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Techno-Economic and Sustainable Challenges for EV Adoption in India: Analysis of the Impact of EV Usage Patterns and Policy Recommendations for Facilitating Seamless Integration

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ABSTRACT

The growing interest in EVs as a sustainable transportation option is evident, but hurdles like battery technology limitations, charging infrastructure, range anxiety, and manufacturing sustainability persist. However, the research community is attempting to actively address these barriers with innovative solutions. This paper explores the intricate challenges that are impeding the widespread adoption of Electric Vehicles (EVs) and explores the concerted efforts of the research community towards addressing these obstacles. The challenges addressed are classified as technical, economical, and sustainable for in-depth analysis and the literature that throws light on the direction in which the research is carried out to tackle each challenge is compiled. Also, an analysis is conducted to evaluate the economic viability of EVs based on daily range considerations. From the analysis, it is observed that the customers with higher daily commuting distances are likely to benefit from EV adoption and this distance will have a huge impact on savings over a period of 5 years as high as INR 0.67 million for a daily commuting distance of 100 km. Furthermore, as part of initiatives and plans for accelerating EV adoption in India, policies that are aimed at establishing a harmonious and balanced EV ecosystem are discussed in detail. Overall, the paper sheds light on the evolving pathway towards a future where EVs can thrive as a mainstream mode of transportation.

Keywords

Electric Vehicles;
EV Charging Station;
Range anxiety;
Second Life Batteries;
Battery Swapping Station;
Renewable energy;
FAME

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1. Introduction

International organizations acknowledge the urgency of combating climate change [1], leading to global efforts, stringent policies, and ambitious carbon neutrality targets. As governments and industries unite in their commitment to combat climate change, the transition to Electric Vehicles (EVs) emerges as a pivotal step towards achieving sustainable and environmentally responsible transportation systems. The evolutionary path of EVs [2] has been truly remarkable since its inception. It was during the early 20th century that EVs garnered some recognition with the advent of improved battery technology and the introduction of Electric Taxis and delivery vehicles in urban centers. However, it was the environmental concerns and energy crises during the late 20th century that revitalized interest in EVs. Since 2017, EV sales have rapidly

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surged, exceeding 1% of the market, and have accelerated further since 2020. The COVID-19 pandemic heightened environmental consciousness [3], driving interest in sustainable transportation. As such in 2022, global car sales [4] slightly rose to 67.2 million, with EVs accounting for about 14% of passenger car sales, a 5.3% increase from the previous year. Governments worldwide are supporting EV adoption, with about 97% of the light-duty vehicle market implementing related initiatives. Global automakers have invested in research and development thus propelling EV technology. However, challenges like limited charging infrastructure and high costs persist, prompting researchers to seek solutions for a sustainable EV future.

1.1 EV Adoption in India and Penetration Targets

As per the India Energy Storage Alliance (IESA), the Indian automobile industry [5] is expected to expand at a compound annual growth rate of 36% and become the third-largest industry by 2030. With the escalating population and increasing vehicular demand, relying on conventional energy sources is not a viable option for India and demands an accelerated rate of EV adoption. The evolution of the EV market in India is driven by a commitment to the Paris Agreement and the penetration rate has grown over the years. The share of EVs [6] against the total vehicle sales was 5% (out of which two-wheelers (2W) – 85% to 90%, 4W – 7% to 9%, and three-wheelers (3W) – 5% to 7%) during the period between October 2022 and September 2023. The latest revision of the 'Faster Adoption and Manufacturing of Electric Vehicles' (FAME) scheme resulted in increased penetration of 3W and 4W EVs. A total of 1,529,706 EVs were sold during the year 2023. Figure 1a) gives an overview of category-wise sales of EVs during the year 2023. Figure 1b) and Figure 1c) provide a summary of fuel-wise sales trends and percentage of penetration of 2W and 3W respectively and Figure 1d) shows the EV sales share of various countries.

EV sales flourished mainly in Metro and Tier 1 cities. The reason for the lack of popularity in Tier 2 cities is a lack of awareness of environmental issues

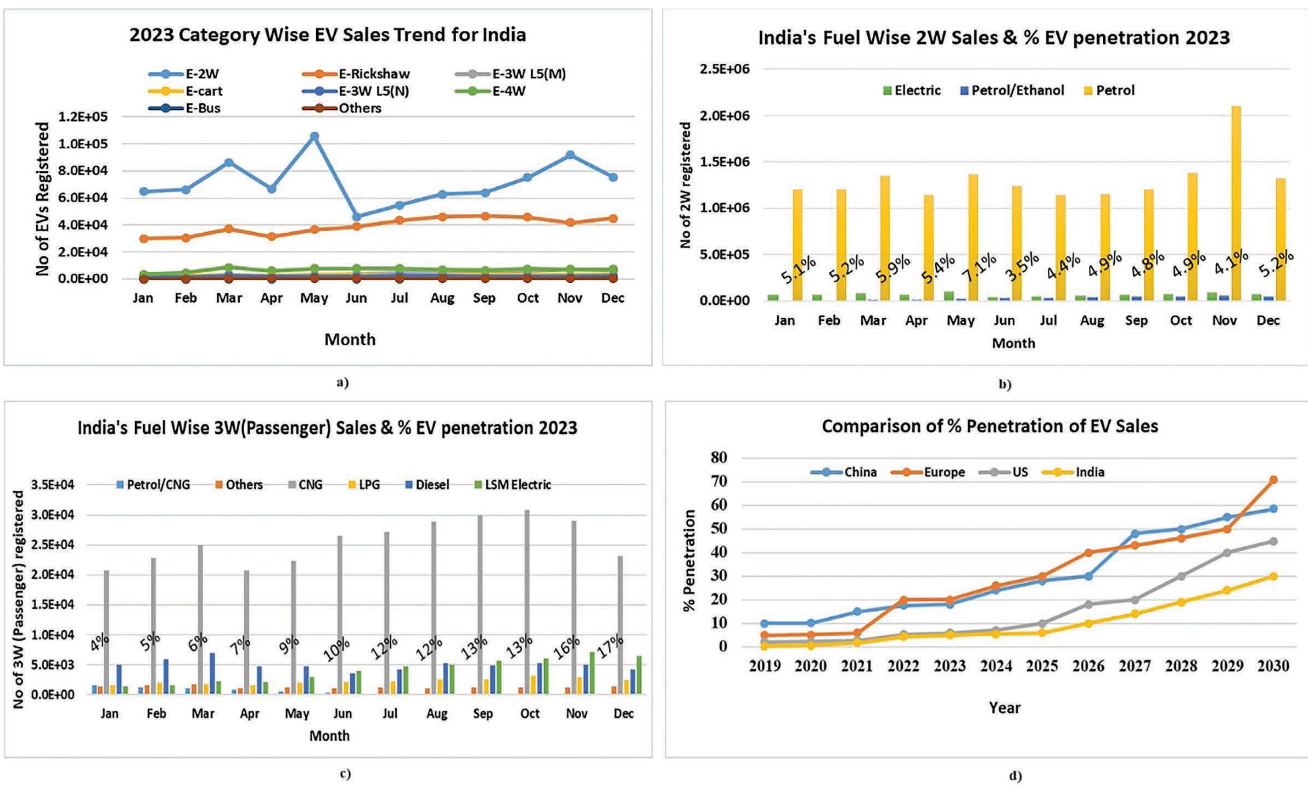


Figure 1: a) Category wise EV sales 2023 b) Fuel wise 2W Sales trend & EV penetration c) Fuel wise3W (Passenger) Sales trend & EV penetration d) Comparison of EV penetration of various countries (Based on data from [6])

such as global warming, climate change, high cost of vehicles, range anxiety, etc. The following data [7] gives an overview of the most popular EVs among Indian customers: The Tata Tiago EV (INR 0.87 million) leads EV sales in Q2 2023, comprising 40% of total EV sales at 10,695 units. Following closely is the Tata Nexon EV (INR 1.5 million), securing the second position with 5,072 units sold (19% of passenger EV sales). The third spot goes to the Tata Tigor EV (INR 1.25 million), selling 3,257 units and constituting 12% of passenger EV sales. Mahindra's XUV400 (INR 1.59 million) occupies the fourth position, contributing 8% to passenger EV sales with 2,234 units sold. MG's Comet EV (INR 0.79 million) takes the fifth spot, selling 1,914 units and accounting for just over 7% of passenger EV sales in Q2, 2023. NITI Ayog targets EV sales penetration [8] of 70% for all commercial cars, 30% for private cars, 40% for buses, and 80% for 2W and 3W by 2030. This goal aligns with the broader perspective of net zero carbon emissions by 2070.

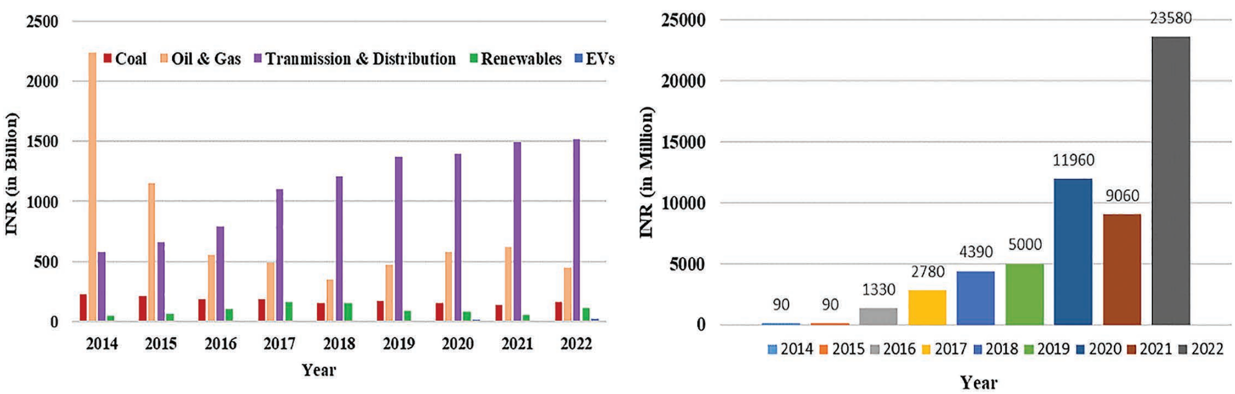
1.2 Policy Initiatives for accelerating EV adoption in India

The Indian government [9] has implemented numerous initiatives to promote EV adoption in India which are explained as follows:

1. The FAME-II: To provide demand incentives that result in a reduced upfront purchase price for customers.
2. Production Linked Incentive (PLI) Scheme (2021) for the automotive sector: To foster domestic manufacturing of advanced automotive technology products and attract investments in the automotive manufacturing value chain.
3. PLI Scheme for the National Program on Advanced Chemistry Cell (ACC) Battery Storage: To enhance India's manufacturing capabilities for ACC production.
4. State-wise EV policies: Several states have introduced policies like reduction of road tax and other incentives.
5. The Ministry of Power issued that charging an EV is classified as a service and that no license is required for this business activity.
6. Other measures like customs duty exemption on machinery for Li-ion cell production, reducing GST on EVs, chargers from 12% to 5% and 18% to 5%, respectively, green license plates, road tax waiver, 22,000 EV charging stations by oil marketing companies, revised guidelines for private players.

1.3 Status of Government Subsidies

India's subsidies for renewable energy and EVs have increased over the years but it will be critical for the government to build this momentum over the coming years to reach the targets. The government of India [10] has used subsidies to support different types of energy as illustrated in Figure 2. It is observed that in 2022, India allocated four times more support to fossil fuels than clean energy, although the gap narrowed significantly since 2021 when the support was nine times greater. The government ought to contemplate reallocating subsidies from fossil fuels to clean energy to achieve the ambitious targets.



a) b)

Figure 2: a) Comparison of subsidies for different categories b) Subsidy of EVs (Based on data from [10])

1.4 Article Contribution and Paper Organisation

Despite concerted efforts and initiatives, the pace of EV adoption remains stagnant, facing various challenges. It is imperative to address these obstacles, and the research community must contribute to pave the way for a more promising future in EV adoption. [11] discusses the barriers and problems of EV adoption in the Indian context in detail. In [12] the authors comprehensively examine the various aspects of EVs, including their types, utilized technology, advantages in comparison to the ICE vehicles, the sales trends in recent years, diverse charging modes, and potential future technologies. Around thirteen obstacles to the widespread adoption of EVs were identified in [13] and these were studied in terms of their interrelationships, with the aim of modeling and understanding the dynamics among them. [14] summarizes the advantages of EVs and barriers to their popularization. In [15] the authors provide the decision-makers with a structured framework that empowers them to focus their efforts on addressing high-priority barriers or sub-barriers, thereby directing resources for effective resolution. In [16] research on user attitudes and their willingness to accept new technologies was conducted to develop comprehensive methods to encourage EV adoption.

Existing papers mainly focus on understanding and explaining these challenges individually. The existing gap is centered around consolidating works pertinent to each individual barrier, a consolidation that can provide aspiring researchers with valuable insights for potential contributions. Recognizing proactive research strategies initiated by the research community is crucial for situational awareness and inspiring our contributions to advance these efforts. This paper aims to address EV adoption obstacles and discuss technical, economic, and sustainable solutions. It analyzes each challenge, highlights research approaches, and proposes solutions. Moreover, a conscientious venture has been undertaken to assess the cost-effectiveness of integrating EVs into usage. This assessment considers a spectrum of elements, including depreciation, operational outlays, and maintenance expenditures, rather than confining the evaluation solely to operational expenses. Furthermore, the investigation delves into the reverberations of escalated EV adoption, scrutinizing the consequences of investing in the charging of EVs from the grid on the overall financial landscape.

The overall structure of the paper is as follows: Section 2 gives an overview of the various technical challenges associated with EVs. Section 3 explains the economic challenges associated with EVs. Section 4 gives a brief of the various sustainability challenges associated with EVs. Section 5 makes a cost analysis for EV operation. Section 6 proposes policies to address the challenges concerning limited infrastructure for EV charging and the issue of grid overloading due to EV Charging. Section 7 concludes the discussion.

2. Technical Challenges hindering EV adoption

EVs face technical challenges, including long charging times, short battery lifespan, limited range, and inadequate charging infrastructure which are highlighted below along with the concurrent endeavors of researchers in quest of viable solutions.

2.1. Prolonged charging time

EVs offer various charging [17] methods: Level 1 (120V) for slow overnight charging, Level 2 (240V) for faster daily charging, and Level 3 (fast charging, 480V or higher) for quick charging, although still slower than ICE vehicles. Table 1 gives an insight into the charging times (from 20% to 80% SoC) for some of the popular EVs.

Extended EV charging times disrupt plans and worsen congestion with limited high-speed charging access. Swift reduction in charging durations is very crucial for the widespread adoption of EVs. Various research papers in the literature offer insights into the development of technologies, strategies, and optimization models to

Table 1: Charging duration for some popular EVs [18].

Car Model	Battery Capacity (kWh)	Time (hr)		
		Level 1	Level 2	Level 3
Tesla Model 3	75	28	8	0.5
Volkswagen ID.4	77	50	7	0.5
Nissan Leaf	40	20	8	0.67
Hyundai Kona Electric	64	9.25	9	0.83
Kia EV6	77.4	34	7	0.3
Ford Mustang Mach-E	75	7.5	5.5	0.75
Audi-e Tron	95	15	8.5	0.5
BMW i4	81.5	11	7	0.5
Mercedes-Benz EQS	107.8	18	11	0.36
Tiago EV	19.2	6	4	1

reduce EV charging time. Figure 3 outlines the research areas addressing the challenges related to longer EV charging duration. To address the extended charging time of EV batteries, several research avenues are explored:

a) Efforts focus on developing next-generation battery technologies with improved energy density, faster charging capabilities, and longer cycle life [19],[20],[21]. The research also focuses on cell design (electrodes and electrolytes), charging profile, and influence of temperature [22]. b) Thermal management systems can prevent overheating during fast charging, enabling higher charging rates without compromising battery life [23],[24]. c) Wireless charging technologies can simplify the charging process, potentially reducing the time required to plug in [25],[26],[27]. d) Advanced algorithms are created for quick and effective charging that take into consideration variables like battery temperature, SoC, and cell balance [28],[29],[30]. e) Machine learning algorithms and predictive analytics may be employed to optimize the charging schedules based on user behavior, grid demand, and battery conditions. f) Charging times [31],[32] can be significantly decreased with the development and implementation of fast-charging infrastructure.

Battery Swapping Station (BSS) is an emerging concept [33] in the EV ecosystem, wherein the depleted batteries are swapped with fully charged ones instantly, thus avoiding long waiting times. However, its successful implementation [34] needs substantial infrastructure investments, standardized batteries, and manufacturer-service provider coordination. a) Research may focus on developing standardized battery designs [35] and interfaces to guarantee interoperability among various EV models making it universally applicable. b) Exploration of real-time monitoring systems for evaluating battery health and performance [36], along with developing strategies for prolonging the overall lifecycle of batteries deployed in the stations. c) Advanced automated systems [37] for BSS may be developed to enhance efficiency, reduce downtime, and minimize the need for manual intervention. d) Research on integrating BSS with smart grids [38] and RES may be conducted to optimize the sustainability of the system. e) Proper economic viability analysis [39] and environmental impact analysis need to be performed before its widespread adoption.

2.2. Life span of batteries

EV batteries face inevitable degradation and limited lifespan due to factors like high temperatures, overcharging, charging immediately after driving, and fast charging [40]. This leads to a reduced range, more frequent recharging, and eventually costly battery replacement. Ongoing research is crucial to overcome this longevity issue. Figure 4 delineates the research domains aimed at addressing the issue of limited battery life in EVs. Several research directions are investigated to overcome this issue: a) Research may focus on implementing effective Battery management systems and Thermal management systems [41],[42] for optimal control and temperature regulation. b) There is a need to study the impact of fast charging on battery degradation [43],[44],[45] and develop strategies to mitigate its effects. c) Battery health may be predicted using ML and predictive analytics [46],[47],[48] based on

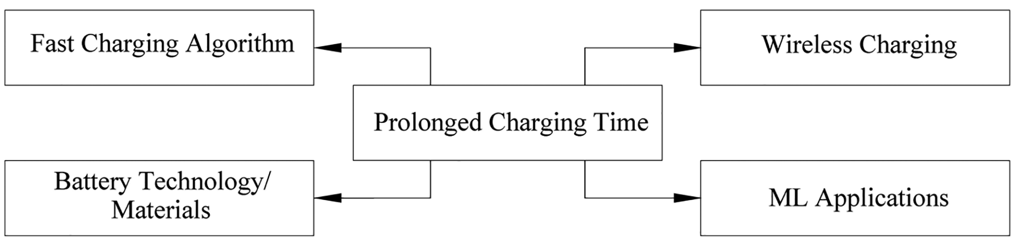


Figure 3: Areas of research to tackle charging time issues of EVs

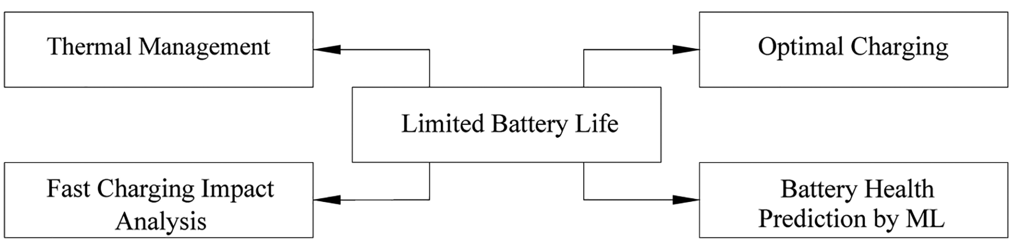


Figure 4: Areas of research to tackle Limited battery life of EVs

consumption trends, ambient factors, and charging habits, enabling proactive maintenance and optimization. d) To reduce battery stress, research may concentrate on smart charging strategies [49],[50] that take grid conditions, off-peak charging, and ideal charging rates into account.

Research also aims to assess battery condition and its feasibility for secondary applications [51] like energy storage for homes, businesses, and renewable energy facilities, to extend their overall lifecycle. In [52] numerous projects and research works were examined to gain insights into the current state of the art regarding Second Life Batteries. [53] focuses on examining the environmental advantages associated with the End-of-Life (EoL) stage of lithium iron phosphate (LFP) batteries.

2.3. Limited Range of EVs

Another notable drawback of EVs is their limited driving range, which refers to the maximal travel distance of an EV on a single charge and this can trigger range anxiety among EV owners mainly for long distances [54]. Table 2 gives some of the popular models and their ranges.

Figure 5 illustrates the continued efforts of the researchers aimed at addressing the restricted range of EVs. The following are the research priority areas: a) There is a need to develop an extensive charging infrastructure network to alleviate range anxiety [56] and promote long-distance travel. b) Research on wireless charging technologies [57] to enhance the convenience of EV owners c) Develop advanced models using ML algorithms [58],[59] to predict driving range based on factors such as driving patterns, weather conditions, etc. d) Explore algorithms for smart route planning [60] that optimize driving routes for maximum range by considering the elevation variations, real-time traffic, and the availability of charging stations. e) Improve the EV components [61] to extend the range. Some of the other innovative areas include that of improving driver tolerance [62], blockchain [63] based power trading, PV [64] based charging of moving EVs, etc.

2.4. Lack of adequate EV charging station infrastructure

Surging EV popularity highlights the demand for accessible charging stations. Lack of infrastructure induces range anxiety, hindering urban EV adoption, especially during extended trips. Strategic investment and collaboration are vital for a widespread charging network. Figure 6 illustrates the research focus areas aimed at tackling the limited charging infrastructure.

Table 2: Some popular EV models and their ranges [55].

Model Name	Range (km)	Battery (kWh)
Tesla Model 3	428	75
Volkswagen ID.4	402	77
Nissan Leaf	240	40
Hyundai Kona Electric	415	64
Kia EV6	385-500	77.4
Ford Mustang Mach-E	370	75
Audi-e Tron	357	95
BMW i4	394	81.5
Mercedes-Benz EQS	563	107.8
Tiago EV	250	19.2

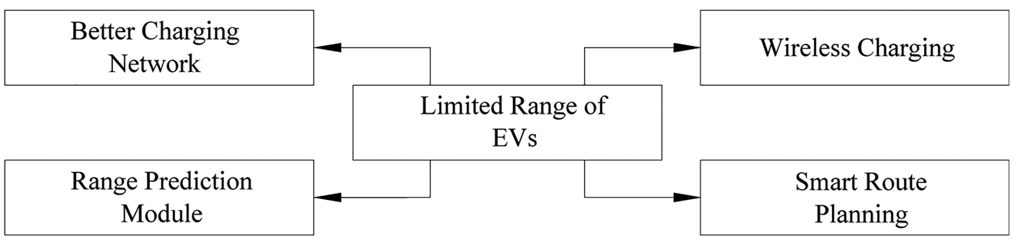


Figure 5: Areas of research to tackle Limited Range of EVs

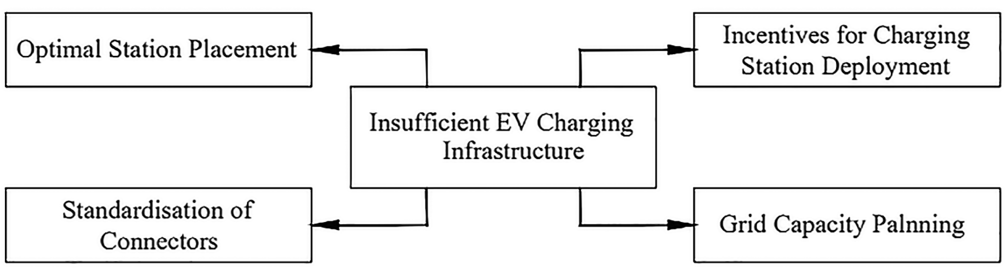


Figure 6: Areas of research to tackle limited charging infrastructure

Various research directions focusing on methodologies for expanding the charging network are: a) Research on finding optimal locations [65],[66] for charging stations based on traffic patterns, urban planning, and travel routes. b) As EV charging infrastructure expands, analyze and prepare for the increased demand [67],[68] on the grid, and also explore the possibilities of RES integration. c) Charging station and EV model interoperability [69] may be encouraged by pushing for standardization of charging connectors, which will streamline the user experience. d) Investigate regulations and rewards that incentivize companies and institutions to allocate funds for the installation of charging stations [70]. The Indian government's FAME initiative promotes electric mobility, incentivizing [71] the nationwide establishment of slow and fast charging stations.

According to the [72] Bureau of Energy Efficiency (BEE), India has 6,586 EV charging stations as shown in Figure 7, out of that 419 functioning on national highways as of March 21, 2023. Phase II of the FAME-India Scheme allocates INR 10,000 million for charging infrastructure, approving 2,877 stations in 68 cities across 25 states/Union Territories and 1,576 stations on 9 Expressways and 16 highways. This approach aims to promote India's electric mobility transition, reinforcing commitment to sustainable transportation and EV market growth. Servotech EV Infra, Tata Power EZ Charge, Charge Zone, Magenta ChargeGrid, Blusmart, Zeon Charging, PlugNgo, Ather Energy, Charzer are some of the Charge Point Operators that play pivotal roles in establishing and managing EV charging stations.

3. Economic Challenges hindering EV adoption

This section discusses economic challenges in EV adoption, including high purchase costs and the lack of specialized workshops. It also explores ongoing efforts to address these challenges.

3.1. High Purchase Cost of EVs

Despite incentives [73] which include subsidies, tax credits, and local manufacturing promotion, the elevated purchase cost of EVs [74] due to expensive batteries and limited economies of scale remains a significant drawback. This discourages potential buyers thus hindering broader adoption in spite of the long-term savings.

Figure 8 gives an overview of the areas of research to overcome the high cost of EVs. The literature provides insights into the development of strategies, optimization techniques, and cost analysis models [75] to reduce the manufacturing cost of EVs: a) Investigate methods to reduce the cost of manufacturing [76] and materials for the batteries. b) Cost savings [77] can be derived by implementing advanced manufacturing technologies [78] and increasing the scale of production. c) Explore

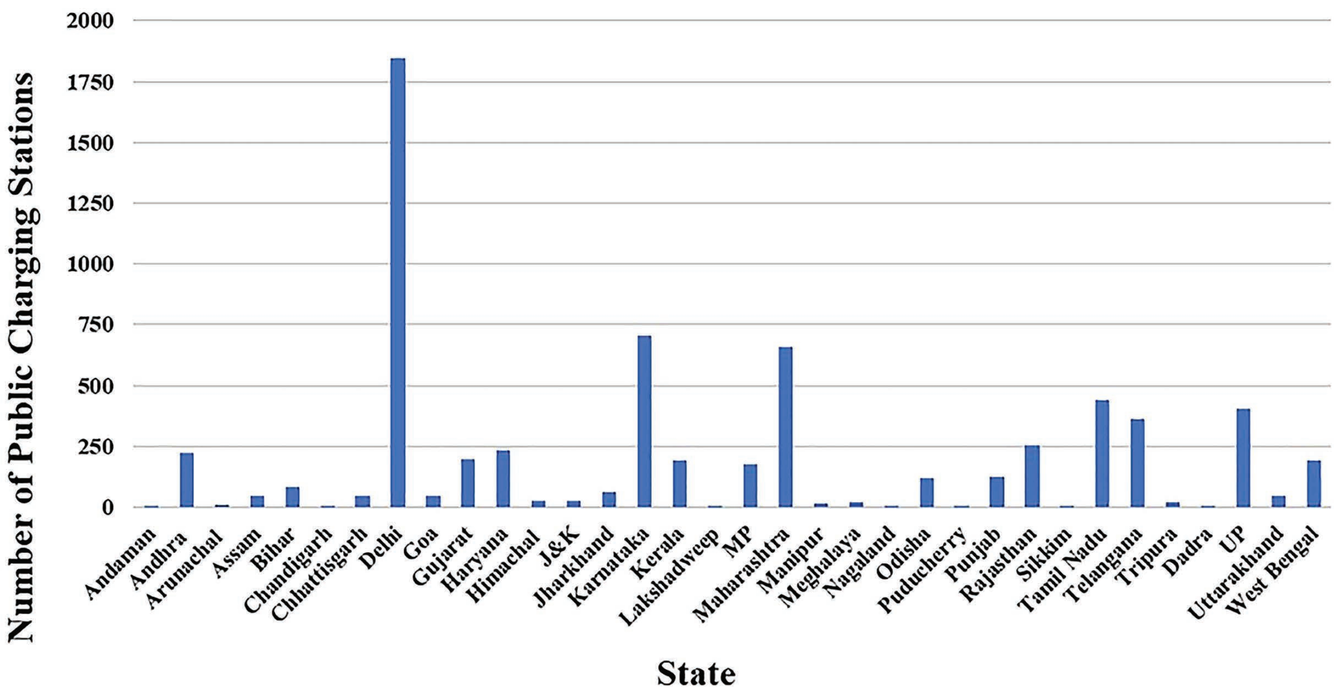


Figure 7: Distribution of Public Charging Stations in India (Based on data from [72])

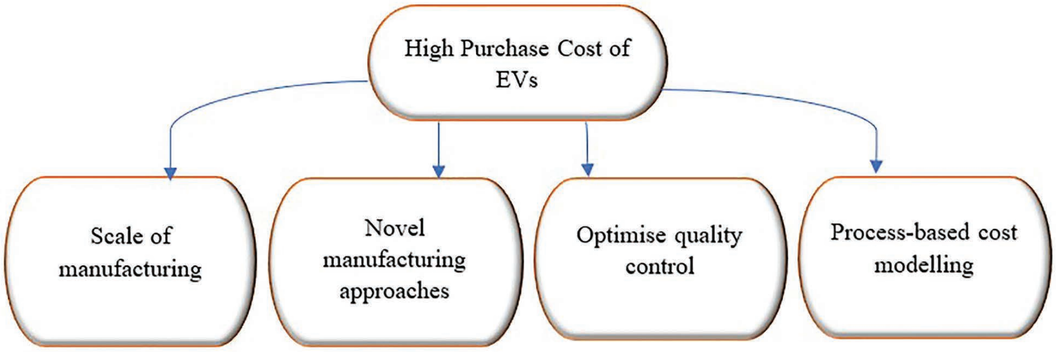


Figure 8: Areas of research to tackle the high cost of EVs

approaches to stimulate the expansion of the used EV market [79], enhancing accessibility for a wider consumer base through the provision of affordable options.
d) Encourage research into innovative technologies [80] that can bring down the costs of critical components, such as electric motors, inverters, and power electronics.
e) Utilize machine learning algorithms [81] to analyze large datasets and optimize the design of battery components.

3.1.1 Consumer attitude towards EV cost

India is ready to embrace EVs [82], with 70% of tier-one Indian car consumers indicating their willingness to consider an EV for their next vehicle as compared to the record-high global average of 52%. However, there is a disparity in the adoption of EVs across income levels which can be attributed to the prevalence of luxury EV models. As the EV market grows, particularly in the used vehicle segment, it is expected that EVs will become more appealing to lower-income households. Also, the rising purchasing power of consumers in India is likely to drive the EV market in the future.

The majority of EV users are men who own numerous vehicles, are well-educated, earn a high income, and have access to charging at home. Low-income households, often lacking home charging and facing budget constraints, also have limited access to workplace charging due to irregular employment. EV incentives lack equity [83], often received post-purchase and favoring higher-income buyers. Charging infrastructure is unevenly distributed, requiring affordable options in lower-income residential areas. Research and policy should take into account how to create a more equitable EV market. This will ensure that everyone benefits from electrification and that low-income households are not burdened with higher transportation costs.

3.1.2 Scope and Future of Domestic Manufacturing

To expedite EV adoption [84], India should focus on a localized supply chain and innovate specific components. Dependence on China for 60%-70% of key EV parts, like lithium-ion battery cells and e-motor magnets, highlights the urgency of reducing reliance. While battery cells may be imported in the short to medium term, accelerating domestic production for other components is crucial to address supply chain vulnerabilities. Some of the major players in the Indian EV market with manufacturing facilities are a) Greaves Electric Mobility Private Limited (Tamil Nadu) b) Ather Energy Private Limited (Karnataka and Tamil Nadu) c) ATUL Auto Limited (Gujarat) d) Bajaj Auto Limited (Maharashtra, Uttaranchal and Maharashtra d) Electrotherm (India) Limited (Gujarat), Hero Electric Vehicles Pvt. Ltd (Punjab and Madhya Pradesh), Hyundai Motor India Ltd (Tamil Nadu and Maharashtra), Mahindra & Mahindra Limited (Maharshtra and Telangana), MG Motor India Private Limited (Gujarat), Okinawa Autotech International Private Limited (Rajasthan), Olectra Greentech Limited (Telengana), Tata Motors Ltd. (Gujarat), TVS Motor Company (Tamil Nadu).

To encourage domestic manufacturing the Central Government is considering the prospect of providing businesses like Tesla with a one-time import duty break on fully completed units. In addition, the government wants to create a legal framework for car makers that use cutting-edge technology, which would require local sourcing.

3.2. Maintenace cost and Dearth of EV-specific workshops

The maintenance costs associated with EVs are low which can be attributed to reasons like simplified mechanical structure, longer lifespan of certain components, regenerative braking which extends the life of brake components, easy software updates to enhance performance, etc [85]. However, the possible costs of battery replacement can be a game changer. Furthermore, these costs might fluctuate between EV models and manufacturers, and an overall assessment of cost-effectiveness is dependent on a variety of factors, including driving patterns, charging habits, and local weather.

Limited specialized EV workshops, crucial for prompt and skilled repairs, hinder its widespread adoption [86] by causing delays, restricting technician access, and resulting in higher costs. Expanding the network of EV-specific workshops is crucial to promote EV adoption. CarZ, ev. care, Mahindra First Choice Services, Pitstop, MyTVS, Bosch Car service, Carnation Auto, 3M Car Care, GreenDrive Auto Solutions, Ampere Electric are some of the EV service, repair, and maintenance companies in India. The National Mission for Transformative Mobility and Battery Storage was founded by the Indian government to provide businesses with assistance by enabling access to technological know-how and fostering an environment that is conducive to the advancement of electric car battery technology.

4. Sustainability Challenges hindering EV adoption

Although the widespread adoption of EVs is considered a transformative solution addressing key sustainability challenges is crucial to unlock its potential and accelerate broad adoption [87]. This section explores the various challenges such as questions on the sustainability of EVs and pollution due to EV tyres.

4.1. Question on the sustainability of EVs

EV sustainability depends on factors like electricity source, battery production, and disposal. Fossil fuel-derived electricity [88] diminishes the environmental benefits associated with EVs. Battery materials extraction and disposal of retired batteries have adverse impacts on the environment.

4.1.1 Charging EVs with Non-Green Electricity

In the current Indian context, a substantial share of electricity generation relies on fossil fuel-based sources. Adopting a substantial number of EVs would increase reliance on non-renewable energy thus contradicting its underlying principles of green initiatives thus necessitating proper planning in this regard [89]. An overview of the status of the Indian National Electric grid with the breakdown of various [90] sources (Figure 9) is given:

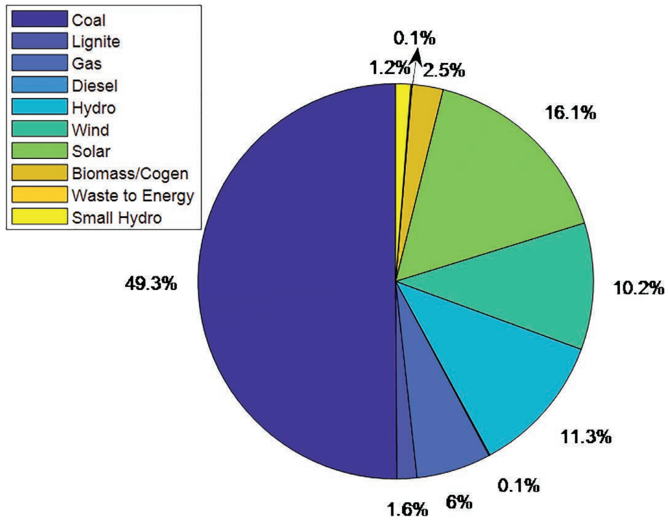


Figure 9: Break down of sources of Electricity in India 2023 (Based on data from [90])

As of March 31, 2023, the grid had an installed capacity of 416.0 GW. India aims to install 275,000 MW of renewable energy capacity by 2027. Adapting existing coal and gas power plants to be flexible is crucial to accommodate variable renewable energy, emphasizing the need for capabilities like ramping up, ramping down, warm start-up, and hot start-up.

The share of non-fossil fuel in the total electricity production during the year 2022-23 was 25.44%. The share of non-fossil-based capacity is expected to rise to 57.4% by the end of 2026–2027 and is expected to further increase to 68.4% by the end of 2031-32, according to the National Electricity Plan [91] (Generation Volume I) Gazette, which was notified in May 2023. By 2030, India aims for half of its electric power capacity to be from non-fossil fuel sources, aligning with the revised Nationally Determined Contribution (NDC) submitted to the United Nations Framework Convention on Climate Change (UNFCCC). The Ministry of New and Renewable Energy [92] targets 500 GW of non-fossil energy capacity by 2030, with 176.49 GW deployed, 51.43 GW in bidding, and 88.81 GW in implementation as of June 30, 2023.

Figure 10 gives an overview [93] of the various initiatives taken by the government to boost Renewable Energy adoption in India. Some of the other measures taken are a) waiver of Inter-State Transmission System (ISTS) charges for inter-state sale of solar and wind power for projects to be commissioned by 30th June 2025, laying of new

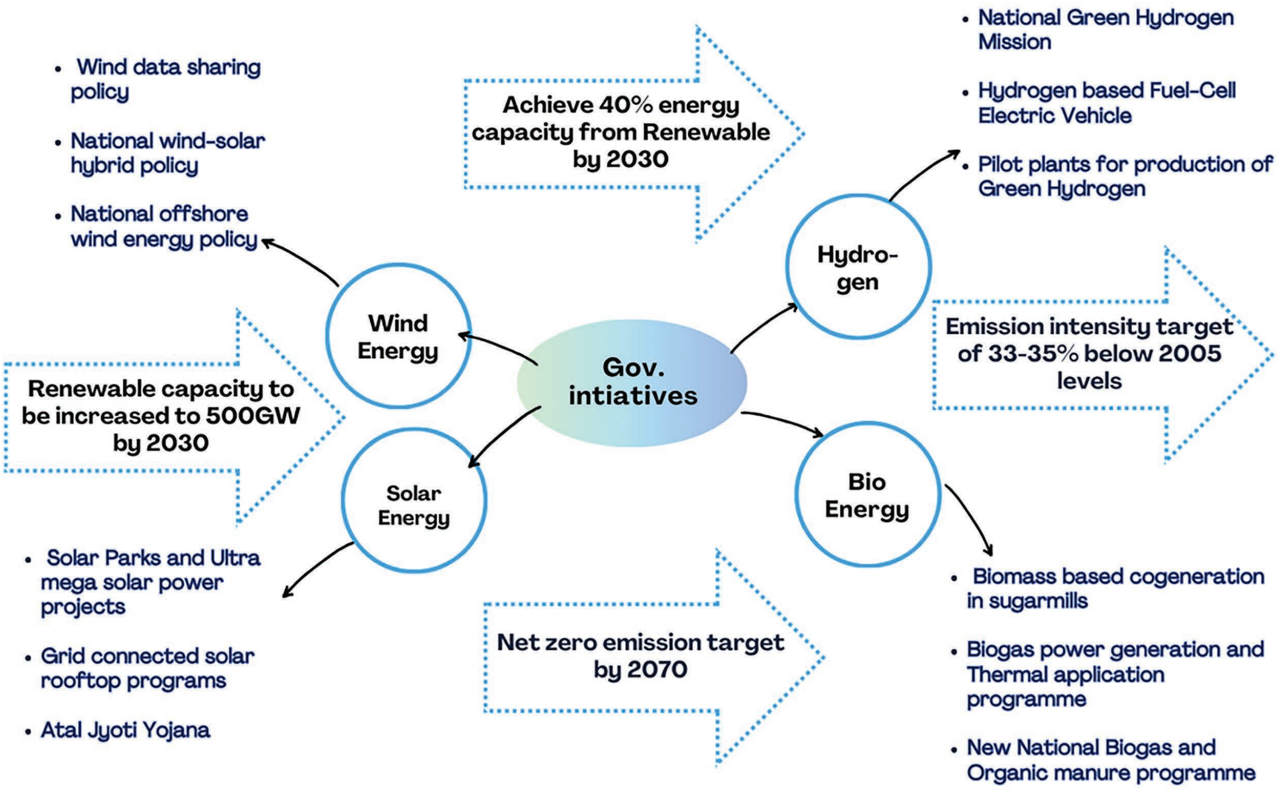


Figure 10: Government initiatives to boost Renewable Energy adoption in India (Based on data from [93])

transmission lines, and creating new sub-station capacity under the Green Energy Corridor Scheme for evacuation of renewable power b) the launch of Green Term Ahead Market (GTAM) to facilitate sale of Renewable Energy Power through exchanges c) schemes such as Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM) and 12000 MW CPSU Scheme Phase II d) setting up of Ultra Mega Renewable Energy Parks to provide land and transmission to RE developers for installation of RE projects at large scale etc.

The research community [94],[95],[96] also has been addressing various aspects of sustainability in the form of various ecological and lifecycle assessments. Prioritizing renewable energy [97], efficient battery recycling, and infrastructure improvements are vital for EV sustainability. Proper economic analysis [98] is also needed for large-scale renewable integration.

4.1.2 Scrappage of EV batteries

Disposing of retired EV batteries raises environmental concerns [99]. In India approximately 90% of discarded batteries, including non-lithium-ion types like lead-acid, are handled by informal sectors or end up in landfills, posing significant environmental and human risks that call for innovative battery recycling solutions. The slow progress in this sector is attributed to the lack of a centralized initiative by authorized bodies.

The charge-holding capacity of EV batteries diminishes at a rate of approximately 2.3% each year, typically resulting in an effectiveness of only 85-90% by the end of the vehicles' 5–8-year life cycle. In the context [100] of carbon neutrality there is a need to emphasize the importance of battery recycling due to the following reasons:

1. The batteries heavily utilize lithium, nickel, cobalt, graphite, manganese, and copper. Disposal in landfills poses a risk of soil and groundwater contamination, leading to broad environmental impacts.
2. Critical for rechargeable batteries, India lacks sufficient domestic production of lithium and cobalt, relying on expensive imports. Recovering lithium from used batteries is seen as a prudent solution until new deposits in Jammu and Kashmir become commercially viable.

3. Used EV batteries can be reconditioned for energy storage thus optimizing second-life applications.
4. Battery recycling can potentially reduce carbon emissions from production cycles by up to 90%.

The Indian government introduced draft regulations in August 2022 known as the Battery Waste Management Rules that focus on recycling Li-ion batteries from EVs, mandate Extended Producer Responsibility (EPR) for battery manufacturers with penalties for non-compliance, and aim for a minimum of 90% material recovery by 2027. Additionally, the regulations mandate 5% recycled materials in new batteries by 2027, increasing to 20% by 2030-31. The following measures need to be taken:

1. Central and state governments collaborate to collect used batteries in major cities.
2. Certifications for authorized agencies, along with capacity building, ensure the collection, storage, transportation, and recycling of all EV batteries adhere to international safety and quality standards.
3. EV owners, dealerships, and potential buyers must be educated that, like lead-acid batteries, li-ion units should be returned to manufacturers.

Establishing this chain will involve regular checks to ensure compliance with targets, preventing used batteries from ending up in landfills. India currently has just a few players that recycle Li ion batteries: Exigo (Haryana), Attero (Uttarakhand), Ziptrax (New Delhi), Lohum (Uttar Pradesh), Batx (Uttar Pradesh), TATA Chemicals (Maharashtra), Eco Tantra (Maharashtra) and LICO Materials (Maharashtra).

4.2. Pollution due to EV tyres

Although EVs claim environmental benefits tyre abrasion releases microplastics [101], harming ecosystems and human health, contaminating waterways, and causing atmospheric pollution. EVs are heavier, demanding robust tyres for their unique needs. For instance, Volkswagen's e-Golf differs by around 400 kilograms from the gasoline-powered Golf VII. This imposes extra strain on the vehicle's tyres, emphasizing the necessity for more robust tyre options. Furthermore, EVs often produce greater torque so the tyres must be capable of swiftly transferring this augmented power to the road. As addressing this issue is crucial tyre manufacturers are working on solutions, including specialized tyres for EVs.

5. Comparative Operating Cost Analysis of EVs

While it is acknowledged that the price of an EV, in comparison to a conventional ICE vehicle with analogous specifications, tends to be higher, a thorough evaluation is necessary to ascertain the viability of the additional investment. In the following analysis, a comprehensive comparison is conducted between the Tiago EV XE and the Tiago XE models, examining their respective features, specifications, and associated costs. Tiago EV is the most widely used and preferred choice of customers in India. Since its launch it has achieved remarkable milestones, evolving into the 'Fastest Booked EV in India' and swiftly reaching the landmark of 10,000 deliveries, making it the fastest EV in the country to achieve this feat. The analysis is conducted to establish a comparison regarding the economic rationale for customers to opt for EVs. Table 3 shows the various parameters for the two variants.

The Tiago Petrol gives an average mileage of 19 kmpl. To cover a distance of 60 km which an average person makes daily for commuting, the car would need 3.15 litres of petrol. With the price of Petrol being taken as INR 110 per litre, it would cost INR 347.36 to cover the distance. The Tiago EV with a battery pack 19.2 kWh and a range 315 km would need 3.65 units of power to cover a distance of 60 km. Taking the tariff rate as INR 8.5, it would cost around INR 31.08 to cover the same distance which is around 1/11th the cost incurred for the ICE counterpart.

In discussions on EVs, much attention is often directed towards their lower operational costs. Nevertheless, for a comprehensive assessment, it is imperative to consider both the initial capital outlay and the ongoing

Table 3: Comparison of specifications of Electrical and Petrol variants of a model [102].

Feature	Tiago EV XE	Tiago XE
Engine	Electric	1.2L petrol
Power	85 kW	63 kW
Torque	250 Nm	113 Nm
Transmission	Automatic	Manual
Top speed	120 kmph	108 kmph
Driving range	250 km	379 km
Price	INR 0.869 million	INR 0.560 million

maintenance expenses as well. The various associated costs for a vehicle are a) Capital Cost b) Operational Cost c) Maintenance Cost. Initial EV purchase prices are higher due to battery costs, but operational expenses are lower with cheaper electricity. EVs have fewer moving parts, resulting in reduced maintenance costs compared to ICE vehicles with more complex components, regular oil changes, and higher maintenance needs.

For ease of calculation, the straight-line depreciation method is used to allocate the cost of the vehicle evenly over its useful life. The scrappage values of Tiago Petrol (Price - INR 0.56 million) and Tiago EV (Price - INR 0.869 million) are taken as INR 0.224 million and INR 0.369 million and the maintenance cost is taken as INR 0.08 million and INR 0.04 million respectively for a period of 5 years assuming that there is no tyre replacement. The running cost for Tiago petrol is INR 5.78/km (taking INR 110 as the rate per litre of petrol and 19 km/litre as mileage) and for Tiago EV it is INR 0.75/km (taking the charging tariff as INR 8.5 and practical range 89% of 250 km). The total operating cost for both is calculated over a period of 5 years (taking 6 days a week). Figure 11 gives the comparison of cost for both variants for different commuting distances.

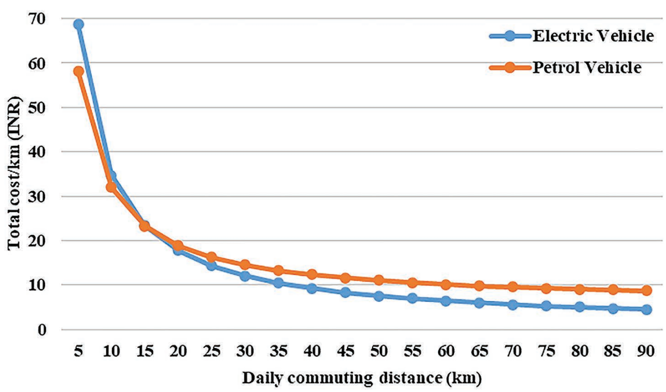


Figure 11: Comparison of Cost/km for an EV and a Petrol vehicle

It is observed that for short-distance daily commuting, the petrol vehicle proves to be more economical when factoring in all costs. As the daily commuting distance grows, the cost savings from using an EV becomes progressively more substantial. Consequently, it can be inferred that the advantages of transitioning to an EV are feasible primarily for individuals with longer daily commuting distances. Figure 12 illustrates the relationship between cumulative annual operating costs and the corresponding year for 50 km and 100 km daily commuting distances. At the end of the fifth year, the total operating cost for all five years can be observed in the graph. It can thus be inferred from the two figures that by the end of the fifth year the total savings for an EV customer with a daily commuting distance of 100 km is INR 0.67 million as opposed to the EV customer with a daily commuting distance of 50 km who has INR 0.27 million.

6. Solutions and Policies for a smoother EV penetration

By 2030 [103] it is expected that the EV industry will cross 10 million EVs with an adoption rate of around 30%. For the purpose of computation, we will be taking into account the mean battery capacity at 30 kWh. With a complete charge, an EV equipped with a 30 kWh battery can comfortably sustain two to three days of typical usage and idle drainage. In the context of a 30 kWh battery-powered car, energy consumption amounts to approximately 15 units of electricity. Taking 1 million EVs itself requires about 15 million kWh of electricity daily. Presently, EV charging infrastructure primarily consists of slow (3-4 kW) and fast (50-100 kW) chargers. The public charging station will necessitate nearly 100 kW of load and if we assume that 30 cars are served by one station, to serve a total of 1 million cars we shall

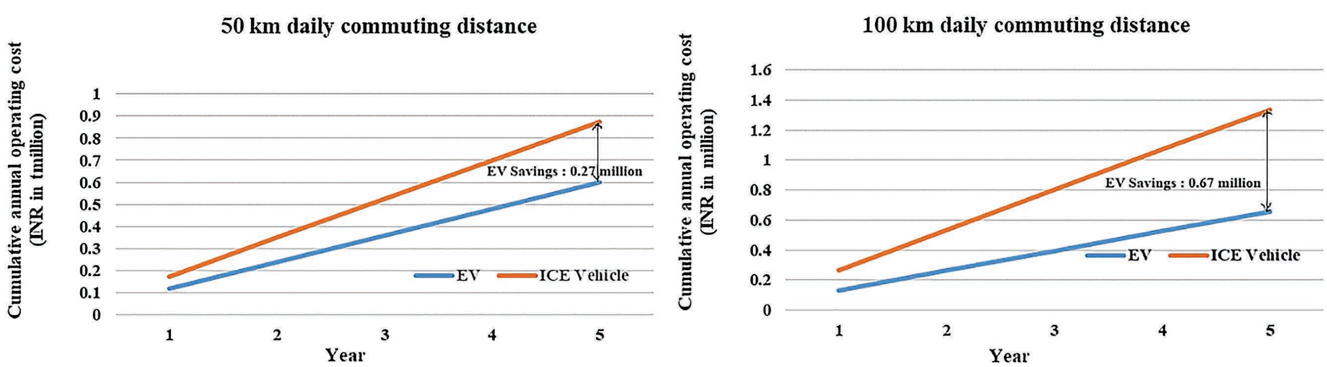


Figure 12: a) Cost savings analysis for 5 years with daily 50 km usage b) Cost savings analysis for 5 years with daily 100 km usage

require a total of around 33,334 stations with a total capacity of 3333 MW.

6.1 Proposed Solutions for Addressing Limited EV Infrastructure

A pressing concern is the need for significant space to establish EV charging stations, especially compared to traditional petrol stations. Petrol stations can serve around 20 vehicles in 30 minutes, while EV stations currently serve only one vehicle in the same time frame, highlighting the logistical challenge of accommodating the required charging infrastructure for widespread EV adoption by 2030. Creating a sustainable EV ecosystem requires well-planned policies to address various adoption challenges. These policies aim to transform transportation habits and urban planning, enhancing convenience while reducing the environmental footprint.

The following policies as summarized in Figure 13 when effectively implemented in coordination, can contribute to establishing a well-balanced and sustainable EV ecosystem within the country:

1. Parking Lot EV Charging Facilities [104]: Use existing parking lots for EV charging, generating additional income for owners.
2. Integration of EV Charging Stations with Leisure Facilities: Install EV charging at restaurants and parks along travel routes to enhance customer experiences.
3. Highway Fast Charging Infrastructure Expansion [105]: Expand fast-charging stations on highways for convenient long-distance travel.

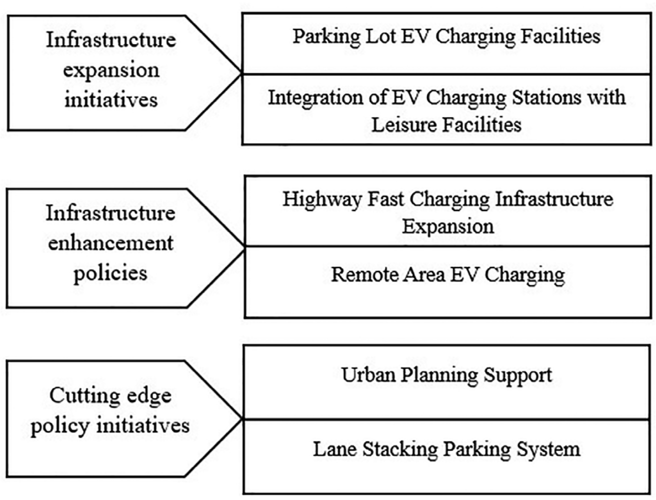


Figure 13: Suggested Policies and Solutions

4. Remote Area EV Charging: Extend EV charging to remote areas, boosting local economies.
5. Urban Planning Support: Promote EV-friendly urban planning, including dedicated EV spaces, exclusive lanes, and mixed-use zoning.
6. Lane Stacking Parking System [106]: Implement efficient lane-stacking parking to overcome space constraints.

6.2 Proposed solutions to address the issue of EV-associated grid overloading

EV's popularity poses grid challenges, necessitating solutions for grid overloading during charging. As more EVs are connected to the grid for charging, the increased demand for electricity can potentially strain the existing infrastructure, leading to grid stress in terms of increasing peak load demand, increased transmission line flows, etc. This necessitates the development of solutions and upgrades in the electrical grid to accommodate the growing demand for EV charging and ensure a stable and reliable power supply. Expanding renewable energy generation [107], policy frameworks [108], and intelligent Energy Management [109] can help. The following strategies may be adopted to harmonize charging demands, optimize energy distribution, and ensure the robustness of the power infrastructure as the EV fleet expands.

1. The Time of Use (TOU) tariff [110] plays a pivotal role in enhancing EV penetration by encouraging off-peak charging when electricity demand is lower. This strategy not only leads to cost savings for consumers but also promotes efficient use of the electrical grid.
2. Demand Response (DR) programs [111] enable utilities to manage electricity demand by encouraging EV owners to adjust their charging patterns in response to grid conditions. By incentivizing users to shift charging to periods of lower demand or when renewable energy is abundant, DR programs contribute to grid stability.
3. Smart charging infrastructure [112] optimizes processes with real-time data, efficiently managing electrical loads. It dynamically adjusts based on grid demand, electricity prices, and renewable energy availability, reducing strain on the grid while enhancing charging flexibility.
4. Renewable Energy Integration when combined with smart grid technologies, facilitates more efficient charging practices by reducing the dependence on the grid.

6.3 Proposed solutions to address the Financial Implications of EV Charging

The economic analysis of the financial burden associated with EV charging can be outlined as follows.: As calculated earlier taking the average daily electricity consumption of 15 units for charging EVs and assuming a charging rate tariff of INR 8.5, the estimated charging cost would approximate INR 127.5 per day, considering a battery capacity of 30 kWh. As such for 1 million vehicles, the total cost would be approximately INR 127.5 million (INR 12.75 Cr) resulting in a staggering annual cost of around INR 46.53 billion. This may be assumed for a moderate estimate of 1 Mn EVs with an average value of battery capacities taken. As the energy demand continues to rise, the need for a swift transition to sustainable power sources becomes increasingly clear and pressing. Renewable energy emerges as the logical solution to meet the burgeoning electricity demand posed by EVs. Failure to address this transition could lead to power shortages and energy anxiety within the EV ecosystem. Industry experts highlight the potential of solar energy to solve this. For one million EVs, approximately 62 MW of electricity per day is needed from renewable sources. This implies establishing nearly equivalent solar power plants nationwide to sustain the envisioned EV fleet. The shift toward renewables will significantly impact the energy landscape, reducing the reliance on power generation based on fossil fuels. This transition aligns with the increasing energy demand for EV charging, ensuring a more sustainable and balanced energy ecosystem.

7. Discussion and conclusion

In summary, this paper offers an extensive exploration of the complex challenges hindering the widespread adoption of EVs and underscores the collaborative efforts within the research community and their innovative solutions to overcome these obstacles. This article attempted to analyze the technical, economic, and sustainability challenges in EV adoption. Each challenge is meticulously dissected in Sections 2, 3, and 4, offering a multidimensional analysis that includes research directions for potential solutions through dedicated research directions. While analyzing the technical aspects, users are more concerned about the charging time, limited range, battery life span, and inadequate charging infrastructure. From the economic point of view, the high cost of EVs compared to their ICE counterpart is a major deterrent that hinders the adoption of EVs and makes ICEV a choice for users. The fact underpinned in such choices is the lack of awareness of the environmental consequences associated with the use of ICE vehicles. To overcome the sustainability challenges, focusing on renewable energy-based charging is imperative.

The economic viability of EVs is thoroughly examined in Section 5, incorporating diverse daily driving distances, and considering overall costs, including maintenance, repair, and depreciation – a novel approach to measure the level of economic changes contributed by EVs, which is concisely presented in Figure 14. It is noted that individuals with longer daily commuting distances stand to gain significantly from the adoption of EVs, and the extent of these distances plays a substantial role in the accumulated savings over a span of 5 years. It was concluded from the analysis that below a daily commuting distance of 15 km, it is not economical to prefer EVs considering the overall costs rather than just operating costs. It can be inferred from the cost analysis that by the end of the fifth year the total savings for an EV

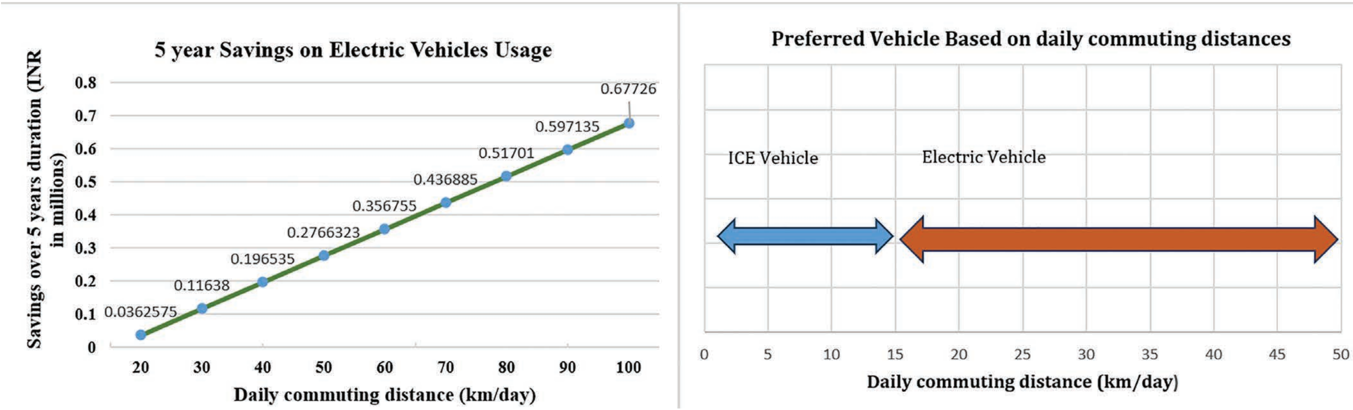


Figure 14: Cost Savings over 5 years of usage of EV and preferred Vehicle for different daily commuting distances

customer with a daily commuting distance of 100 km is INR 0.67 million and of 50 km is INR 0.27 million. A detailed survey can be carried out to collect insightful data in the future for comprehensive economic analysis.

Furthermore, the manuscript delves into the operational difficulties tied to the large-scale penetration of EVs, presenting a numerical analysis. The operational challenges arising from inadequate charging infrastructure are examined, with a specific focus on spatial constraints. Proposed solutions addressing these challenges are of primary importance to overcome over the years. Through a preliminary projection, the calculated charging rates for future EVs indicate a potential substantial financial burden on the economy. To mitigate this challenge, a recommended solution involves transitioning to renewables. Overall, the paper traces the evolution of EVs, evaluates their current status in India, outlines penetration targets, assesses public acceptance based on economic analysis and its repercussions, and proposes strategies for seamless integration into the existing grid. This holistic examination provides valuable insights for policymakers, researchers, and industry stakeholders as the EV landscape continues to evolve.

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