacity per day**.
4. **Partial (12-hour) utilization** of all charging guns at the station.

The resulting estimations are summarized in **Table 25** below.

Table 25. Storage and RE Sizing based on charging guns

Number of Chargers in the station	Energy Demand for the station per day (kWh)	Solar capacity required (MW)	Wind capacity required (MW)	Storage required for Solar (MWh)	Storage required for Wind (MWh)
5	21600	4.8	3.6	5.0	Subjected to variation based on location
10	43200	9.6	7.2	9.9	
15	64800	14.4	10.8	14.9	
20	86400	19.2	14.4	19.9	

³³ Uttar Pradesh Expressways Industrial Development Authority, "Chapter 4 – Traffic Studies Expressway", June 2020.

³⁴ IJPREAMS, "Study the effect on delay and fuel consumption on toll plaza", April 2025

5.2.2 Cost Estimate for battery storage

Today, Li-ion batteries are a cost-effective option given the high cost of capital in India. The Li-ion NMC batteries score better than LTO batteries, as interest rates typically tend to be much higher comparatively. Nickel, Manganese and Cobalt (NMC) cells give about 10000 cycles, with battery pack costs under ₹20k per kWh for a one MWh battery or larger system. Whereas a lithium-titanium-oxide (LTO) cell with about 15000 cycles and battery pack costs at around ₹40K per kWh. The cost of LTO batteries goes up from ₹4 per kWh at 2% interest rate (prevalent in the West) to ₹12 per kWh at 10% interest (prevalent in India and other emerging countries). The cost of capital is of huge significance, and the storage costs would sky-rocket if interest rates are high. Hence choosing NMC battery is more practical³⁵.

Based on actual data the cost computation of a Li-ion battery per kWh is tabulated below:

Table 26. Li-ion NMC Battery Cost computation per MWh

A. Manufactured Battery Cost		
Particular	Value	Percentage
Cost per Cell (Rs./kWh)	₹ 2,663	
Total Cell cost for 1MWh	₹ 26,63,000	14%
Miscellaneous Charges (including insurance, tax, transport and duty charges)	₹ 47,39,366	25%
BMS Hardware	₹ 3,35,081	2%
Mechanics	₹ 38,59,634	21%
B. Converter Cost		
Converter Cost	₹ 15,53,500	8%
C. Miscellaneous Charges		
Container Cost	₹ 3,35,081	2%
Ventilation Cost	₹ 1,67,540	1%
Additional Cost for safety and fire protection	₹ 5,02,621	3%
Cable Cost and accessories	₹ 10,05,242	5%
Installation, commissioning and EMS	₹ 35,47,000	19%
Total Cost for 1MWh Pilot Battery excluding Operations Cost	₹ 1,87,08,066	

The annual operational and maintenance cost is 5%, and warranty is 2% of the CAPEX cost.

5.3 Incentives and Financing Options

An adaptive financial ecosystem is key to advancing ZET market development through tailored financing instruments, novel risk management models, and effective de-risking practices. Recognizing the principal role of Charge Park Operators (CPOs), this section attempts to find financial instruments to address demand of the significant capital investment required for charging infrastructure, with a focus on leveraging incentives and financing mechanisms to ensure economic viability of the charge parks.

5.3.1 Financing Mechanisms

- **Equity investment** anchors the essential capital to establish and scale charging infrastructure without the immediate burden of debt repayment. Concessional equity from climate funds or, Multilateral Development Banks (MDBs) through dedicated investment platforms offers patient capital with lower return expectations, reducing financial strain in the early stages.

³⁵ Zero to Green Report – IIT Madras Research Park

- **Concessional Debt:** Below-market-rate financing from governments, Multilateral Development Banks (MDBs), and Development Finance Institutions (DFIs) lowers capital costs, provides access to low-cost and long-tenure financing.
- **Commercial Loans:** As revenue streams from charging services stabilize, CPOs can secure commercial loans on standard lending terms to fund infrastructure expansion, technology upgrades, and operational scaling. Unlike concessional loans, these loans do not require government subsidies but rely on the financial viability of the charging business. They also establish creditworthiness, making it easier to secure further investments as the market matures.
- **Green Bonds:** Investing in energy storage solutions to optimize electricity costs and participating in Public-Private Partnership (PPP) projects lower financial risks. Government-issued green bonds may qualify for additional incentives, tax benefits, and corporate ESG financing.

5.3.2 Risk-Sharing Facilities

Risk-sharing facilities mitigate potential financial losses in case of lower-than-expected revenue during the early adoption phase of ZETs.

- **Loan Guarantees** reduce lenders' risk, making it easier for them to secure loans with better terms such as lower interest rates, longer tenures, or reduced collateral requirements. It comes handy for charging infrastructure projects with high upfront capital and long payback periods.
- **First & Second Loss Guarantees:** Since banks and NBFCs often hesitate to finance charging infrastructure due to uncertain revenue models, first-loss guarantees ensure that a guarantor such as the government, MDBs, or DFIs absorbs initial losses, encouraging lenders to extend credit on favourable terms. Second loss guarantees further mitigate risk by covering larger potential losses, making private investment more attractive and support early-stage market growth by securing funding for projects that may not yet be profitable while also facilitating network expansion along freight corridors, leading to higher utilization rates and revenue generation.
- **Escrow Funds:** Funds backed by philanthropic organizations, MDBs, or industry players like OEMs, act as a financial safety net by covering loan defaults.

5.3.3 Viability Gap Funding (VGF)

- **Government Grants & Purchase Incentives** help offset the cost of procuring high-power charging equipment, installing electrical infrastructure, and integrating renewable energy solutions. The Ministry of Finance could extend its existing VGF to offset the revenue-to-cost gap incurred through a one-time grant to develop public charging projects.
- **Tax Incentives & Waivers:** Reduced land lease rates lower the fixed costs associated with setting up charging parks; toll exemptions and import duty waivers reduce the cost of essential components such as charging equipment and energy storage systems which directly reduce the operational and capital costs incurred by CPOs. Such fiscal benefits enhance profitability, improve return on investment, and make charging services more competitive.
- **Public-Private Partnerships (PPPs):** Collaborations between government bodies and private companies can tap public resources and private expertise to deploy charging stations, often with shared risks and rewards. Government participation in co-investment and risk-sharing arrangements helps abate financial uncertainties, making large-scale charging deployments more attractive to investors. PPP frameworks can also enable streamlined regulatory approvals, access to strategic locations, and integration of grid infrastructure with ease.

Inference:

- In a renewable-energy-integrated ZET charge park, returns maximisation and demand charges management can directly affect the park's revenue, operating cost, and ultimately its commercial viability. In addition, an adaptive financial ecosystem is key to advancing ZET charge park market development through tailored financing instruments, novel risk management models, and effective de-risking practices.

CHAPTER 6

Power Converter Specification for RE Integration

6.1. Power Converter Specifications for RE Integration

Power conversion systems (PCS) are power electronic systems that transform electrical energy between different forms (AC/DC) to ensure compatibility between RE sources, energy storage systems (ESS), the grid and the charging station. Annex 6.1 details the fundamentals of power converter technology. Different types of power converters, like AC-DC, DC-AC, AC-AC, and DC-DC, serve specific purposes in power conversion. Figure 11 presents power conversions required at different stages in charging stations and the associated converters are briefed in Annex 6.2. In a charging park, a single bidirectional PCS serves as the critical bridge between the AC power from the electrical grid and the DC power required by the charging equipment, creating a common DC bus. From this shared DC bus, individual chargers then perform a final conversion step, adjusting the common voltage to match the specific requirements of different vehicle models, ensuring safe and efficient charging regardless of the vehicle type connected to the station.

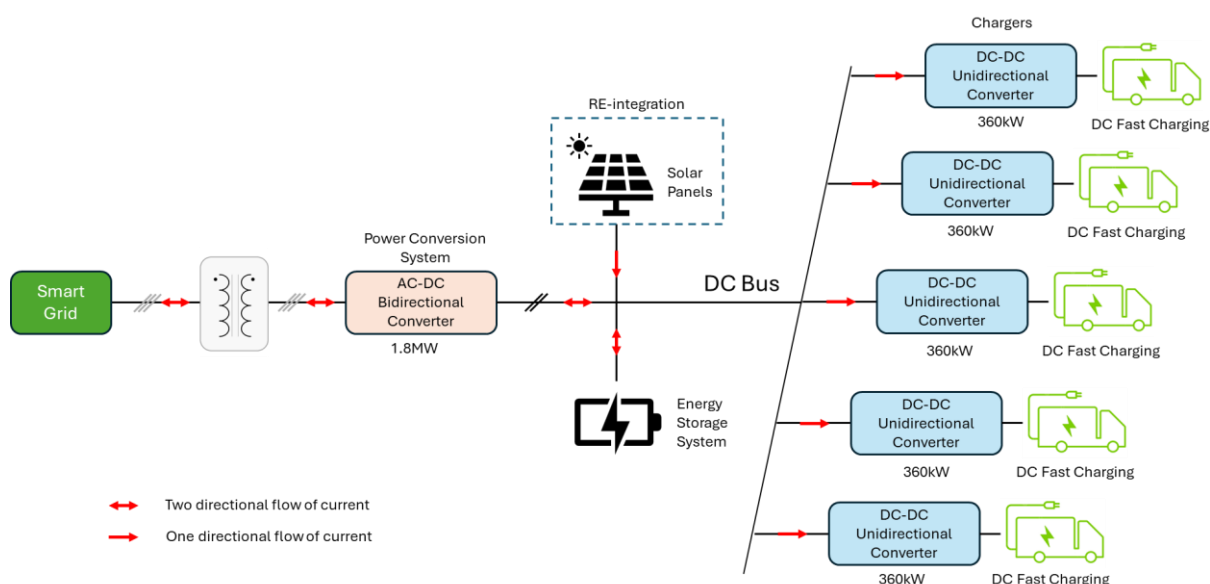


Figure 13. The integration of various power converters at sources placed in ZET charging parks

The key specifications for the 1.8MW bi-directional PCS and the DC-DC unidirectional charger are mentioned in Table 27.



Table 27. Key Specifications of PCS and Chargers

	Parameter	Specification	Description
Power Conversion Unit	Total Power Capacity	1.8 MW	Scalable via master/slave parallel configuration
	AC Grid Voltage	400 - 480 VAC	Three-phase, 50 (India) /60 Hz (US, Canada)
	DC Bus Voltage	800–1000 VDC	Standardizes voltage for solar, BESS, and EV chargers, reducing conversion losses
	Bidirectional Capability	Yes	Supports grid-to-vehicle and vehicle-to-grid power flow
	Efficiency	>93%	Peak
	Power Factor Correction (PFC)	>0.99	PFC is a set of techniques that improve the power factor of an electrical system, enhancing overall efficiency
	Total Harmonic Distortion (THD)	<5 %	THD is a measurement of the harmonic distortion present in a signal
	MPPT DC-DC Converter	300–1000 VDC input/output, ≥98% efficiency	Extracts max solar power by adjusting PV voltage/current
	Topology	Three-stage conversion	Boost converter, isolated DC-DC converter, grid inverter
	Cooling	Liquid-cooled	For high-power stability
	Communication Protocols	CAN, OCPP 1.6, ISO 15118, RS485	
	Protections	OVP, OCP, OTP, LVP, and fault isolation	Voltage, current, temperature protections
	IP Rating	IP54	
DC-DC Chargers	Power per Charger	360 kW	
	Input Voltage	800–1000 VDC	Same as DC bus
	Output Voltage	300-1000 VDC	
	Max Current	400-500 A	
	Charging Ports	Dual CCS 1/2, CHAdeMO, or NACS	Configurable
	Cooling System	Liquid-cooled cables	Prevents overheating during high-current operation
	Efficiency	>92%	Typical
	Communication	OCPP 1.6, ISO 15118 (Plug & Charge), Ethernet, 4G/Wi-Fi	

Alongside the PCS, the transformer and Energy Management System (EMS) are crucial components to ensure safe and reliable operations of charging infrastructure. Transformers are used externally for grid integration, stepping up or down voltages as necessary to ensure compatibility with the electrical grid and facilitate efficient energy transfer. The EMS acts as the control center, managing the flow of energy between various sources and loads. It optimizes energy usage, monitors system performance, and ensures efficient operation by coordinating with the PCS and other related systems. For a brief understanding of the financial aspects, Table 28 provides an overview of the approximate costs associated with the power converter and its related subsystems.

Table 28. Converter and subsystem costs

Converter Cost per kW	
Converter Cost	2500
Isolation Transformer	1000
EMS	200
Total	3700
For 1800 kW (5 nos of 360kW Guns)	6,660,000
For 900 kW PCS - Captive	3330000
For 1800 kW PCS - Group Captive	6660000

6.2. Converter Topologies and Ratings

Power converter topology refers to the specific arrangement and interconnection of power electronic components, such as switches, diodes, inductors, and capacitors, within a power conversion system. Table 29 provides a comprehensive overview of various power converter topologies and key features that are applicable to ZET charge parks.

Table 29. Power Converter Topologies and Their Characteristics

Category	Topology	Key Features	Typical Power Range
AC/DC Converters (Non-isolated)	Two-level PFC	Simple, robust, cost-effective, bidirectional	Up to 300 kW
	Vienna PFC	Lower switch stress, better efficiency	50-250 kW
	NPC 3-level PFC	Reduced harmonics, higher efficiency	100-500 kW
	T-type Neutral Point Clamped PFC	Lower conduction losses than conventional NPC	100-500 kW
DC/DC Converters (Isolated)	Full Bridge Boost	High power capability, ZVS possible	50-500 kW
	Isolated ZVS	Soft switching, high efficiency	10-100 kW
	LLC Resonant	Highest efficiency, soft switching, isolation possible	1-50 kW
DC/DC Converters (Non-Isolated)	Interleaved Boost	Reduced ripple, higher efficiency	10-250 kW
	Buck-Boost	Flexible voltage conversion	1-50 kW
	Cuk	Low output ripple, low EMI	1-10 kW
	SEPIC	Non-inverting buck-boost operation	1-10 kW
Bidirectional Converters	H-bridge	Simple bidirectional operation	10-100 kW
	Dual Active Bridge (DAB)	High efficiency, galvanic isolation	50-500 kW
	Bidirectional Buck-Boost	Flexible, non-isolated	10-100

A combination of such power converters in parallel enables Megawatt Charging Stations (MCS). The key technologies in Power conversion and efficiency considerations are detailed in Annex 6.4, followed by the glossary of common terms outlined in Annex 6.5.

6.3. Grid Integration and Compliance

National guidelines for EV charging infrastructure emphasize the integration of renewable energy and compliance with advanced communication protocols to ensure sustainability and interoperability. In India, the Ministry of Power has issued guidelines requiring Green Charging Stations to source at least 70% of their energy from renewable sources to qualify as sustainable. This initiative aligns with the country's broader goals for renewable energy adoption and carbon reduction.



Regulatory Framework and Standards for EV charging infrastructure, including ZET charge parks, have evolved significantly in recent years. Key standards and regulations are based on the category of application for the PCS are mentioned in Table 30.

Table 30. Standards for Bi-Directional PCS and DC Chargers Aligning National and Global Protocols

Category	Standard/R egulation	Key Requirements	National /Global	Status in India
Safety Standards	IEC 61851-1	General safety for EV conductive charging systems, including construction and testing protocols.	Global	Mandatory (referenced in CEA Safety Regulations)
	IEC 61851-23	Safety and operational requirements for DC EV charging stations (voltage levels, protection, insulation).	Global	Mandatory for DC fast chargers
	IEC 61851-24	Defines digital communication between DC chargers and EVs for control and monitoring.	Global	Recommended for intelligent charging
	IS/IEC 62305	Lightning protection and earthing for EV charging stations (TN system compliance).	Global & India	Mandatory (CEA Amendment 2023)
	CEA Safety Regulations (2023)	Requires compliance with Technical Standards for Connectivity, anti-islanding, and reverse power flow protection.	India	Mandatory
Technical Standards	IS 17017 (Part 23)	Specifies DC charger requirements (50-250 kW) for buses/trucks, including voltage/current limits.	India	Mandatory for public charging stations
	IEC 62196	Defines AC/DC charging connectors (Type 1/2) for interoperability.	Global	Widely adopted for CCS/Type 2 chargers
Communication Standards	ISO 15118	Enables Plug & Charge and V2G communication via secure digital certificates.	Global	Recommended for high-power DC chargers
	OCPP 1.6	Ensures interoperability between charging networks and remote monitoring/billing.	Global	Mandatory for public charging networks

Grid Connection & Power Quality	IEEE 1547-2018	Grid-forming capability, voltage/frequency ride-through, and DER synchronization.	Global	Under review by CEA; partially adopted
	SAE J2894	Limits harmonic distortion and ensures power quality for PEV chargers.	Global	Referenced in MNRE guidelines
	IEC 61000-3-2	Limits harmonic current emissions (<16 A per phase) for EVSE.	Global	Mandatory for commercial chargers
RE Integration	IEC 62109-1/2	Safety of PV converters and MPPT systems.	Global	Adopted via MNRE's Quality Control Order (2017)
	UL 1741 SA	Anti-islanding and grid-support functions for inverters.	USA	Required in states adopting IEEE 1547 (e.g., Gujarat)
Cybersecurity	ISO 21434	Secures EV charger communication networks against cyber threats.	Global	Recommended for public charging networks
	NIST IR 7628	Guidelines for securing grid-connected DER systems.	USA	Referenced in Grid-India's DER guidelines

Inference:

National guidelines for EV charging infrastructure emphasize the integration of renewable energy and compliance with advanced communication protocols to ensure sustainability and interoperability. With significant progress in standards development for EV charging infrastructure scope of RE integration with charge parks is perpetually increasing in recent years.

Chapter 7

Maintenance Considerations for Solar and Wind

7.1. Maintenance Considerations for Solar PV Systems

Effective maintenance of Solar Photovoltaic (PV) systems is crucial to ensure optimal performance and longevity. Some of the key considerations for the maintenance of a healthy Solar PV system includes:

7.1.1 Soiling Losses

The accumulation of materials such as dust, dirt, pollen, bird droppings, and other particulates on solar panels leads to soiling losses, which reduce the light reaching the photovoltaic cells and, consequently, the system's power output. In high dust or pollen areas, soiling can decrease power capabilities by up to 30% within a month. Globally, the average soiling loss was estimated to be at least 3%–4% in 2018.

7.1.2 Mismatch Loss

Mismatch loss occurs when interconnected modules exhibit differences in electrical characteristics, leading to suboptimal performance. Causes include partial shading, uneven soiling, or inherent variations among modules. Such mismatches can reduce the overall efficiency of the PV system by at least 20% - 25%³⁶.

7.1.3 Temperature Effects

Solar cell efficiency decreases as temperature rises above 25°C, with performance typically reducing by about 0.25% to 0.5% per °C, depending on the module's temperature coefficient. This coefficient varies across different module makes and series. Therefore, it is advisable to select modules with a lower temperature coefficient for better performance in hotter climates. Additionally, managing temperature through adequate ventilation and careful site selection further helps mitigate efficiency losses due to heat.

7.1.4 Environmental Degradation

Over time, components of PV systems may deteriorate due to environmental factors such as thermal expansion and contraction, ultraviolet (UV) light exposure, and damage from windblown particles. Regular inspections and maintenance are necessary to identify and address such wear and tear.

7.1.5 Inverter and Electrical Component Maintenance

Regular inspection and maintenance of inverters, wiring, and other electrical components are crucial to prevent failures and ensure system efficiency.

7.1.6 Structural Integrity Checks

Periodic assessment of mounting structures for corrosion, alignment, and mechanical stability helps in maintaining the physical integrity of the PV system.

7.1.7 Vegetation Management

Ensuring that surrounding vegetation does not cast shadows on the panels is essential to maintain optimal energy production.

³⁶ [Current Flow Analysis of PV Arrays under Voltage Mismatch Conditions and an Inverter Failure, \(MDPI\) \(2019\)](#)

7.2. Operation and Maintenance Best Practices for Solar

Implementing best practices in the operation and maintenance of solar PV systems ensures sustained performance and extends the system's lifespan. Key practices include:

7.2.1 Regular Cleaning

Routine cleaning of solar panels is vital to prevent soiling losses. The frequency and method of cleaning depend on the local environment and specific soiling factors. In regions with frequent rain, natural cleaning may suffice, whereas arid areas may require cleaning twice a month.

7.2.2 Scheduled Inspections

Conducting regular inspections helps identify potential issues such as loose connections, corrosion, or physical damage. Timely detection allows for corrective actions before problems escalate, ensuring system reliability.

7.2.3 Performance Monitoring

Continuous monitoring of system performance enables the detection of anomalies or declines in efficiency. Utilizing monitoring software can assist in tracking energy production and identifying underperforming components.

7.2.4 Tracker-Specific Maintenance

- **Motor and Drive Maintenance:** Regular testing of motor currents, checking for overheating, and ensuring torque is within specified limits.
- **Lubrication and Wear Monitoring:** Lubricate rotating joints, slewing drives, and actuator pins based on manufacturer schedules.
- **Firmware/Software Updates:** Trackers often rely on programmable controllers. Periodic updates and recalibration may be needed for optimal performance.

7.3. Performance Monitoring and Troubleshooting for Solar

Effective performance monitoring and troubleshooting are essential to maintain the efficiency of solar PV systems. Key strategies include:

7.3.1 Utilizing Monitoring Systems

Implementing advanced monitoring systems allows for real-time tracking of energy production and system performance. These systems can alert operators to issues such as reduced output or component failures.

7.3.2 Data Analysis

Analysing performance data helps identify trends and potential problems. Comparing actual performance against expected benchmarks can reveal inefficiencies or faults needing attention. Key metrics to be analysed includes:

- **Solar Panel Output (Voltage & Current)** – Measures the DC voltage and current generated by the solar panels.
- **Inverter Efficiency** – Ensures that the inverter is effectively converting DC to AC power.
- **AC Output (kWh)** – Tracks the total usable energy delivered by the system over time.
- **Performance Ratio (PR)** – A key indicator that compares actual energy output to expected output under ideal conditions which should ideally be above 80%

- **Capacity Utilization Factor (CUF)** – Reflects the actual energy generated over a given period as a percentage of the maximum possible generation if the system operated at full capacity continuously. CUF is particularly useful for comparing system output across different plants or locations.

7.3.3 Proactive Troubleshooting

Addressing identified issues promptly prevents minor problems from developing into major failures. Proactive troubleshooting involves diagnosing the root cause of performance declines and implementing corrective measures swiftly.

By adhering to these maintenance considerations and best practices, solar PV system operators can ensure optimal performance, reduce operational costs, and extend the lifespan of their installations.

7.4. Maintenance Considerations for Wind Power Plants

Effective maintenance of wind power plants is critical to ensuring reliable operation, maximizing energy output, and extending the life of turbines and auxiliary equipment. Some of the key considerations include:

7.4.1 Blade Erosion and Soiling

Wind turbine blades are prone to erosion from rain, hail and dust especially near the leading edge of the turbine blade. Over time, this degradation alters the blade profile, reducing aerodynamic efficiency and lowering annual energy production (AEP) by up to 5%³⁷.

7.4.2 Gearbox and Drivetrain Wear

The gearbox and drivetrain components experience significant mechanical stress due to varying wind speeds and turbulence. Issues such as misalignment, lubrication degradation, and bearing failures can lead to costly downtime

7.4.3 Generator and Electrical System Reliability

Wind turbine generators, converters, transformers, and switchgear are vital for energy conversion and transmission. Failures in insulation, cooling systems, or power electronics may disrupt production.

7.4.4 Tower and Structural Integrity

The turbine tower and foundation are exposed to cyclic loading and environmental stresses. Corrosion, fatigue cracks, or foundation settlement can compromise stability. Routine non-destructive testing (NDT) is necessary to preserve structural integrity.

7.4.5 Control System and Sensors

Advanced control systems regulate pitch, yaw, and turbine performance. Sensor malfunctions (e.g., anemometers, wind vanes, temperature sensors) can lead to incorrect responses and power losses. Periodic calibration and software updates ensure accurate operation.

7.4.6 Environmental and Site Challenges

Turbines operating in coastal, desert, or cold climates face additional challenges such as salt corrosion, sand abrasion, or ice accumulation. Site-specific preventive strategies such as protective coatings, must be employed.

³⁷ Akmak, C. Z., Hemmati, M., & Avila, A. L. 2024. *Impact of leading-edge erosion on the annual energy production of wind turbines*. *Journal of Physics: Conference Series*, 2767(1), 022066.

7.5. Operation and Maintenance Best Practices for Wind

Implementing structured O&M practices improves the efficiency and longevity of wind power plants. Key practices include:

7.5.1 Scheduled Preventive Maintenance

Routine servicing of critical components such as gearbox oil changes, lubrication of moving parts, bolt retightening, and cooling system checks according to manufacturer guidelines needs to be performed at least twice annually³⁸.

7.5.2 Predictive Maintenance

Employing condition monitoring systems (CMS) with vibration, oil, and temperature sensors enables early detection of faults in gearboxes, bearings, and generators. Predictive approaches significantly reduce unplanned downtime and repair costs.

7.5.3 Remote Monitoring and SCADA Integration

Supervisory Control and Data Acquisition (SCADA) systems allow real-time monitoring of turbine performance, wind conditions, and fault detection. Advanced analytics and alarms help operators respond quickly to abnormalities.

7.5.4 Blade Maintenance Programs

Periodic inspection via drones, rope access, or ground-based cameras enables early identification of cracks, erosion, and delamination. Preventive measures such as leading-edge protection tapes and resin coatings extend blade life.

7.5.5 Yaw and Pitch System Maintenance

The yaw system ensures the rotor faces the wind, while pitch systems regulate blade angle. Failures can cause energy losses and increased mechanical stress. Regular lubrication, actuator testing, and hydraulic system checks are necessary for smooth operation.

7.6. Performance Monitoring and Troubleshooting for Wind

Effective monitoring and troubleshooting safeguard performance and availability of wind turbines.

7.6.1 Key Performance Indicators (KPIs)

- **Availability (%)** – Percentage of time turbines are operational versus total time.
- **Capacity Utilization Factor (CUF)** – Ratio of actual energy generated to the maximum output.
- **Power Curve Analysis** – Comparing actual output with expected output for given wind speeds.
- **Downtime Metrics** – Tracking planned vs. unplanned outages to improve O&M planning.

7.6.2 Data-Driven Diagnostics

Analysing SCADA data, vibration signals, and thermal profiles helps detect anomalies early. For example, deviation from the reference power curve can indicate blade damage, yaw misalignment, or gearbox inefficiency.

7.6.3 Proactive Troubleshooting

Rapid identification and resolution of issues such as electrical faults, lubrication failures, or control system errors prevent cascading failures and minimize downtime. Root cause analysis ensures corrective actions are effective and long-lasting.

³⁸ Chan, D., Mo, H., & Yeung, T. 2017. Wind turbine maintenance optimization under uncertainty: A review. *Energy Procedia*, 110, 267–272.

Chapter 8

Policies and Regulatory Compliances

A slew of policy incentives, regulatory support, and fiscal measures have been initiated to facilitate a smooth shift from ICE vehicles to EVs over the past decade. India's EV growth was catalysed in 2010 by MNRE's "Alternate Fuels for Surface Transportation Program (AFSTP)" offering a 20% capital subsidy. This resulted in increase in e-bike sales, though later discontinued, the initiative resurfaced as National Electric Mobility Mission Plan (NEMMP) 2020 as a flagship initiative under the National Mission for Electric Mobility (NMEM). The NMEM was a key milestone, designed to enhance energy security and domestic EV manufacturing. Under this, the National Council for Electric Mobility (NCEM) and the National Board for Electric Mobility (NBEM) were established to drive e-mobility initiatives.

The demand incentives systematically introduced under Faster Adoption and Manufacturing of Electric Vehicles (FAME) India Scheme in 2015-16, marked a turning point for India's EV sector.

Thereafter, FAME-II scheme and the Production Linked Incentive (PLI) program have played a vital role in reducing the costs of electric trucks and promoting domestic manufacturing. The newly introduced PM Electric Drive Revolution in Innovative Vehicle Enhancement (PM e-DRIVE) scheme has allocated \$1.3 billion to subsidize electric vehicle purchases and develop charging infrastructure. Lower GST rates (5% for EVs and chargers) and scrappage incentives for older diesel trucks have further strengthened the economic rationale for electrification.

Driven by an enabling policy framework, Indian companies are increasingly focusing on zero-emission trucking solutions, primarily through electrification. GreenLine Mobility, supported by the Essar Group, has pledged \$275 million to roll out over 10,000 LNG and electric trucks, along with a nationwide network of EV charging stations and battery-swapping facilities. Blue Energy Motors is ramping up its production of LNG trucks and is set to introduce its first electric truck, aiming to sell 3,000 trucks in the upcoming fiscal year. Major original equipment manufacturers (OEMs) like Ashok Leyland and Tata Motors are also making strides in electric truck development. Ashok Leyland aims for carbon neutrality by 2030, while Tata's ACE EV has already begun serving last-mile logistics through collaborations with Amazon and Flipkart.

Industry participants have been actively involved in shaping regulatory frameworks and standards to support a market-driven transition. Through initiatives like the e-FAST India coalition, companies have collectively expressed demand for over 7,750 electric trucks by 2030, offering essential insights for infrastructure and policy planning. The GearShift Challenge, launched by NITI Aayog, promotes collaborative efforts for fleet electrification. Series of workshops organized by Smart Freight Centre India in collaboration with state governments have facilitated further discussions on challenges and implementation strategies, promoting a co-development approach for zero-emission freight policies.

The table 31 provides at a glance tabular summary of EV policy landscape of India and subsequent parts of this chapter provides brief details of each scheme and plan.



Table 31. Evolution of E-mobility Policies and Initiatives in India: A Timeline

YEAR	POLICY/INITIATIVE	KEY HIGHLIGHTS
2006	Automotive Mission Plan 2006–2016	Laid the foundation for promoting fuel-efficient and alternative fuel vehicles, including initial considerations for electric mobility.
2010	MNRE EV Subsidy Scheme	Introduced early-stage subsidies (up to ₹1 lakh) for electric vehicles to encourage initial adoption.
2011	National Council for Electric Mobility (NCEM)	Constituted as an apex body in the GoI for making recommendations to promote electric mobility and manufacturing of electric vehicles.
2012	National Automotive Board (NAB)	Constituted to act as the nodal agency for implementation of FAME India scheme including disbursement of funds for the various components.
2013	National Electric Mobility Mission Plan (NEMMP) 2020	The 2020 roadmap estimated a cumulative outlay of about ₹14,000 crore during the span of the scheme, including industry contribution which aimed for ambitious deployment of 5–7 million EVs by 2020 to reduce fossil fuel dependence and emissions.
2015	FAME India Scheme – Phase I	Phase-I of the FAME India scheme launched under the NEMMP 2020 for a two-year period between April 1, 2015, and March 31, 2017, to promote the adoption of electric/hybrid vehicles with demand incentives across various vehicle segments and support for pilot projects.
2017	National Board for Electric Mobility (NBEM)	Constituted six years after its approval.
2018	Green Urban Mobility Scheme	Proposed to promote low-emission urban transport solutions, including EVs, with many objectives integrated into other urban development and EV promotion schemes.
	Technology Platform for Electric Mobility (TPEM)	Set up to support R&D consortia projects.
	Draft Amendment to Central Motor Vehicles Rules	Draft amendment allowing retrofitting conventional vehicles into electric vehicles or hybrid electric-based vehicles.
2019	FAME India Scheme – Phase II	Extended and expanded support with a significant budget of ₹10,000 crore, with a stronger focus on public transport electrification and the development of robust charging infrastructure.
	Amendments to Model Building Bye-Laws (MBBL)	Amendments made to MBBL 2016 and URDPFI Guidelines 2014 making provisions for establishing Electric Vehicle Charging Infrastructure.
	National Mission on Transformative Mobility and Battery Storage	Union Cabinet has approved setting up the National Mission on Transformative Mobility and Battery Storage, chaired by CEO NITI Aayog.
	Guidelines on EV Charging Infrastructure	Charging Infrastructure for Electric Vehicles Guidelines and Standards notified.
2020	EV Charging Stations (Phase II)	DHI approves 2636 EV charging stations in Phase-II of FAME India Scheme.
	Amendment to Charging Infrastructure Guidelines	Amendment to the "Charging Infrastructure for Electric Vehicles-Guidelines and Standards," capping the maximum tariff applicable to EV public charging.
2021	Production Linked Incentive (PLI) Scheme for ACC Batteries	Approved ₹18,100 crore to boost domestic manufacturing of advanced chemistry cells (ACC) for EV batteries, aiming to reduce import dependence.
2022	Battery Swapping Policy (Draft)	Proposed to standardize battery swapping protocols and infrastructure to address range anxiety and reduce charging time, currently still under finalization and implementation.
2023	PLI Scheme for Automobile and Auto Components	Allocated ₹25,938 crore to incentivize domestic manufacturing of electric vehicles and their components, further strengthening the EV supply chain in India.
2024	PM E-DRIVE (Electric Drive Revolution in Innovative Vehicle Enhancement) Scheme	Launched by the Government of India to accelerate the adoption of electric vehicles (EVs) and enhance the EV ecosystem in the country, with a total outlay of ₹10,900 crore and is effective from October 1, 2024, to March 31, 2026

8.1 EV Policies in India

8.1.1 National Electric Mobility Mission Plan (NEMMP) 2020

The National Electric Mobility Mission Plan (NEMMP) 2020 was launched as a flagship initiative under the National Mission for Electric Mobility (NMEM) to enhance national energy security and promote EV adoption in India. The plan aimed to put 6-7 million electric and hybrid vehicles on Indian roads by 2020, representing 5-10% of the total vehicle population, with an expected fuel savings of 2.2 to 2.5 million tonnes.

Key Objectives:

- **EV Penetration** – Achieving the deployment of **6-7 million EVs** to reduce fossil fuel dependency.
- **Infrastructure Development** – Establishing EV charging infrastructure to support widespread adoption including the development of 300–400 charging terminals for buses and other vehicles.
- **Technology Advancement** – Investing in **new EV and battery technologies** to strengthen domestic capabilities.
- **Local Manufacturing** – Promoting indigenous production of **EVs, batteries, and related components** to enhance self-reliance.
- **Consumer Awareness & Acceptance** – Encouraging EV adoption through incentives and awareness programs.

8.1.2 Faster Adoption and Manufacturing of (Hybrid and) Electric Vehicles (FAME I)

Launched in April 2015 under the NEMMP 2020, the FAME I scheme was the Indian government's flagship initiative to accelerate EV adoption and develop a strong domestic market for electric and hybrid vehicles. By offering subsidies and financial incentives, the scheme aimed to reduce EV prices, making them more accessible to consumers.

Under FAME I, buyers received direct subsidies for EV purchases and funds were also allocated for charging infrastructure development and EV technology advancements. The scheme played a pivotal role in raising consumer awareness, encouraging industry participation, and laying the foundation for India's transition toward cleaner transportation systems.

8.1.3 Faster Adoption and Manufacturing of (Hybrid and) Electric Vehicles (FAME II)

FAME II aimed to build on the success of its initial phase by promoting the adoption of electric vehicles (EVs) in India, with 86% of its budget dedicated to demand incentives. The initiative was primarily geared towards increasing EV sales by providing subsidies for 1.56 million vehicles across various categories. However, these subsidies were only available for EVs that feature advanced lithium-ion batteries and other cutting-edge technologies, ensuring that support is directed towards next-generation mobility solutions.

Table 32. Summary of FAME I and FAME II Schemes

PARAMETER	FAME I (2015–2019)	FAME II (2019–2024)
Budgetary Outlay	₹895 crore	₹11,500 crore
Duration	April 1, 2015 – March 31, 2019	April 1, 2019 – March 31, 2024
Total Vehicles Supported	~2.8 lakh electric and hybrid vehicles	16,71,606 electric vehicles
Subsidy Disbursed	₹359 crore	₹6,825 crore (as of July 31, 2024)
Category-wise Vehicle Sales	Not specifically detailed; included 2W, 3W, 4W, hybrids	2-Wheelers: 14,69,343 units 3-Wheelers: 1,78,952 units 4-Wheelers: 23,311 units
Electric Buses	425 buses sanctioned (subsidy: ₹280 crore)	6,862 buses sanctioned; 4,853 supplied
Charging Infrastructure	520 charging stations sanctioned (₹43 crore allocated)	2,877 public EV charging stations sanctioned
Electric Trucks	Not included	Not supported under FAME II; included later under PM e-DRIVE Scheme (2024)

8.1.4 PM E-DRIVE (PM Electric Drive Revolution in Innovative Vehicle Enhancement) Scheme [October 2024 - March 2026]

The scheme intends to develop a strong EV manufacturing ecosystem in the nation, build charging infrastructure, and hasten the adoption of electric vehicles (EVs) by providing upfront incentives for EV purchases and promoting the construction of charging infrastructure. In keeping with the Aatmanirbhar Bharat initiative, the program aims to enhance air quality and lessen the environmental effects of transportation while simultaneously encouraging a productive and competitive EV manufacturing industry. It is being rolled out in the manner of a Phased Manufacturing Program (PMP) aimed at strengthening the EV supply chain and increasing domestic manufacturing.

Table 33. PM E-Drive Key Components

KEY COMPONENTS		
Demand incentives	Capital asset creation grants	Scheme administration
✓ The program aims to lower CO₂ emissions and promotes electric trucks as a key solution for future logistics. ✓ A dedicated fund of ₹500 crore has been established to provide demand incentives for e-trucks as well. ✓ Incentives are available only to individuals or entities that present a scrapping certificate from a Registered Vehicle Scrapping Facility (RVSF) approved by the Ministry of Road Transport and Highways (MoRTH). ✓ Scrapping certificates will be verified through designated monitoring systems.	✓ The program aims to boost user confidence by establishing a robust network of public charging stations across India. ✓ The charging infrastructure will include: • 22,100 fast chargers for electric four-wheelers (e-4Ws), • 1,800 fast chargers for electric buses (e-buses), • 48,400 fast chargers for electric two-wheelers (e-2Ws) and electric three-wheelers (e-3Ws). ✓ Charging stations will be strategically located along major highways and in cities with high electric vehicle (EV) adoption rates. ✓ A total allocation of ₹2,000 crore has been earmarked for the development of this charging infrastructure.	✓ The program aims to modernize and upgrade testing agencies under the Ministry of Heavy Industries (MHI) to equip them with new and advanced technologies. ✓ The objective is to strengthen the technical capabilities necessary for supporting the evolving electric mobility ecosystem. ✓ An allocation of ₹780 crore has been approved for the upgradation of these testing agencies.

8.1.5 Automotive Mission Plan 2016-26 (AMP)

The Automotive Mission Plan 2016-26 (AMP) is a joint initiative by the Government of India and the Indian automotive industry, aimed at defining a strategic roadmap for the sector's growth over a decade. It outlines key development goals for the vehicle, auto components, and tractor industries, with a focus on enhancing manufacturing capabilities, employment generation, mobility solutions, and exports.

The plan's success will be measured through its contribution to GDP growth, technological advancements, global competitiveness, and sectoral capabilities. Its primary objectives emphasize boosting manufacturing and economic growth and also envision advancing electric vehicle (EV) adoption, infrastructure development, and implementing new fuel-efficiency regulations to support India's transition toward sustainable mobility.

8.1.6 Building Bye-Laws for EV Charging in India

Establishing EV charging infrastructure in residential and commercial areas is the first step for integrating EVs into mainstream transportation. Building bye-laws govern the adequacy of charging infrastructure, specifying the required number of stations based on charging technology, EV types, and location. The Ministry of Housing and Urban Affairs (MoHUA) has amended the Model Building Bye-Laws (MBBL – 2016) to mandate that at least 20% of a building's parking capacity be allocated for EV charging.

EV charging locations include private residences, fuel refilling stations, commercial buildings, and standalone charging stations. In Public Charging Stations (PCS) within buildings, service providers must install more charging points than the minimum requirement and offer spot payment options.

To accommodate increased EV charging load, DISCOMs must sanction additional power requirements. The 2019 amendment to MBBL 2016 advises that premises assign 1.25 times the cumulative power capacity of all charging points to meet future demand.

Several states, including Delhi, Karnataka, Gujarat, Maharashtra, Tamil Nadu have adopted or facilitated the MBBL amendments to streamline EV charger installation.

Table 34. Building Bye-Laws and Policies in States

STATE	Building bye-laws and related policies
Delhi	The Delhi government has mandated that all new buildings incorporate EV charging infrastructure, with a target to have charging points in every parking space by 2041
Maharashtra	Drafted a Standard Operating Procedure (SoP) for EV charging stations in multi-story residential and commercial buildings under its EV Policy 2021.
Karnataka	Karnataka Municipal Corporations Model Building Bye-Laws, 2017, have been amended to include provisions for EV charging infrastructure. The Karnataka Electricity Regulatory Commission (KERC) has also issued guidelines for installing EV charging points in buildings, particularly for those with a significant power load.
Tamil Nadu	The state is in the process of amending its Development Control Regulations to facilitate the installation of EV charging infrastructure in new constructions and apartments.
Kerala	The Kerala High Court directed the state government to draft guidelines for installing EV charging points in residential complexes.
Gujarat	Ahmedabad Municipal Corporation (AMC) is actively planning to make EV charging stations mandatory in new buildings and offers incentives for installation.

8.1.7 Amendments to Urban and Regional Development Plans Formulation and Implementation (URDPFI) Guidelines for EV Charging Infrastructure

Recognizing the importance of EVs for long-distance travel and inter-regional mobility, the URDPFI Guidelines, 2014 have been amended to integrate EV charging infrastructure. It considers a 30-year implementation horizon, factoring in technological advancements, evolving charger types, and the required number of charging points at public charging stations to support seamless EV adoption.

8.1.8 National Programme on Advanced Chemistry Cell (ACC) Battery Storage

The Ministry of Heavy Industry and Public Enterprises launched the Production Linked Incentive (PLI) Scheme for ACC Battery Storage in 2021, to reduce import dependence, boost domestic manufacturing, and create battery storage demand in India.

Key Outcomes Expected:

- Establish 50 GWh of ACC manufacturing capacity.
- Attract INR 45,000 crore in direct investment.
- Strengthen Make-in-India by reducing imports and enhancing domestic value capture.
- Generate net savings of INR 2–2.5 lakh crore on oil imports by accelerating EV adoption.
- Support India's renewable energy goals and reduce GHG emissions.
- Achieve INR 20,000 crore in annual import substitution.
- Boost R&D for higher energy density and cycle life.
- Promote new and advanced cell technologies.

8.1.9 Star labelling program for High Energy Lithium-Ion Traction Battery packs and systems

The Bureau of Energy Efficiency (BEE) introduced a Star Labelling Program in 2021 to establish energy labelling requirements for high-energy lithium-ion battery packs and systems used in electric surface transport vehicles to enhance the energy efficiency of batteries, including potential applications for electric trucks. Under this voluntary scheme, battery packs/modules are rated on a 5-star scale based on parameters like specific energy (up to 350 Wh/kg), cycle life (up to 4,000 cycles), and energy efficiency, helping OEMs and fleet operators select better-performing, durable batteries for freight operations. Battery performance is tested in accordance with **IS 12405-4:2018** standards across varied temperatures and load cycles. The program incentivizes manufacturers with reduced labelling fees for 5-star rated batteries and requires proof of compliance through a structured registration, application, and testing process.

8.2 EV State Policies in India

In line with the Government of India's ambitious goal of achieving large-scale EV adoption by 2030, several states have introduced dedicated EV policies to boost manufacturing and demand. Karnataka was the first state to announce an EV policy, and as of February 2024, 33 states/UTs have notified their final or draft versions of their EV policies.

Key Promotional Measures in State EV Policies:

- **Funding Sources:** Financial incentives and subsidies to support EV adoption.
- **Shared Mobility:** Encouraging EV-based ride-sharing and public transport electrification.
- **R&D Support:** Incentivizing innovation in EV technology and battery systems.
- **Skill Development:** Training programs for workforce readiness in the EV sector.
- **Battery Recycling:** Frameworks for **battery reuse and disposal** to promote sustainability.
- **Vehicle Scrapping Incentives:** Encouraging replacement of old ICE vehicles with EVs.
- **Retrofitting:** Supporting the conversion of conventional vehicles into EVs.
- **EV Tariff:** Special electricity tariffs for EV charging infrastructure.
- **Building Bye-laws:** Mandating EV charging provisions in new commercial and residential buildings.
- **Home & Workplace Charging:** Policies to facilitate private and corporate EV charging setups.
- **Digital Payments:** Encouraging cashless transactions for seamless EV charging services.
- **Public Awareness:** Campaigns to promote EV adoption and its environmental benefits.

Table 35. State-wise EV-sales penetration targets (all vehicle segments)

State	Target share of new vehicle registrations	Target year
Goa	30 %	2025
Assam	25 %	2026
Odisha	20 %	2025
Meghalaya	15 %	2025
Maharashtra	10 %	2025

Nine states (including the five above) have set “all-vehicle” sales-penetration goals; the rest of the states either set targets only for particular segments or did not quantify overall penetration.

Table 36. 100 % electrification targets for specific vehicle segments

State	Segment(s)	Target year
Uttar Pradesh	Public-transport vehicles	2030
Bihar	Rickshaws; Public-transport vehicles	2022; 2030
Madhya Pradesh	Public buses; Government fleet; Commercial & logistics vehicles	2028

Thirteen states have committed to full (100 %) electrification—but only for one or more specific segments rather than their entire new-vehicle market.

Table 37. Charging-infrastructure deployment targets of Key States

State	City network	Highways
Maharashtra	3 km × 3 km grid or ≥ 50 chargers per 1 million inhabitants	≥ 1 charger every 25 km
Goa	3 km × 3 km grid	≥ 1 charger every 25 km
Punjab	≥ 1 charger per 15 registered EVs; fast-charger spacing: 1 per 25 km	—
Haryana	—	≥ 1 charger every 50 km on “prominent” highways
Chandigarh	≥ 1 charging station at every public parking facility	—

Eight states/UTs define explicit charger-deployment densities; the rest 17 provide various subsidies or land-concessions for chargers without setting numeric roll-out goals.

States like Andhra Pradesh, Bihar, Delhi (NCT), Gujarat, Karnataka, Kerala, Tamil Nadu, Telangana, Uttarakhand and West Bengal do not yet specify quantified sales-penetration or charging-infrastructure targets; instead, they rely on subsidies, tax exemptions or land-concessions to accelerate deployment. Per-vehicle purchase subsidies are typically offered up to ₹10,000–₹100,000 depending on segment, alongside charging-station capital grants and/or road-tax waivers, opting for demand-driven or incentive-led expansion.

	Target of Charging network (# of chargers or density)	Support for grid upgradation	Conducive market for participation of private players	Financial incentives			Facilitation of affordable and accessible land	Support for battery swapping	Focus on RE integration for EV charging	Infrastructural recommendations (modification of building bye laws/ parking spaces reserved for EV charging etc)
				Home/ workspace chargers	Public chargers	Energy operators				
Delhi	✓	x	✓	✓	#	✓	✓	✓	✓	✓
Karnataka	✓	x	✓	x	✓	✓	✓	✓	✓	✓
Haryana	✓	x	✓	x	✓	✓	✓	✓	✓	✓
Maharashtra	✓	✓	✓	✓	✓	✓	✓	✓	x	✓
Andhra Pradesh	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Kerala	✓	✓	✓	x	✓	✓	x	✓	✓	✓
Bihar	✓	x	✓	x	✓	✓	✓	✓	✓	✓
Uttar Pradesh	✓	x	✓	x	✓	✓	✓	✓	x	✓
Gujarat	x	x	✓	x	✓	✓	x	✓	x	✓
Tamil Nadu	x	x	✓	x	✓	✓	✓	x	✓	✓
Chandigarh	✓	x	✓	✓	✓	x	x	x	x	✓
Madhya Pradesh	✓	x	✓	x	✓	✓	✓	✓	✓	✓
Punjab	✓	x	✓	x	✓	x	✓	✓	✓	✓
Uttarakhand	x	x	✓	x	x	x	✓	x	x	x
Telangana	✓	x	✓	x	x	x	✓	✓	✓	x
Meghalaya	x	x	✓	x	x	x	✓	x	x	x
West Bengal	✓	x	✓	x	✓	x	✓	✓	✓	✓
Assam	x	x	✓	x	✓	x	x	✓	x	x
Odisha	x	x	✓	✓	#	✓	✓	✓	x	✓
Goa	✓	x	✓	x	#	✓	✓	✓	✓	✓
Rajasthan	✓	x	✓	x	x	x	x	✓	✓	x

Figure 14. Cross Comparison of State EV Policies

Source: Electric Vehicle Charging Infrastructure and its Grid Integration in India- Status Quo, Critical Analysis and Way Forward (NITI Aayog, 2021)

Please note that to monitor the latest developments in state electric-vehicle policies, stakeholders are advised to consult the [eAMRIT portal](#) of NITI Aayog, which serves as a comprehensive repository encompassing purchase incentives, charging-infrastructure guidelines, and related provisions.

8.3 EV Regulations in India

The Government of India has introduced comprehensive guidelines, regulations, and notifications to facilitate the seamless development and operation of EV charging stations nationwide encompassing technical standards, safety protocols, tariff frameworks, and subsidy provisions, for a structured and efficient expansion of charging infrastructure.

8.3.1 Guidelines for Charging Infrastructure for Electric Vehicles

Issued by the Ministry of Power (MoP) | Revised: January 14, 2022

The Ministry of Power has introduced guidelines to address the regulatory, technical, and operational aspects, for streamlined rollout of EV infrastructure.

1. Institutional Framework

- The Bureau of Energy Efficiency (BEE) is designated as the central nodal agency for public EV charging infrastructure.
- State Nodal Agencies (SNA) are responsible for facilitating charging station deployment at the state level.
- Charging stations do not require a license and are classified as a service, not electricity sale.
- Charging equipment must be tested by National Accreditation Board for Testing and Calibration Laboratory (NABL)-accredited labs.
- The State Electricity Regulatory Commissions (SERCs) can set electricity tariffs for residential and office charging are based on their respective regulatory frameworks.

2. Private & Captive Charging

- Any charging station or group of charging stations may obtain electricity from any generation company through open access.
- EVs can be charged at existing residential/workplace connections without additional approvals.
- Private charging points for self-use are exempt from infrastructure requirements.
- Captive charging infrastructure for fleet operators is exempt from public charging standards.

3. Public Charging Infrastructure (PCI)

- De-licensed activity: Any individual/entity can set up a Public Charging Station (PCS) complying with technical and safety norms.
- DISCOMs must provide grid connectivity within 7 days in metro cities, 15 days in municipal areas, and 30 days in rural areas.
- Mandatory PCS density: At least one PCS every 3 km x 3 km in cities and every 25 km on highways.
- Fast Charging Stations (FCS) for heavy-duty EVs must be installed every 100 km on highways, equipped with high-power (≥ 100 kW) chargers.
- State/UT governments must use density/distance guidelines to plan land allocation for PCSs and prioritize grid infrastructure.
- Governments may prioritize installing PCSs at existing oil retail outlets, ensuring compliance with safety norms.
- High-speed charging stations should include liquid-cooled cables for EVs with fluid-cooled batteries, if required.
- Companies using FCSs exclusively for their EV fleets can decide their own charging specifications.
- Extra PCS/FCS can be installed even if a charging station already exists in the area.
- Priority locations: Government land, oil retail outlets, malls, office complexes, restaurants, and hotels.
- BEE will maintain a national database of PCS locations.

4. Charging Infrastructure Requirements

- Technical specifications: PCS must include transformers, substation equipment, cabling, and safety provisions.
- Mandatory network integration: PCS operators must partner with at least one online Network Service Provider (NSP) for real-time charging slot reservations.
- Land allocation: Government/public land is leased at INR 1/kWh, while private operators participate through competitive bidding.

5. Public Charging Standards

The public charging standards for electric vehicles, including provisions relevant to Zero Emission Trucking (Heavy Duty EVs), are primarily governed by the Ministry of Power (MoP) through its "Guidelines for Installation and Operation of Electric Vehicle Charging Infrastructure." The Bureau of Indian Standards (BIS) also formalizes the technical specifications, adopting international standards. The guidelines cover several standards catering to different vehicle segments and the standards applicable to electric trucks in public charging scenarios are briefly discussed in this section-

a. CCS2 (Combined Charging System 2)

This is a global standard for DC (Direct Current) fast charging. It uses a Type 2 connector with additional DC pins, allowing both AC and DC charging through a single vehicle inlet. In India, CCS2 chargers typically offer power outputs starting from 50 kW and can go much higher (e.g., 120 kW, 240 kW, up to 350 kW or more), with operating voltages generally ranging from 200V to over 750V. It was adopted to establish a universal, high-power DC fast charging standard in public areas, enabling faster turnaround times for vehicles with larger battery packs like electric trucks and buses, facilitating long-distance electric mobility and fleet operations.

Features:

- Widely adopted internationally and increasingly in India for passenger cars, buses, and compatible trucks.
- Capable of delivering high power necessary for significantly recharging large truck batteries in a reasonable time.
- Supports complex communication protocols between the charger and the vehicle for efficient and safe charging.
- Considered a future-proof standard for fast charging.

Ministry of Power guidelines specify the inclusion of CCS2 chargers in public charging infrastructure. BIS adopts the relevant IEC standards (e.g., IEC 61851, IEC 62196) that define CCS. Owing to its high-power capabilities, it is regarded as the most pertinent and increasingly prevalent standard and is therefore recommended.

b. CHAdeMO

This is another DC fast charging standard, developed in Japan. It uses a different connector type than CCS2. While historically offering power levels starting from 50 kW, newer versions of the standard can support higher power. The standard aims to provide a DC fast charging

option and ensure charging availability for compatible electric vehicles, including some heavy-duty vehicles.

Features:

- One of the earlier DC fast charging standards.
- India's public charging guidelines have historically included CHAdeMO, specifically mentioning its relevance for long-distance electric vehicles and/or heavy-duty vehicles.
- Provides interoperability for vehicles equipped with a CHAdeMO port.

c. Type 2 AC (High Power)

While primarily an AC charging standard, Type 2 connectors can support higher AC power levels (typically 22 kW or 43 kW three-phase AC) compared to basic AC chargers and was adopted as a standardized, higher-power AC charging option in public and semi-public locations, offering flexibility for different charging needs and vehicle capabilities.

Features:

- Uses the same connector type as the AC part of CCS2.
- Offers faster AC charging than basic low-power chargers.
- Can be used for public charging where DC fast charging might not be necessary or available, such as at depots for overnight charging or locations where vehicles are parked for longer durations. Trucks would need to be equipped with an onboard charger capable of handling these power levels.

MoP's guidelines specify the inclusion of Type 2 AC chargers (minimum 22 kW) for public charging stations catering to 4-wheelers and above and BIS adopts the relevant IEC standards (IEC 62196).

d. Standards related to Light-Duty Vehicles (LDVs):

Bharat DC-001: This is a lower-power DC standard (typically 15 kW) designed primarily for low-voltage EVs (<120V), common in segments like electric 2-wheelers, 3-wheelers, and some early electric cars.

Bharat AC-001: This is a basic, low-power AC standard (typically offering multiple 3.3 kW outputs). It is suitable for slow overnight charging but not for the fast charging required by heavy-duty trucks during operational hours in public or highway settings.

Charger Type	Charger Connectors*	Rated Voltage (V)	No. of connector Guns	Charging vehicle type (W-wheeler)
Fast	Combined Charging System (CCS) (min 50kW)	200-750 or higher	1 CG	4-W
	CHArge de Move CHAdeMO (min 50 kW)	200-500 or higher	1 CG	4-W
	Type 2 AC (min 22 kW)	380-415	1 CG	4-W, 3-W, 2-W
Slow/moderate	Bharat DC-001 (15 kW)	48	1 CG	4-W, 3-W, 2-W
	Bharat DC-001 (15 kW)	72 or higher	1 CG	4-W
	Bharat AC-001 (10 kW)	230	3 CG of 3.3 kW each	4-W, 3-W, 2-W

Figure 15. Standards Specific for Charging stations

Source: Electric Vehicle Charging Infrastructure and its Grid Integration in India- Status Quo, Critical Analysis and Way Forward (NITI Aayog, 2021)

e. Additional EV Charging Standards:

- Light EV AC (up to 7 kW) – **IS-17017-22-1**
- Light EV DC (up to 7 kW) – **IS-17017-25**
- Parkbay AC (11 kW / 22 kW) – **IS-17017-1**
- Parkbay DC (50 kW to 250 kW) – **IS-17017-23**
- eBus Charging Station (250 kW – 500 kW)
- Dual Gun Charging Station- **IS-17017-23-2**
- Automated Pantograph Charging Station- **IS-17017 3-1**

6. Phased Rollout of EV Chargers

- **Phase I (2022-25):** Coverage of mega cities with 4M+ population, expressways, and major highways.
- **Phase II (3-5 years 2025-27):** Expansion to state capitals, UT headquarters, and key intercity highways.

As of May 2025, the Phase I deployment has made substantial headway. Under central schemes such as PM E-DRIVE and FAME II, more than 10,000 public charging stations are now operational nationwide, approaching the original target of roughly 22,000 sites by the end of 2024. The baseline network has ensured that even long-distance routes offer frequent access to charging, alleviating early “range-anxiety” concerns for truck and bus operators.

In India’s mega-cities, the guideline-mandated grid-coverage norm—one public charger per 3 km × 3 km cell—has been fully achieved in all eight qualifying urban agglomerations. Delhi alone reported 306 million units (MU) of electricity dispensed for EV charging during April 2024–February 2025 signifying the scale of infrastructure rollout and rising user uptake. Along the national highway network, the requirement of at least one standard public charger every 25 km

on each side has likewise been realised, with some 8,738 stations active as of mid-2024 and numerous additional fast-charging points (≥ 50 kW) now spaced at approximately 100 km intervals for heavy-duty vehicles.

The captive and semi-public fleets such as municipal bus depots and private logistics operators have implemented bespoke fast-charging and battery-swap facilities under more flexible technical norms. Looking ahead, Phase II commenced in January 2025, with state capitals and inter-capital highways now receiving priority. Efforts are under way to streamline site approvals, improve grid integration through smart metering and demand-response mechanisms and scale up ultra-high-power chargers (≥ 150 kW) to serve the heavy-duty EV segment.

8.3.2 Technical Standards for Connectivity of the Distributed Generation Resources, 2013

Issued by the Central Electricity Authority (CEA) | Amended: 2019

- Defines charging points and charging stations separately.
- Recognizes EVs as energy generation resources.
- Establishes standards for charging stations seeking grid connectivity.
- Requires EV charging operators to install fault detection and protection systems to prevent grid disturbances.
- DISCOMs must conduct network adequacy and stability studies before permitting connections.
- Operators must install power quality meters, with harmonics and voltage fluctuations monitored as per IEC 61000-4-30 Class A standards.
- Unique Registration Number to be issued for the connection of EV charging stations to the grid.

1. General Safety Requirements

- Overload protection for both input and output power supply.
- EV charging points must be at least 800mm above ground.
- No adaptors, portable socket outlets, or extension cords allowed for EV charging.
- Lightning protection as per IS/IEC 62305.
- EV parking must ensure the charging connection is within 5 meters of the charging point.
- Charging stations must have a protective device to prevent uncontrolled reverse power flow.
- Within one second of unplugging, voltage on exposed parts must drop to 42.4V peak (30V rms) for AC or 60V for DC, with stored energy below 20J (IEC 60950). If exceeded, a warning label must be displayed.
- For DC charging above 60V, the vehicle connector must stay locked and not unlock if hazardous voltage is detected. A safe disconnection method must be provided in case of a malfunction.
- DC charging points must cut power if the output voltage exceeds the vehicle's limit to prevent overvoltage.
- Charging cables must not be energized when the connector is unlocked, and unlocking voltage must be below 60V.

2. Earth Protection System

- Residual Current Devices (RCDs) must have:
 - $\leq 30\text{mA}$ operating current
 - Interrupt all live conductors, including neutral
- Must perform at least at Type A level and comply with IS 732-2018.
- Residual current devices must be permanently marked to indicate their function and the charging station or socket they protect.
- Each EV charging point must have a dedicated sub-circuit with an overcurrent protection device as per IEC standards and be part of a switchboard.
- EV charging stations must be connected to a sub-circuit with a voltage-independent RCD for personal protection.
- A protective earth conductor must connect the EV's conductive parts to the supply earth terminal, meeting IEC 60364-5-54 standards.

3. Fire Hazard Prevention

All equipment enclosures shall be constructed from fire-retardant, self-extinguishing materials and shall be free of any halogenated compounds. They must incorporate fire detection and suppression systems that conform to the relevant Indian standards. Also, the power-supply cables used within the installation shall comply fully with the requirements of IEC 62893-1.

4. Testing and Inspection

- Insulation resistance of all apparatus must comply with IEC 61851-1.
- The EVSE (Electric Vehicle Supply Equipment) owner must conduct all tests for the RCD and charging station as per the manufacturer's instructions.
- Regular inspections by Electrical Inspectors/Chartered Electrical Safety Engineers before energization.
- Charging station owners must set up a regular safety assessment program.
- EVSE owners must regularly assess and ensure the electrical safety of their charging stations.

5. Record Maintenance

- The EVSE owner must maintain records on design, construction, and labelling to ensure compatibility with a 50Hz standard voltage supply.
- The charging station owner must keep records of relevant test certificates as per regulations and IEC 61851.
- The EVSE owner must maintain records of inspections, tests, assessments, detected issues, and corrective actions taken.

6. International Standards Compliance

Safety provisions should be in accordance with:

- **AC Charging:** IEC 61851-1, IEC 61851-21, IEC 61851-22
- **DC Charging:** IEC 61851-1, IEC 61851-21, IEC 61851-23, IEC 61851-24

8.3.3 Notification of Standards for Electric Vehicle Conductive Charging System

The standards entail product specifications, dimensions and testing methods, including safety requirements that focus on protection against electric shock (direct and indirect contact), overcurrent, overvoltage, earth fault detection, and emergency shutdown mechanisms alongside environmental protection in terms of resistance to water ingress, temperature variations and electromagnetic compatibility (EMC) to guarantee safe operation across diverse conditions.

8.3.4 Notification of Standards for Road Vehicles- Vehicle to Grid Communication Interface

Sets technical and legal requirements for smooth energy transfer between electric vehicles (EVs) and the electrical grid. By defining standardized communication protocols, it makes bidirectional charging possible for applications involving vehicles connected to the grid (V2G) and vehicles connected to homes (V2H). It ensures cybersecurity and secure data exchange to guard against unwanted access and facilitates a cohesive ecosystem by encouraging interoperability among EV manufacturers, charging networks, and grid systems. In order to support EV integration into the energy infrastructure, lower peak load stress, and enable EV owners to profit from stored battery energy, it establishes performance and safety requirements for EVs include voltage control, load balancing, and protective mechanisms to prevent grid instability.

8.4 EV Regulations in Indian States

India does not have a separate national or state regulatory framework for the adoption of EVs. The majority of states adhere to Ministry of Power (MoP) and Central Electricity Authority (CEA) regulations. Nonetheless, these rules have been mentioned in passing in the EV policies of Madhya Pradesh, Andhra Pradesh, Haryana, Tamil Nadu, and Rajasthan. According to national tariff policies and the Electricity Act of 2003, State Electricity Regulatory Commissions (SERCs) are in charge of setting electricity tariffs. Since EVs are a new consumer category, they need their own tariff structure. In order to establish suitable tariffs, distribution companies and regulators are still evaluating the demand for EV charging.

Understanding EV tariffs in Indian states is indispensable because the cost of charging highly impacts the adoption rate of electric vehicles and the financial health of the charging infrastructure providers. Unlike regular household or commercial electricity connections, EV charging stations often require a specific tariff structure designed to meet the unique needs of electric mobility. The ecosystem involves several key entities:

8.4.1 State Nodal Agencies (SNAs)

Appointed by respective state governments, SNAs often act as the central coordinating body for EV policy implementation within the state. Their role concerning tariffs might involve identifying locations for government-supported charging stations, facilitating their setup, and as mentioned, sometimes setting the ceiling for the service charge that can be levied at these specific government-backed stations to ensure affordability and encourage usage in priority areas. They translate state policy goals into actionable plans on the ground.

8.4.2 Charging Service Providers (CSPs)

These are the businesses ranging from large corporations to startups that invest in, install, operate, and maintain the actual EV charging stations. Their primary revenue comes from the

fee they charge EV users for the charging service. The service charge is influenced by the underlying electricity tariff they pay to the DISCOM and any ceiling set by the SNA or regulatory commission. The viability of CSPs is directly tied to the profitability of their operations, which is heavily dependent on the tariff structure.

8.4.3 DISCOMs (Distribution Companies)

These are the local electricity distribution utilities responsible for supplying power to homes, businesses, and importantly, to the EV charging stations within their licensed area. DISCOMs are regulated entities. They facilitate the physical electricity connection for charging stations and bill the CSPs based on the tariff determined by the state regulatory commission. They don't set the retail tariff for EV charging themselves instead act as a critical link in the chain, connecting the charging infrastructure to the grid and implementing the tariff structure.

8.4.4 Regulatory Commissions (State Electricity Regulatory Commissions - SERCs)

These are independent statutory bodies established under the Electricity Act, 2003. They play the most significant role in the tariff ecosystem. SERCs are responsible for determining the retail tariffs for various categories of consumers, including a dedicated category for EV charging. They conduct public consultations, consider inputs from DISCOMs, CSPs, and consumers, and issue tariff orders. Regulations issued by SERC aim to balance the interests of consumers (affordable charging), DISCOMs (recovering costs), and CSPs (business viability) while promoting EV adoption and potentially managing grid impact through tariff design (e.g., Time-of-Day tariffs).

Initially, as EV charging infrastructure was nascent, there were no specific EV tariffs in every state. Charging stations were billed under commercial tariffs, which weren't always suitable. The Ministry of Power (MoP) recognized the need for a standardized approach and issued guidelines to encourage states to notify a specific EV charging tariff.

An earlier approach in some guidelines included a suggestion or a cap on the EV tariff, such as limiting it to 15% above the Average Cost of Supply (ACoS) for the DISCOM. The intention behind this cap was likely to ensure that electricity for EV charging remained affordable compared to traditional fuels.

- State commissions now have greater autonomy to determine the EV tariff based on local conditions, DISCOM costs, investment required for charging infrastructure, and the specific goals of the state's EV policy. They are not strictly bound by a national percentage cap over ACoS.
- Tariffs set by SERCs can potentially be more reflective of the actual cost of supplying electricity for charging, the demand profile, and the need to attract investment in charging infrastructure.
- SERCs can design tariffs that incorporate elements like Time-of-Day (ToD) pricing, where electricity is cheaper during off-peak hours to encourage EV users to charge when grid load is low, helping in better grid management and potentially lowering the cost for the consumer.
- The responsibility now squarely lies with SERCs to balance the interests of DISCOMs (ensuring they can recover costs and potentially invest in grid upgrades for EV load), CSPs

(providing a viable business model), and consumers (keeping charging affordable enough to encourage adoption).

The fact that some states like Andhra Pradesh, Telangana, and Uttar Pradesh had already established EV tariffs even before this formal national mandate indicates their proactive approach, likely utilizing earlier MoP guidelines or their inherent power under the Electricity Act to create a conducive environment for EV charging infrastructure development.

8.5 National Level Renewable Energy Policies for EV Charge Parks

Renewable Energy policies offer important support through regulations, financial incentives, and operational flexibility for the electrification of freight and the development of ZET charge parks. This section outlines the key national RE policies, schemes, and regulatory frameworks that stakeholders, such as charge point operators (CPOs), fleet owners, and energy service providers, can use to integrate renewable energy into their operations.

8.5.1 National Electricity Policy (NEP) & National Energy Policy (NEP - NITI Aayog)

The grid is not just a source of electricity; it's the **platform for integration**, optimization, and regulation of EV and renewable energy systems. The **National Electricity Policy** emphasizes the importance of integrating EV charging with RE sources and smart grids. It encourages **load balancing, renewable purchase obligations (RPOs), and distribution-level planning** to accommodate new demand from e-mobility. To enable synergy between transport electrification and renewable generation, the **NITI Aayog** promotes sector coupling under the **National Energy Policy**. The network of EV charge parks is seen as a strategic anchor point for sector coupling as it goes beyond charging vehicles and talks about creating **multi-modal, renewable-powered energy hubs** that smoothen grid demand curves and lower charging costs.

8.5.2 National Tariff Policy (2016, revised 2023)

NTP 2016 sought to fix financial instability of DISCOMs, promote renewable energy integration, standardise tariff practices, reduce cross-subsidies, improve grid planning, ensure competitive procurement, and enhance supply quality, all under a transparent and market-oriented framework. The major provisions discussed are-

- **Time-of-Day (ToD) tariffs** during solar or off-peak hours.
- Transfer of savings and benefits to consumers as a result of adopting **net-metering**.
- Minimal cross-subsidy surcharges for **green open access consumers**.

EV charging stations can benefit from off-peak ToD tariffs and participate in demand-side management programs for grid optimization. It creates a friendlier electricity market environment for Charge Parks, making large-scale truck charging both **financially viable** and **environmentally sustainable**.

8.5.3 Green Energy Open Access Rules, 2022

The rules were issued by the **Ministry of Power (MoP)** to facilitate non-captive consumers (≥ 100 kW) to purchase **renewable energy through open access**.

Key Provisions:

- **Eligibility:** Consumers with sanctioned load ≥ 100 kW can avail open access from RE sources.
- **Approvals:** Single-window clearance via a national portal.
- **Charges:** Rationalization of surcharges such that green power is not costlier than conventional power.
- **Banking:** Banking of RE allowed as per respective SERC regulations.
- **Priority Approval:** Distribution licensees are mandated to provide connectivity within 15 days.

EV charge parks, being high-load installations, often multi-MW consuming entities, are ideal candidates for green open access procurement as discussed in Chapter 4.

8.5.4 Renewable Energy Generation Schemes

Schemes like PM-KUSUM and CPSU facilitate co-location of solar generation near charge parks, depots or on idle industrial land.

A. PM-KUSUM Scheme

Component C of the scheme enables DISCOMs to set up decentralized solar plants up to 2 MW on vacant land. CPOs can partner with farmers or landowners for **captive solar supply** to their parks.

B. CPSU Scheme (Ph-II)

It offers **VGF-based support** for government-backed entities setting up large-scale solar projects which can be explored for **public-sector freight depots** or **logistics hubs**.

8.5.5 Battery Energy Storage Policy Framework (2023)

Co-locating storage with RE-powered ZET charge parks can reduce grid dependency and lower peak demand charges. The National Framework for Promoting Energy Storage Systems-

- Aims to create a strong ecosystem for **grid-connected and off-grid battery storage systems**.
- Recommends BESS deployment alongside RE for **peak shaving, backup power, and arbitrage**.
- Envisions storage as a **grid asset** and supports hybrid RE + storage business models.

8.5.6 Renewable Purchase Obligations (RPO) & Energy Storage Obligations (ESO)

CPOs using open access or captive RE are subject to RPO and ESO which makes it convenient to invest in RE + storage systems and trade credits.

- The **MoP's RPO trajectory (2022–2030)** mandates DISCOMs, open access, and captive users to source a minimum percentage of electricity from renewables.
- **Energy Storage Obligations (ESO)** have also been introduced starting FY 2023–24, requiring a portion of RE procurement to be backed by storage.

8.5.7 National Green Hydrogen Mission (2023)

Green hydrogen may power **fuel cell EVs** in future long-haul freight corridors. Considering that, ZET ecosystems can plan for **multi-energy integration** (battery + hydrogen) using common RE

infrastructure. Despite largely focused on industrial decarbonization, certain provisions in the *National Green Hydrogen Mission* point out the use of **RE-based hydrogen production**, especially near RE-rich states.

8.5.8 Grid Modernization & Smart Metering Programs

National Smart Grid Mission (NSGM) and Revamped Distribution Sector Scheme (RDSS) provides the distribution-level readiness necessary for EV Charge Parks to draw large loads sustainably from the grid as well as maximizing renewable energy utilization through open access and hybrid setups. These programs were launched with a view to address:

- Feeder separation, transformer upgrades, and smart meter rollout.
- Renewable Energy Integration, real-time data access and grid responsiveness.

CPOs can participate in **demand response programs** and adopt **smart charging methods** enabled by digital infrastructure.

8.5.9 Other Enablers

Table 38. Other Policy Enablers and Opportunities

Policy/Regulation	RE Integration Opportunity
Net Metering Regulations by CERC/SERCs	Allows solar feed-in for self-consumption (where permitted)
UDAY 2.0 and DISCOM Reform Initiatives	Improve DISCOM health, enabling faster approvals and grid upgrades

Rational utilization of central policy with state-level enablers, backed by DISCOMs, regulators, and RE developers, will be the key to harnessing government policies and regulations.

8.6 EV Policies of States related to Charging infrastructure & Renewable Energy (RE) Integration

Though the broad policy framework is set at the national level, individual states play a crucial role in taking forward the set goals through fiscal incentives, regulatory enablers, land and power facilitation.

Major EV States and Their Policy Enablers

8.6.1 Delhi

As a leader in EV adoption, the city offers capital subsidies for slow and moderate chargers and requires rooftop solar installations, especially at depots and residential complexes, to generate renewable energy on-site. It encourages solar-powered charging stations and supports net metering to make the most of clean energy. Delhi is also piloting time-of-day tariffs and looking into vehicle-to-grid (V2G) solutions to boost grid efficiency. The government and private partnerships help allocate land for charging and battery-swapping facilities, which allows for rapid deployment in areas with high demand. In order to reduce the overall operational challenges for CPOs, DISCOMs are mandated to offer low-cost connections with dedicated EV tariffs.

8.6.2 Maharashtra

Maharashtra's EV Policy 2021, particularly the revamped 2025 framework aims to strictly deploy EV charging stations every 25 km along state, national highways and equipping the existing fuel stations and MSRTC bus depots with fast chargers supported by viability-gap funding up to ₹5 lakh for standard DC chargers and ₹10 lakh for high-capacity ones. It includes incentives for public and private charging stations, stamp duty waivers, and demand aggregation models. Importantly, it promotes RE-based charging through gross metering and co-location of solar panels with charging infrastructure. Industrial tariffs and electricity duties have also been exempted for adopting clean energy solutions. A single-window digital portal streamlines approvals, and the policy explicitly supports pilot programs including V2G technology, green charging station labelling, battery recycling hubs, and R&D funding via a ₹15 crore CM EV R&D Grant.

8.6.3 Tamil Nadu

The state requires the installation of charging stations every 25 km along national and state highways. It supports both public and private charging setups with substantial capital subsidies: ₹10 lakh for fast chargers and ₹1 lakh for slow chargers. Insurance for EV aggregators and battery swapping facilities is also covered. The policy introduces tariff changes to improve the financial viability of charging operations. There is a 75% reduction in demand charges for the first two years, followed by a 50% cut after that. It offers 50% lower energy rates during the 8 AM to 4 PM window to match peak renewable generation. Charging stations that source at least 75% of their energy from renewable sources receive more subsidies. It has also launched key initiatives, including dedicated EV cities in Chennai and other metropolitan areas, a Future Mobility Park at Krishnagiri, and high-capacity fast-charging hubs for commercial vehicles that can fully charge in 30 minutes.

8.6.4 Karnataka

Karnataka is set to expand its charging network by approximately 2,600 stations through public-private partnerships and utility-led models. Karnataka works in coordination with ESCOs to install fast chargers at all RTO offices, highways, and key tolled corridors like Bengaluru–Pune and Bengaluru–Mysuru every 50 km. In a pioneering move toward RE integration, the state inaugurated India's first solar-integrated EV charging station near Bengaluru airport that operates 24/7 using repurposed EV batteries. Incentives such as capital subsidies for charging and battery-swapping stations up to 25% of fixed asset value, stamp duty waivers, and preferential land leases are ways in which the state extends its financial support.

8.6.5 Telangana

Telangana is poised to install an RE capacity of 20 GW and 6,000 EV charging stations by 2030 and is actively deploying large-scale EV charging infrastructure. TSREDCO, the state nodal agency, is rolling out hundreds of fast charging and battery swapping stations across urban centres, industrial areas, and highways targeting a station every 50 km under PPPs, franchises, and licence arrangements. It has dedicated EV tariff categories in place and promotes rooftop solar installations, captive RE supply via net-metering, and green power for charging stations. The state has been attracting manufacturing and R&D through EV-ESS clusters, single-window land and clearance facilitation, and battery reuse and recycling frameworks.

Other states like **Rajasthan, Uttar Pradesh, Madhya Pradesh, Odisha, and Punjab** have EV policies but there is limited proactive support for RE integration in the charging infrastructure.

8.7 Guide for ZET Stakeholders for Harnessing RE Policies

This section details out the necessary steps to be undertaken by key stakeholder groups involved in planning, implementing and supporting RE integration at EV charging hubs.

8.7.1 Charge Point Operators (CPOs) / ZET Charge Park Developers

- **Adopt Green Open Access:** Register as an eligible consumer under the *Electricity Rules, 2022 (Promoting Renewable Energy through Green Energy Open Access)* for RE procurement.
- **Use Group Captive/Third-Party PPAs:** Structure power purchase agreements under group captive models to reduce energy and compliance cost with related regulations.
- **Install Rooftop Solar + BESS:** Take advantage of *net metering* or *gross metering* provisions under state-specific policies.
- **Apply for concessional grid connectivity:** Coordinate with DISCOMs to utilize RE transmission incentives mentioned in NEP 2021.

8.7.2 Fleet Operators / Trucking Logistics Companies

- **Collaborate with CPOs for RE charging:** Enter group captive PPAs for dedicated RE-powered charge points.
- **Incentivize off-peak charging:** Align fleet schedules with time-of-day (ToD) tariffs that favour solar or wind usage.
- **Advocate for RE reliability:** Work with technology providers for solar + BESS solutions at fleet depots to mitigate intermittency.

8.7.3 State Nodal Agencies / DISCOMs

- **Facilitate open access approvals swiftly:** Simplify procedures and operationalize the approval deadlines as stipulated in the state-specific policies.
- **Enable net/gross metering for CPOs:** Clarify and standardize metering rules for commercial EV charging applications.
- **Support Park allocation:** Promote allocation of solar and wind park capacity to CPOs under SECI or RE state programs.
- **Disseminate RE tariff data:** Publish ToD and RE-specific tariffs for EV sector stakeholders.

8.7.4 Energy Regulators (CEA / SERCs)

- **Issue clear tariff orders for RE charging use-cases:** Define wheeling, banking, and cross-subsidy charges for CPOs.
- **Create a regulatory sandbox:** Allow innovation pilots (e.g., V2G, RE+BESS for heavy-duty EVs) under controlled settings.
- **Track the compliance status:** Set up mechanisms for periodic evaluation of implementation status.

8.7.5 RE Project Developers & EPC Companies

- **Target ZET hubs as off-takers:** Develop business models catering to CPOs and industrial EV zones.
- **Offer Solar + BESS solutions tailored for charge parks:** Ensure modular design, quick installation, and optimized storage sizing.
- **Bundle services:** Combine RE generation, energy storage, and operations into integrated energy-as-a-service offerings.

8.7.6 Investors & Financial Institutions

- **Support RE-powered charging parks as green infrastructure:** Classify eligible ZET charge park projects under green financing guidelines.
- **Use government-backed guarantees:** Capitalise on IREDA and World Bank credit enhancement programs for RE-EV integrations.
- **Finance BESS and hybrid RE systems:** Provide differentiated loan products to promote renewable-based storage applications.

8.7.7 Central Government Agencies (MNRE, MoP, NITI Aayog)

- **Publish implementation toolkits for RE-EV convergence:** Create model frameworks, tender templates, and SOPs for stakeholders.
- **Align PLI schemes for BESS with ZET needs:** Prioritize fast-charging compatible storage technologies.
- **Coordinate inter-ministerial strategy:** Harmonize EV charging, RE development, and logistics electrification plans.

8.7.8 Technology Providers / Startups

- **Develop integrated energy management systems (EMS):** Enable smart scheduling, RE forecasting, and battery optimization for ZET parks.
- **Provide mobile-based dashboards for fleet operators:** Track RE consumption and charging cost benchmarks in real-time.
- **Pilot solar-wind-battery-V2G setups:** Innovate on scalable solutions for future-ready ZET infrastructure.

8.8 Environmental Regulations for EV Charge Parks

The establishment of EV charge parks integrated with renewable energy sources must adhere to a range of environmental regulations to meet the norms of environmental sustainability, minimizing ecological disruption, and enabling long-term compliance with India's green development goals. The regulations entail land use, air quality, waste management, and renewable energy implementation with different stakeholders bearing varying responsibilities.

8.8.1 Site Selection and Land Use Compliance

Before setting up an EV charge park, developers must comply with local land zoning and environmental clearance norms, particularly when large-scale solar or wind installations are planned. According to the **Environment Impact Assessment (EIA) Notification 2006**, certain infrastructure projects, mainly those involving land conversion or installations above a particular

size may require prior environmental clearance from the **State Environment Impact Assessment Authority (SEIAA)** or **Ministry of Environment, Forest and Climate Change (MoEFCC)**. Charge Park developers and operators must also comply with **Coastal Regulation Zone (CRZ)** norms or **forest land diversion rules** under the **Forest Conservation Act**, if applicable.

8.8.2 Air and Noise Pollution Norms

The construction and auxiliary power systems like diesel gensets used for backup at EV charge parks may cause temporary pollution. Hence, it becomes important to adhere **Central Pollution Control Board (CPCB)**, **State Pollution Control Boards' (SPCBs)** norms and provisions under the **Air (Prevention and Control of Pollution) Act, 1981** pertaining to permissible limits for noise, dust, and emissions from auxiliary sources.

8.8.3 Waste and Water Management

RE-powered EV charge parks essentially involve waste generation from used batteries, solar panel disposal, or water used in cooling systems which necessitates the CPOs and developers to comply with:

- **Hazardous Waste Rules** for battery disposal,
- **E-Waste Management Rules, 2016** for solar modules and electronic components,
- **Water (Prevention and Control of Pollution) Act, 1974**, for water discharge and treatment norms,
- State-specific solar panel recycling policies which are currently under development in several states.

Operators should maintain on-site documentation and forge tie-ups with authorised recyclers for end-end waste management.

8.8.4 Grid and Renewable Energy Regulations

Charge Park developers aiming to integrate renewable energy must follow the **State Electricity Regulatory Commission (SERC)** guidelines, to a great degree for open access, group captive or net metering models with respect to:

- Securing grid connectivity approvals from **DISCOMs**,
- Complying with **CEA's grid code, forecasting requirements** and **Deviation Settlement Mechanism (DSM)** rules
- Meeting **Renewable Purchase Obligations (RPOs)**, where applicable,
- Implementing **energy accounting and audit practices** for hybrid or RE-integrated facilities.

If green hydrogen is co-located as an emerging use-case, additional environmental clearances under chemical safety and pollution norms would apply.

8.8.5 Fire and Electrical Safety Standards

Charge parks must also follow the **National Building Code (NBC)** and **CEA Safety Regulations** with regard to EVSE (Electric Vehicle Supply Equipment), solar inverters, battery storage, and associated switchgear. Fire safety requirements are governed by the **National Fire Protection Association (NFPA)** guidelines and local municipal by-laws. Lithium-ion battery storage areas must include fire suppression systems, ventilation, and thermal management provisions in accordance with environmental and safety best practices.

Table 39. Stakeholder-wise Environmental Compliance Responsibilities

Stakeholder	Key Environmental Compliance Areas
Charge Point Operators (CPOs)	Site clearance, e-waste handling, noise/dust control, energy audits
RE Developers (Solar/Wind/Hybrid)	Grid compliance, land use approvals, solar waste disposal, emissions standards
DISCOMs	Grid integration and forecasting compliance, renewable energy accounting
State Pollution Control Boards (SPCBs)	Monitoring and approvals for emissions, waste, and water discharge
State Nodal Agencies / Urban Local Bodies	Zoning permissions, building code compliance, fire safety inspections
Battery Storage Vendors	Hazardous material handling, battery disposal, safety certification

Chapter 9

Conclusion

Shifting from grid powered EV Charging stations to Renewable powered EV Charging stations presents an opportunity for cost and carbon savings which are clear given the above assessment.

Table 40. Benefits of Grid vs RE Scenario

	Grid Scenario	Renewable Scenario
Energy Mix	Primarily coal-based electricity	Possible mix of Solar and/ or Wind
CO₂ Emissions (tCO₂/ MWh)	1371	~ 85 - 238
Considering 100% EVs		
Cost per unit of Electricity (Rs/ kWh)	~ 7 – 9	~3–4 (group captive with T&D) ~1.5 (generation + O&M)
Payback period (Years)	No investment involved rather a continuous per unit payment for the lifetime of the station	~0.7–2 years (group captive) ~3–7 years (captive plant)

Shifting to solar power can reduce emissions by up to 90%, while wind can achieve an 83% reduction. This transition also enhances energy system reliability and reduces dependence on diesel generators, especially when combined with battery storage solutions.

The economic case is equally strong with group captive models offering payback in under two years. Moreover, the operational needs of Zero Emission Trucks (ZETs) present opportunities for direct and indirect employment at charging hubs ranging from plant maintenance to auxiliary services like rest stops.

Widespread adoption of renewables in EV infrastructure could also spur the development of impromptu *Green Corridors*, contributing significantly to India's clean energy goals.

Ultimately, integrating renewables into EV charging infrastructure is not just an environmental imperative but a strategic move towards a cleaner, more resilient, and economically sustainable transport ecosystem for India.

ANNEXURES

A.1 Cost-Benefit Analysis of Captive and Group Captive Renewable Energy Models for ZET Charging Parks and CO₂ Emissions

Formula used for Tables 2, 3:

1. Average Daily traffic Maximum = $\frac{\text{Maximum Truck traffic in the corridor}}{30}$
2. Average Daily Traffic Minimum = $\frac{\text{Minimum Truck traffic in the corridor}}{30}$
3. Battery Capacity considered for 14 - 18 Ton trucks (kWh) = *Median*(100,240)
= 170 kWh
4. Battery Capacity considered for 28 - 40 Ton trucks (kWh) = *Median*(160,300)
= 230 kWh
5. Charging Frequency of Trucks (%) = $\left(\frac{\text{Length of the corridor}}{\text{Range of the truck}} \right) \times 100$
6. Number of vehicles needing charge per day (number/ day)
= Number of Trucks $\times$ Charging Frequency of trucks $\times$
Percentage of Charge available in the vehicle
7. Energy required by EVs (kWh) per day
= Number of vehicles needing charge per day $\times$ Battery Capacity considered
8. Total Energy required by EVs (kWh) per day
= *Average of Energy required by EVs (kWh) per day in the higher end and lower end*
8. Number of stations required = $\frac{\text{Length of the corridor}}{\text{Distance between each station}}$
- Number of chargers required = $\frac{\text{Energy required per station}}{\text{Charger capacity}}$

Case Study 1: Chennai - Bangalore Corridor

Captive Power Plant Savings per Charging Station (Rs.)

Scenarios	Charging station powered by 100% solar	Charging station powered by 100% wind	Charging station powered by 50:50 solar and wind
Considering 100% of the traffic are from EVs	266,706,069	268,813,723	267,759,896
Considering 50% of the traffic are from EVs	133,353,034	134,406,861	133,879,948
Considering 25% of the traffic are from EVs	66,676,517	67,203,431	66,939,974



Case Study 1: Chennai - Bangalore Corridor

Captive Power Payback period per Charging Station (Years)

Scenarios	Charging station powered by 100% solar	Charging station powered by 100% wind	Charging station powered by 50:50 solar and wind
Considering 100% of the traffic are from EVs	3.29	4.71	4.00
Considering 50% of the traffic are from EVs	3.29	4.71	4.00
Considering 25% of the traffic are from EVs	3.37	4.79	4.09

Group Captive Power Plant Savings per Charging Station (Rs.)

Scenarios	Charging station powered by 100% solar	Charging station powered by 100% wind	Charging station powered by 50:50 solar and wind
Considering 100% of the traffic are from EVs	150,082,539	151,838,918	150,960,728
Considering 50% of the traffic are from EVs	75,041,270	75,919,459	75,480,364
Considering 25% of the traffic are from EVs	37,520,635	37,959,729	37,740,182

Group Captive Power Plant Payback period per Charging Station (Years)

Scenarios	Charging station powered by 100% solar	Charging station powered by 100% wind	Charging station powered by 50:50 solar and wind
Considering 100% of the traffic are from EVs	0.76	0.94	0.85
Considering 50% of the traffic are from EVs	0.76	0.94	0.85
Considering 25% of the traffic are from EVs	0.91	1.08	1.00



Case Study 2: Solapur –Vijayapura Corridor

Captive Power Plant Savings per Charging Station (Rs.)

Scenarios	Charging station powered by 100% solar	Charging station powered by 100% wind	Charging station powered by 50:50 solar and wind
Considering 100% of the traffic are from EVs	104,978,402	103,113,424	104,045,913
Considering 50% of the traffic are from EVs	52,489,201	51,556,712	52,022,957
Considering 25% of the traffic are from EVs	26,244,601	25,778,356	26,011,478

Captive Power Payback period per Charging Station (Years)

Scenarios	Charging station powered by 100% solar	Charging station powered by 100% wind	Charging station powered by 50:50 solar and wind
Considering 100% of the traffic are from EVs	4.13	6.47	5.29
Considering 50% of the traffic are from EVs	4.27	6.62	5.43
Considering 25% of the traffic are from EVs	4.55	6.90	5.72



Case Study 2: Solapur –Vijayapura Corridor

Group Captive Power Plant Savings per Charging Station (Rs.)			
Scenarios	Charging station powered by 100% solar	Charging station powered by 100% wind	Charging station powered by 50:50 solar and wind
Considering 100% of the traffic are from EVs	54,313,167	55,090,241	54,701,704
Considering 50% of the traffic are from EVs	27,156,583	27,545,121	27,350,852
Considering 25% of the traffic are from EVs	13,578,292	13,772,560	13,675,426
Group Captive Power Plant Payback period per Charging Station (Years)			
Scenarios	Charging station powered by 100% solar	Charging station powered by 100% wind	Charging station powered by 50:50 solar and wind
Considering 100% of the traffic are from EVs	0.98	1.28	1.13
Considering 50% of the traffic are from EVs	1.25	1.55	1.40
Considering 25% of the traffic are from EVs	1.80	2.09	1.94

CO₂ Emissions:

Case Study 1: Chennai - Bangalore Corridor			
	Considering 100% are EV	Considering 50% are EV	Considering 25% are EV
Total Energy required in a day (MWh)	1,342	671	336
Per unit emissions from Grid (tCO ₂ / MWh)	0.727 ³⁹	0.727	0.727
Per unit emissions from Wind (tCO ₂ / MWh)	0.126 ⁴⁰	0.126	0.126
Per unit emissions from Solar (tCO ₂ /MWh)	0.045	0.045	0.045
Emissions if Grid powered (tCO ₂)	976	488	244
Emissions if 100% Wind powered (tCO ₂)	169	85	42
Emissions if 100% Solar powered (tCO ₂)	60	30	15
Percentage decrease in emissions for Wind (%)	82.67%	82.67%	82.67%
Percentage decrease in emissions for Solar (%)	93.81%	93.81%	93.81%

³⁹ CO₂ Database, CEA

⁴⁰ LCA Analysis, NREL



Case Study 2: Solapur –Vijayapura Corridor

	Considering 100% are EV	Considering 50% are EV	Considering 25% are EV
Total Energy required in a day (MWh)	235	118	59
Per unit emissions from Grid (tCO ₂ / MWh)	0.727	0.727	0.727
Per unit emissions from Wind (tCO ₂ / MWh)	0.126	0.126	0.126
Per unit emissions from Solar (tCO ₂ /kWh)	0.045	0.045	0.045
Emissions if Grid powered (tCO ₂)	171	85	43
Emissions if 100% Wind powered (tCO ₂)	30	15	7
Emissions if 100% Solar powered (tCO ₂)	11	5	3
Percentage decrease in emissions for Wind (%)	82.67%	82.67%	82.67%
Percentage decrease in emissions for Solar (%)	93.81%	93.81%	93.81%

A.2 Fundamentals of Power Converter Technology

Power converters facilitate fast charging capabilities, with high-power converters, significantly reducing charging times for heavy-duty trucks. Power converters efficiently integrate renewable sources like solar and wind, while optimizing battery storage through smart charge/discharge cycles. They facilitate bidirectional energy flow and demand-side management, enabling seamless grid interaction and load balancing. Additionally, these systems maintain grid stability and power quality through precise voltage and frequency regulation. By performing these functions, power converters contribute to the overall efficiency, reliability, and flexibility of ZET charging parks, making the system feasible for reliable and long-term deployment.

Power converters are electronic devices designed to transform electrical energy into different forms, based on system requirements, typically altering voltage levels, current characteristics, or frequency. This process is governed by the fundamental laws of electromagnetism and circuit theory. PC operate on the principle of controlled energy storage and release, utilizing various components to achieve the desired conversion.

Their key functionalities include:

- **Rectification:** Converts Alternating Current (AC) to Direct Current (DC), commonly used in EV chargers and energy storage systems.
- **Inversion:** Converts DC to AC, enabling interaction with the grid and AC loads.
- **DC-DC Conversion:** Adjusts voltage levels within a DC system for optimal energy utilization.
- **Regulation and Control:** Ensures smooth and stable power delivery, improving efficiency and longevity of connected equipment.

The basic operation of most power converters involves three key elements:

1. Switching devices: MOSFET, IGBT
2. Energy storage components: Inductor, capacitor
3. Control circuitry: analog or digital

High frequency switching devices play a fundamental role in power conversion techniques. These components, typically IGBTs, MOSFET or SiC devices, function as controllable switches that rapidly alternate between on and off states. This high frequency switching action enables efficient energy transfer and voltage transformation while allowing for fast and precise control of the output characteristics. Energy storage components, primarily inductors and capacitors, temporarily store energy during the conversion process. Inductors store energy in their magnetic field, while capacitors store energy in their electric field. The control circuitry manages the timing and sequence of the switching actions, ensuring the desired output is achieved and maintained.

The efficiency and effectiveness of power converters hinge on the intricate interplay between these components. High-frequency switching, typically in the range of tens of kilohertz to several megahertz, allows for smaller energy storage components and faster response times. However, it also introduces challenges in terms of electromagnetic interference (EMI) and switching losses.

A.3 Power Converter Types and their Functions in ZET Charging Infrastructure

Converter Type	Subcategory	Function in ZET Charging Parks
DC-DC Converters	Buck Converter	Regulates voltage for low-voltage auxiliary systems used for control and monitoring purposes
	Boost Converter	Increases voltage from renewable sources (e.g., solar panels) to match charging requirements
	Buck-Boost Converter	Step up or step down the input voltage and manage voltage fluctuations from various power sources
	Cuk Converter	Provides smooth power delivery for sensitive charging equipment where high efficiency, low output ripple and low EMI are required
AC-DC Converters	Rectifiers	Converts grid AC power to DC for high-power truck charging
	Power Factor Correction (PFC) Circuits	Improves grid power quality and efficiency of charging stations
DC-AC Converters	Inverters	Converts DC from energy storage or solar to AC for grid support or auxiliary power
	Bidirectional converters	Works both as rectifier and inverter
AC-AC Converters	Cycloconverters	Manages frequency conversion for grid integration of charging systems
	Matrix Converters	Enables efficient power conversion between charging stations and the grid

A.4 Key Performance Metrics

In the context of heavy-duty electric truck charging, power converters must meet exceptionally high standards. They need to handle substantial power levels, often in the megawatt range, while maintaining high efficiency and power quality. The technical performance of these converters influences not only the charging experience for truck operators but also the integration with the electrical grid and the overall environmental impact of the charging infrastructure.

1. **Charging Speed / Power Levels:** Charging speed, measured in minutes or hours, is directly related to the amount of power a converter can feed into the electric trucks. Typically, there are three levels of charging based on the power output delivered by the power converter and are presented in Table 3. This table provides a clear comparison of the three EV charging levels, highlighting their key differences in power output, charging speed, typical locations, and use cases. Figure 2 illustrates the various charging stations categorized by their different levels.

Characteristic	Level 1	Level 2	Level 3
Voltage	240V AC, single phase	240V AC, three phase	300 -600V DC
Power Output	1.3 - 2.4 kW	3 - 19 kW	50 - 350 kW
Charging Speed	2 - 5 miles per hour	10 - 30 miles per hour	Up to 20 miles per minute
Time to Fully Charge (60 kWh battery)	40 - 50 hours	4 - 10 hours	20 minutes - 1 hour (to 80%)
Typical Locations	Most homes, some workplaces	Homes with charging stations, workplaces, public stations	Public charging stations, highway services
Connector Type	Standard outlet	J1772 (non-Tesla), Tesla connector	CCS, CHAdeMO, Tesla Supercharger
Installation Cost	Minimal (comes with EV)	\$300 - \$1,000 plus installation	~\$10,000 plus installation
Use Case	Overnight home charging	Home, workplace, destination charging	Long-distance travel, quick top-ups

For heavy-duty electric trucks, high-power DC fast charging at Level 3 (DC Fast Charging), which supplies between 50 and 350 kW and Ultra-fast charging charger power level is **400kW or higher**.

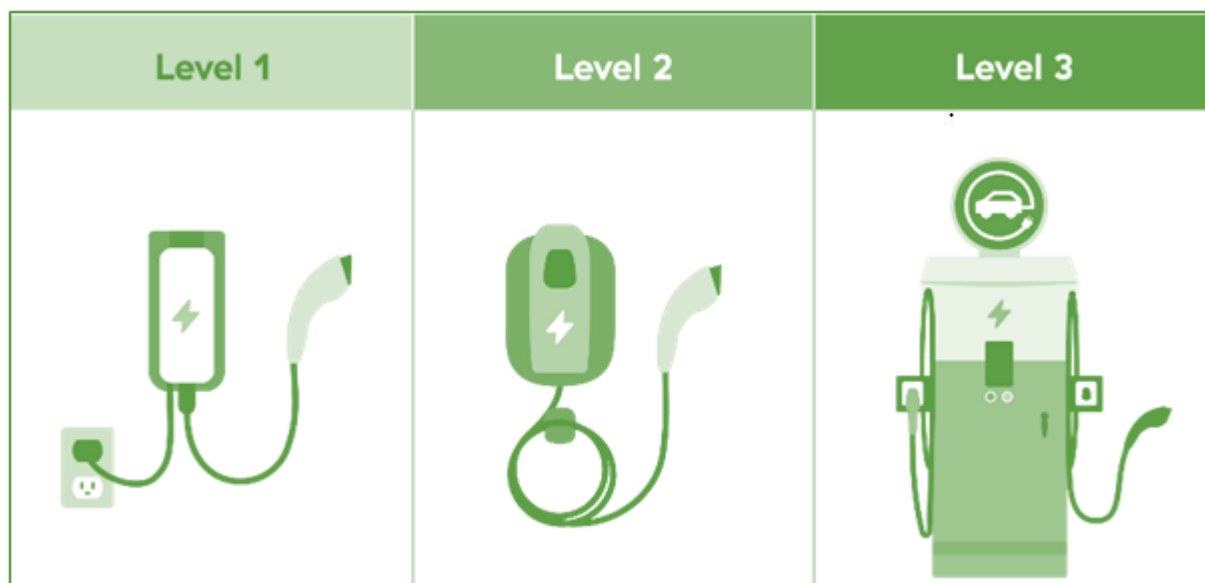


Figure 2. Charging stations categorized by their different levels

2. **Efficiency:** Power converter efficiency is typically in the range of 91-96%. Higher efficiency leads to:
 - Reduced energy losses
 - Lower operational costs
 - improved overall system performance
3. **Power Quality:** The power quality is defined by the Total Harmonic Distortion (THD) value. THD quantifies the level of harmonic content in the voltage or current waveforms, which is essential for maintaining power quality and grid compatibility. In ZET charging parks, low THD (typically <5% for voltage THD) is essential for grid compliance, equipment longevity, efficiency and power quality.
4. **Power factor:** It measures the efficiency of electrical power utilization and has significant implications for energy efficiency, grid stability, and operational costs. Maintaining a high-power factor (close to 1.0) is crucial for charge parks due to its significant impact on energy efficiency and operational costs. A higher power factor translates to more efficient use of electrical power, reducing energy losses and strain on the grid. This efficiency is particularly important for utility companies, many of which require a minimum power factor (often 0.95 or higher) to ensure grid stability.

For ZET charge parks, the ideal power factor is 1.0 (unity power factor), though a typical target is ≥ 0.95 (lagging or leading). The minimum acceptable power factor is often 0.90, but this can vary based on local regulations. These standards are crucial for ensuring optimal performance and compliance with grid requirements. The IEEE Standard 519-2014 provides comprehensive guidelines for power factor correction in electrical power systems, offering a framework for ZET charge park operators to maintain high power quality and efficiency in their charging infrastructure.

A.5 Key Technologies, Efficiency Considerations and Power Density in Power Converters

1. Key Technologies in Power Converters

Several key technologies underpin modern power converter designs. Pulse Width Modulation (PWM) is a fundamental technique used extensively in DC-AC and DC-DC converters. PWM involves rapidly switching the power devices on and off, with the ratio of on-time to off-time (duty cycle) controlling the average power delivered to the load. This technique allows for efficient power control and generates high-quality AC waveforms from DC sources.

Switched-Mode Power Supplies (SMPS) represent a significant advancement over traditional linear power supplies. SMPS use high frequency switching and energy storage elements to regulate output voltage efficiently. They offer higher efficiency, especially when there is a large difference between input and output voltages, and allow for smaller, lighter designs due to the reduced size of magnetic components.

Advancements in semiconductor technology have greatly influenced power converter design. The introduction of wide bandgap semiconductors, such as Silicon Carbide (SiC) and Gallium Nitride (GaN), has enabled higher switching frequencies, lower losses, and improved thermal performance. These materials allow for more compact and efficient converter designs, pushing the boundaries of power density and efficiency.

2. Efficiency Considerations in Power Converters

Efficiency is a critical aspect of power converter design, directly impacting energy consumption, thermal management requirements, and overall system performance. The efficiency of a power converter is determined by the ratio of output power to input power, with losses occurring in various components and processes within the converter.

The primary sources of losses in power converters include switching losses, conduction losses, and core losses in magnetic components. Switching losses occur during the transition of power devices between on and off states and increase with switching frequency. Conduction losses are due to the resistance of components when current flows through them. Core losses in inductors and transformers result from hysteresis and eddy currents in the magnetic materials.

Improving efficiency involves addressing these loss mechanisms through various techniques. Synchronous rectification, where MOSFETs replace diodes in rectification stages, can significantly reduce conduction losses. Soft switching techniques, such as zero voltage switching (ZVS) and zero current switching (ZCS), aim to reduce switching losses by ensuring that voltage or current is zero when the switch changes state. The use of advanced semiconductor materials like SiC and GaN also contribute to efficiency improvements due to their superior electrical properties.

3. Power density in Power Converters

Another important dimension for power converters is power density. Power density represents the power processing capability of the converter per unit volume. Modern power converters have high power density of 3 kW/l or more.

A.6 Key Institutions Supporting E-Mobility in India

Government Ministries and Departments

Ministry/Department	Key Roles in E-Mobility
Ministry of Heavy Industries (MHI)	Nodal agency for the FAME scheme (I & II); promotes EV manufacturing, R&D incentives, and demand-side subsidies.
Ministry of Road Transport and Highways (MoRTH)	Issues policies on vehicle registration, scrappage policy, and driving standards; integrates EVs into transportation norms and national permits.
Ministry of Power (MoP)	Facilitates EV charging infrastructure through policies like the Charging Infrastructure Guidelines; oversees power supply for EV adoption.
Ministry of New and Renewable Energy (MNRE)	Initially launched early EV incentive schemes (2010); promotes integration of renewable energy with EV charging infrastructure.
Ministry of Housing and Urban Affairs (MoHUA)	Works with urban local bodies to integrate EVs in public transport and city logistics; supports EV-friendly urban planning.
NITI Aayog	Policy think tank driving holistic EV strategies (e.g., e-FAST platform, GearShift Challenge); advocates regulatory convergence and market design reforms.
Department of Science and Technology (DST)	Funds R&D in battery technology and charging systems under initiatives like the Mission Innovation and Clean Energy Partnership.
Department of Heavy Industries (DHI)	Sub-agency under MHI overseeing schemes like FAME for promoting indigenous manufacturing capabilities within the automotive sector; also collaborates with industry to frame component-level standards.

Regulatory Bodies

Body	Role in E-Mobility
Bureau of Indian Standards (BIS)	Develops and updates technical standards for EVs, batteries, and charging equipment.
Central Electricity Authority (CEA)	Provides technical specifications and planning guidelines for EV charging infrastructure across distribution networks.
Central Pollution Control Board (CPCB)	Tracks emissions data and supports EV adoption under national clean air programs (NCAP).
Goods and Services Tax Council	Decides GST rates on EVs (reduced to 5%) and charging equipment.
Automotive Research Association of India (ARAI)	Certifies electric vehicles and components for type approval, range testing, and homologation.
National Automotive Board (NAB)	Coordinates government-industry projects, including standardization and testing protocols for EV parts.

Industry Associations and Collaborative Platforms

Organization	Contributions to E-Mobility
Society of Indian Automobile Manufacturers (SIAM)	Represents OEMs and component manufacturers; interfaces with government on EV policies and safety norms.
Confederation of Indian Industry (CII)	Runs the Indian Electric Truck Coalition (IETC); organizes industry dialogue and pilot projects for electric logistics.
Federation of Indian Chambers of Commerce & Industry (FICCI)	Hosts forums and studies to influence EV investment policies, local manufacturing, and standard frameworks.
Smart Freight Centre India	Works with logistics players and governments to accelerate zero-emission freight initiatives and sectoral roadmaps.
India Energy Storage Alliance (IESA)	Advocates for battery storage and EV supply chains; provides market intelligence and engages in capacity building.
ACMA (Auto Component Manufacturers Association)	Facilitates localization of EV components; works with OEMs to build resilient EV part supply chains.



References

1. NITI Aayog, Electric Vehicles Charging Infrastructure: Guidelines/Standards (Final), <https://www.niti.gov.in/sites/default/files/2023-05/Final-smaller-Electric-Vehicles-Charging-Infrastructure.pdf>
2. NITI Aayog, Handbook for EV Charging Infrastructure Implementation, Aug. 2021, <https://www.niti.gov.in/sites/default/files/2021-08/HandbookforEVChargingInfrastructureImplementation081221.pdf>
3. Press Information Bureau (PIB), Government of India, "Press Note.", <https://pib.gov.in/PressNoteDetails.aspx?Noteld=153264&ModuleId=3®=3&lang=1>
4. Press Information Bureau (PIB), Government of India, "Press Release.", <https://pib.gov.in/PressReleaseFramePage.aspx?PRID=2040734&utm>
5. Agora Verkehrswende, Indian EV Policy & Guidelines, 2024, https://www.agora-verkehrswende.org/fileadmin/Projekte/2024/Indian-EV-Policy-Guidelines/115_Indian_EV_Policy_Guidelines.pdf
6. [Mapping electric vehicle policy for Indian states](#)
7. Bureau of Energy Efficiency (Govt. of India) — EV Yatra portal, Central Govt Initiative — MOP 2022, <https://evyatra.beeindia.gov.in/central-govt-initiative-details/mop-2022/>
8. [BIS Standards for electric vehicle Charging](#)
9. [Charging for High Voltage EVs](#)
10. [EV Charging Standards in India](#)
11. Ministry of Power (MoP), *The revised guidelines issued by MoP.*, [The revised guidelines issued by MoP](#)
12. [India EV Digest 2023](#)
13. [Mercom India \(news/analysis\)](#)
14. [Ministry of New and Renewable Energy Renewable Watch](#)
15. Invest India (government investment promotion agency). [Invest India](#)
16. Institute for Energy Economics and Financial Analysis (IEEFA)., [IEEFA](#)
17. [NITI Aayog Udyami](#)
18. [NITI Aayog](#)
19. International Energy Agency (IEA)., [IEA](#)
20. Noar (noar.in), [noar.in](#)
21. [KPMG Assets Changing Transport](#)
22. [Changing Transport KPMG Assets](#)
23. Wikipedia, *The Free Encyclopaedia*, [Wikipedia](#)
24. [Ministry of Road Transport & Highways, Press Release, July 2020](#)
25. Transport Department, Government of Maharashtra, <https://transport.maharashtra.gov.in>
26. MahaUrja (Maharashtra energy portal), <https://www.mahaurja.com>
27. Maharashtra Electricity Regulatory Commission (MSERC), <https://mserc.gov.in>
28. Invest Tamil Nadu, <https://investingtamilnadu.com>
29. Tamil Nadu Energy Development Agency (TEDA), <https://teda.in>
30. Tamil Nadu Electricity Regulatory Commission (TNERC), <https://tnerc.tn.gov.in>
31. Invest Karnataka, <https://investkarnataka.co.in>
32. Akmak, C. Z., Hemmati, M., & Avila, A. L. 2024. *Impact of leading-edge erosion on the annual energy production of wind turbines*. Journal of Physics: Conference Series, 2767(1), 022066.
33. Chan, D., Mo, H., & Yeung, T. 2017. Wind turbine maintenance optimization under uncertainty: A review. Energy Procedia, 110, 267–272.
34. Karnataka Renewable Energy Development Limited (KREDL), <https://kredl.karnataka.gov.in>
35. Telangana State Renewable Energy Development Corporation (TSREDCO), <https://tsredco.telangana.gov.in>
36. Telangana State Renewable Energy Development Corporation (TSREDCO), <https://tsredco.telangana.gov.in>
37. Ministry of Power, Government of India, <https://powermin.gov.in>
38. Central Electricity Regulatory Commission (CERC), <https://cercind.gov.in>
39. Reserve Bank of India (RBI), <https://rbi.org.in>
40. NITI Aayog, <https://niti.gov.in>
41. Indian Renewable Energy Development Agency (IREDA), <https://ireda.in>
42. Ministry of Power, <https://powermin.gov.in>
43. State EIA Authority (Tamil Nadu) — SEIAA Tamil Nadu, <https://seiaa.tn.gov.in/en>
44. Tamil Nadu Environment Department, <https://environment.tn.gov.in>
45. *The New Indian Express*, <https://www.newindianexpress.com>
46. The Central Motor Vehicle Rules, 1989 published by MoRTH

Glossary

1. **Alternating Current (AC) Power:** A type of electrical power commonly provided through power outlets and supplied by the electricity grid, characterized by a waveform that alternates direction.
2. **Central Management System (CMS):** An advanced backend system that facilitates the exchange of real-time data between electric vehicles, their chargers, and the charge point operator.
3. **Charge Point Operator (CPO):** An entity responsible for the installation and management of charging infrastructure. A CPO may either own the charging stations or offer services on behalf of the station's owner.
4. **Charging Modes:** A European classification standard that categorizes charging based on power output, charging speed, and the communication protocols between the electric vehicle and its charging equipment. There are four distinct modes.
5. **Conductive Charging:** A charging method that involves a physical wired connection between the electric vehicle and the charging equipment.
6. **C-Rate:** A unit measuring the speed at which a battery charges or discharges. A 1 C-rate means that the battery will be completely discharged in one hour.
7. **Direct Current (DC) Power:** A type of electricity where the electric charge flows in one direction, commonly supplied by batteries, solar panels, or fuel cells, unlike AC power.
8. **Distributed Energy Resources (DER):** Locally connected electricity generation or controllable electrical loads, such as solar panels, combined heat and power systems, storage devices, electric vehicles, and appliances like air conditioners and water heaters.
9. **Distributed Energy Resources Management System (DERMS):** A platform that helps utilities manage and optimize their distributed energy resources, including electric vehicles, within the distribution network.
10. **Distribution Transformer (DT):** A device in the power distribution network that steps down the voltage from high transmission levels to lower levels for use by consumers.
11. **e-Mobility Service Provider (e-MSP):** An organization that provides charging services to electric vehicle owners, enabling them to access charging points within its network or via roaming agreements with other networks.
12. **Electric Vehicle Supply Equipment (EVSE):** A system that provides electrical power to charge electric vehicles. It includes electrical wiring, related equipment, software, and communication protocols that ensure efficient and safe energy delivery to the vehicle.
13. **EV-Roaming (e-Roaming):** A system that enables electric vehicle users to charge their vehicles at any charging station, regardless of the network it belongs to. E-roaming is facilitated by open communication protocols or proprietary roaming networks that connect various charge point operators (CPOs) and e-mobility service providers (e-MSPs) on a shared platform.
14. **Kilovolt (kV):** A unit of measurement equal to 1,000 volts, commonly used to describe the voltage in electrical transmission and distribution lines.
15. **Kilowatt (kW):** A unit of power equivalent to 1,000 watts, used to quantify the power consumed or generated by electrical devices or systems.

16. **Kilowatt-Hour (kWh):** A unit of energy equal to the consumption of one kilowatt (kW) over one hour, used to measure the energy used by an appliance or produced by a generator.
17. **Open Charge Point Interface (OCPI):** An open application protocol that facilitates communication between e-mobility service providers (eMSPs) and charge point operators (CPOs), enabling seamless integration.
18. **Open Charge Point Protocol (OCPP):** An open-source communication standard that enables interaction between electric vehicle supply equipment (EVSE) and a central management system (CMS), also known as a charging station network.
19. **Open Automated Demand Response (OpenADR):** A protocol that enables the transmission of demand response signals between power distribution utilities and electric vehicle users to manage energy consumption.
20. **Power Factor Correction (PFC):**
 - a. PFC is a technique used in electrical systems to improve the power factor (PF) by minimizing reactive power. The power factor is a measure of how efficiently electrical power is used in a system, defined as the ratio of real power (kW) to apparent power (kVA). In ideal conditions, the power factor should be 1 (or unity), indicating that all supplied power is effectively utilized. However, in real-world systems, inductive loads like motors and transformers cause the current to lag the voltage, resulting in a lower power factor. PFC aims to correct this by reducing the phase difference between voltage and current, thereby increasing the power factor closer to unity.
 - b. PFC is crucial because it significantly improves the efficiency and quality of electrical power usage. By correcting the power factor, systems can operate with reduced energy waste, lower heat generation, and increased equipment lifespan. Additionally, many utilities offer incentives for maintaining high power factors or impose penalties for low ones, making PFC economically beneficial. In applications like computer power supplies, PFC is essential for ensuring compliance with regulatory standards and reducing the environmental impact of electrical systems.
21. **Power Purchase Agreement (PPA):** A contractual agreement between a power generator (seller) and a buyer to purchase electricity at agreed-upon terms.
22. **Public Charging Station (PCS):** A public facility that provides charging services for electric vehicles, accessible to all EV users.
23. **Smart Charging:** The active, one-way management of electric vehicle charging, including the ability to adjust charging levels up or down based on demand or other factors.
24. **Thermal Management**
 - a. Thermal management refers to techniques used to dissipate heat generated by electronic power components to prevent overheating and ensure reliable operation.
25. Example:
 - a. A 120 kW AFE converter with 98% efficiency loses 2.4 kW as heat, requiring proper cooling.
 - b. Power modules with low thermal resistance improve heat dissipation.

26. Cooling Methods:

- a. Heat Sinks: Passively dissipate heat through metal fins.
- b. Forced Air Cooling: Fans increase heat dissipation efficiency Liquid Cooling: Uses coolant to remove heat, essential for high-power applications.

27. Time of Day (ToD) Tariffs: A pricing structure where electricity rates vary at different times of day, with higher prices during peak consumption periods and lower prices during off-peak times.

28. Total Harmonic Distortion (THD):

- a. THD measures the level of waveform distortion caused by harmonics in an electrical system. It is expressed as a percentage of the fundamental frequency and impacts power quality. High THD can lead to equipment overheating, reduced efficiency, and malfunctioning of sensitive devices.

29. Example:

- a. Inverters with THD > 5% can cause instability in the grid.
- b. IEEE 519 recommends THD < 5% for most applications.

30. Solution:

- a. Use passive filters (capacitor-inductor networks) or active filters to mitigate harmonics.
- b. Choose power converters with low THD output for better power quality.

31. Voltage Regulation:

- a. Voltage regulation ensures that a power converter maintains a stable output voltage despite variations in input voltage or load conditions. A well-regulated system prevents damage to electrical components and maintains efficiency.

Example:

A 48V DC power supply with $\pm 1\%$ regulation means the output voltage will stay within 47.52V to 48.48V under varying



Acknowledgements

Advisory Committee of Consultative Group on e-Mobility

S.No.	Name, Designation and Organization	Role
1	Prof. Ajay K. Sood, Principal Scientific Adviser, Government of India	Chairperson
2	Dr. Parvinder Maini, Scientific Secretary, O/o PSA	Member
3	Dr. Preeti Banzal, Adviser/Scientist 'G,' O/o PSA	Member-Secretary
4	Sh. Karthick Athmanathan, Honorary PSA Fellow and Professor of Practice, IIT Madras	Member

Working Committee of Consultative Group on e-Mobility

S.No.	Name, Designation and Organization	Role
1	Dr. Preeti Banzal, Advisor/ Scientist G, Office of PSA.	Chair
2	Prof. Karthick Athmanathan, Hon. PSA Fellow, Office of PSA.	Vice Chair
3	Dr. K. Bala Subramanian, Director, Non-Ferrous Materials Technology Development Centre (NFTDC), Hyderabad.	Member
4	Prof. Shankar Ram C S, Professor, Dept. of Engineering Design, IIT-Madras, Chennai.	Member
5	Dr. Amod C. Umarikar, Head, Centre for Electric Vehicle and Intelligent Transport Systems, IIT-Indore, Indore.	Member
6	Prof. S. A. Sundaresan, Professor of Practice, Dept. of Engineering Design, IIT Madras, Chennai.	Member
7	Dr. Shankar Venugopal, Vice President, Mahindra & Mahindra Ltd.	Member
8	Ms. Latha Chembrakalam, Vice President and Head of Technical Centre, Continental Automotive Components (India) Pvt. Ltd., Gurugram, Haryana.	Member
9	Sh. K.C. Sharma, Chief Engineer (Vehicles), Ministry of Road Transport and Highways (MoRTH), New Delhi	Member
10	Sh. Abhijit Mulay, Deputy Director, The Automotive Research Association of India (ARAI), Pune.	Member
11	Sh. Kathiresan Shanmuganathan, Chief Operating Officer, Centre of Excellence for Zero Emission Trucking (CoEZET), Indian Institute of Technology- Madras, Chennai.	Member Secretary



List of Contributors

S. No	Name, Designation and Organization
1.	Dr. Kaushal Kumar Jha, former CEO, Centre for Excellence in Energy and Telecommunications (CEET), IITM Research Park
2.	Sh. Anson Sando, former Head – Energy Programs, IITM Research Park
3.	Dr. Sivakumar Subramanian, Principal Scientist, CEET, IITM Research Park
4.	Sh. Faheera S, former Energy Analyst, Energy Programs, IITM Research Park
5.	Sh. Shubham Gupta, former Project Officer, CEET, IITM Research Park
6.	Sh. Thangamuthu N, former Project Officer, CEET, IITM Research Park
7.	Smt. Mahalakshmi, Project Associate, Energy Programs, IITM Research Park
8.	Sh. Shankar Ram C S, Principal Investigator, CoEZET, Department of Engineering Design, IIT Madras, Chennai
9.	Sh. Anuradda Ganesh, Adjunct Faculty, IIT Madras
10.	Sh. Ajithkumar T.K, former Chief Executive Officer, CoEZET, IIT Madras
11.	Sh. Prakash M, former Senior Project Officer, CoEZET, IIT Madras, Chennai
12.	Sh. Saravanan B, former Lead-Technical, CoEZET, IIT Madras
13.	Prof. S.A. Sundaresan, Professor of Practice, IIT Madras
14.	Sh. Kathiresan Shanmuganathan, Chief Operating Officer, CoEZET, IIT Madras
15.	Sh. Ravi M, Lead-Regulations, CoEZET, IIT Madras
16.	Sh. Pugalarasan M, Project Officer – Market Facing Projects, CoEZET, IIT Madras



भारत सरकार के प्रधान वैज्ञानिक सलाहकार का कार्यालय
Office of the Principal Scientific Adviser
to the Government of India



www.psa.gov.in

Office of the Principal Scientific Adviser to the Government of India
3rd Floor, Kartavya Bhavan - 3, Janpath
New Delhi – 110001

Phone: 011 24011871



/prinsciadvoff/



@ PrinSciAdvOff



/PrinSciAdvOff



/PrinSciAdvOff

