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CHARGING INFRASTRUCTURE AS A KEY ENABLER FOR SUSTAINABLE TWO-WHEELER EV TRANSPORTATION IN PAKISTAN

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ABSTRACT
Electric two-wheelers (E2Ws) have shown themselves to be innovative and sustainable solutions for the future of transport in the developing world, and therefore in the South Asian region in particular, as two-wheeler transport has remained the foremost form of personal transport. However, it has also remained that the widespread use of E2Ws has so far remained restricted by various factors, with the lack of charging infrastructure being one of the foremost among these. This research paper has comprehensively amalgamated the viewpoints of geospatial analysis, analyzing the demand for charging points, the aspect of harnessing solar energy as an alternative to traditional charging methods, and making it user-friendly to cover the subject matter. The current research work has employed a combination of mixed methodologies that aimed at a qualitative and quantitative analysis of spatial optimization strategies as well as a comprehension of user behavior with regards to different scenarios of electric vehicle uptake. The preliminary results indicate that it may be possible to lower operating expenses up to 30-40% by using a charging points network with a 20km range of high demand areas, in addition to emphasizing solar and wind resources. A well-balanced demand with an assorted group of users might also be achieved. The current study makes a valuable addition to a new body of knowledge on sustainable mobility infrastructure planning practices within a South Asian setting and provides useful recommendations regarding strategies that could promote a take-up of electric transportation systems among different stakeholder groups.
Keywords: *EV; electric two-wheelers; charging infrastructure; sustainable mobility; renewable energy integration; developing economies*

1. INTRODUCTION
Currently, the world is at a critical point where the transportation sector is under unprecedented stress to move away from its dependence on fossil fuels to other forms of sustainable energy that can tackle the rise in greenhouse gases due to climate-related effects and environmental concerns that come with the use of conventional fuels. Electric vehicles have rightly become the lighthouses that the transportation sector needs to move towards to address these concerns through electrification schemes that need to be extended to cars, trucks, and now two-wheelers that account for the majority in developing countries in the South Asian economies [1]. In countries like Vietnam

and others in Asia, two-wheelers account for 80% and above of vehicles in the road network **[2]**.

The quick advancement of the electric two-wheeler market in these regions is a result of technological advancement as well as increased environmental awareness among consumers; however, this progress is hindered by the lack of necessary infrastructure progress. In regard to the transport scenario in South Asia, the city of Lahore is the second-most populous city within the country with a population in excess of 12 million citizens. The level of air pollution in the region is high due to the generation of airborne carcinogens throughout the year; however, during peak seasons, the level according to the World Health Organization, is greatly surpassed **[3]**. In the region of Lahore, the transport sector is one of the major polluters that contributes around 30-40% to the particulate matter and nitrogen oxide production in the country due to the high use of fossil fuels in vehicles. Lahore was reported as the most polluted city in the world in 2022 by IQAir (an air quality technology company) when the air quality index reached 173. As of January 31, 2024, the Air Quality Index (AQI) in Lahore stands at 207 with the primary pollutant as $PM_{2.5}$, categorizing it as "Very Unhealthy"**[4]**.

The Nexus of Infrastructure Adoption: It has recently been found that the provisioning of infrastructure is one of the most influential factors in electric vehicle adoption, including consumption behavior, purchase intention, and the long-term viability of the market **[5].**The association of factors occurs in several ways. Adequate accessibility of infrastructure decreases "range anxiety" for users, raises the confidence levels of users about the reliability of the vehicles, decreases the uncertainty of charging time, and provides convenient integration of electric vehicles into the daily mobility system of users. It is important to understand that the deficiency of charging points leads to the generation of a negative feedback process by which the low adoption of EVs leads to the decreased need for infrastructural development in the sector**[6]**.

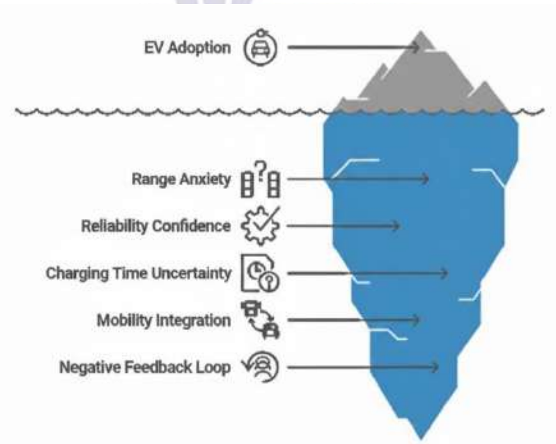

Figure 1: The Hidden Driver of EV Adoption

Figure 1 employs the metaphor of an iceberg to convey the impression that electric vehicle adoption is only the tip of the iceberg, and the true factors are hidden. Such hidden factors, including range anxiety, charge time uncertainty, confidence in reliability, mobility integration, and negative feedback loops, tend to act together and have an impact on consumer trust and behavior. This picture highlights that the provisioning of infrastructure is the true force that has driven these hidden factors and the success of electric vehicle adoption.

The problem of infrastructure within developing countries of South Asia as a whole is vastly different as compared to developed countries, where well-established markets for EVs require supporting charging infrastructure available across cities and countries. Presently, the charging infrastructure for electric vehicles has still been in its infancy stages in the city of Lahore, which appears scattered between a few players in this sector but inadequately distributed across different geographical areas without any relation to a larger urban plan or framework. Despite the phenomenal rise in the EV market, as well as government supporting plans for a transition towards EVs due to rising awareness about environmental concerns, the “Infrastructure Illusion persists without letup**[7].** Lack of comprehensive planning has resulted in a concentration of charging infrastructure in affluent business hubs while overlooking middle-class residential areas, transportation hubs, and employment centers, which in turn face a greater potential demand for charges. The problem of imbalance between the locations of the infrastructure and those of potential users results in inefficiencies in using the infrastructure as well as makes the financial viability of charge operations and the use of electric vehicles unattainable for many citizens. Although a large body of international work exists related to charging infrastructure design and planning for EVs, almost all of that work has been done in developed economies and utilizes fully developed electricity infrastructures and corresponding regulatory and investment environments that differ significantly in terms of urban morphologies and user profiles from those in South Asian cities **[8].**

Figure 2: Charging Infrastructure Transplant Challenges

Figure 2 illustrates charging infrastructure transplant challenges arise from the difficulty of adapting solutions to local contexts rather than directly copying models from elsewhere. Variations in regulations, urban mobility patterns, socio-economic conditions, and urban density influence both demand and feasibility. Additionally, renewable energy variability, institutional capacity, and limitations in existing power distribution networks collectively shape how effectively charging infrastructure can be deployed and sustained.

Although the charging infrastructure for E2W in the South Asian developing cities has expanded rapidly in the market, there is still little research specifically focused on the charging infrastructure in this region. This brings numerous challenges, including that unnamed by scientific evidence may end up being financially unfeasible, ineffective in meeting the demands of the users, contributing towards grid instability, underutilizing the expensive deployed resources, or worsening the equity kind in relation to the sustainable transport modes. Moreover, there would be decreased emissions of greenhouse gases by the transport sector, improvement in the air quality of the cities, improvement in the health outcomes, along with the facilitation of accelerating the EV sector in the market [7].

2. LITERATURE REVIEW

Currently, the transportation industry is in midst of a paradigm shift as governments, industries, and people are becoming aware of the need to move away from dependence on fossil fuels, especially in view of climate change and air pollution **[9].** Strategies set by the Green Deal of the European Union, as well as others in developed and developing countries, target making substantial inroads into the market of electric vehicles and intend to achieve the next milestone of 20-50% of electric vehicle market penetration in the next two decades of this century in developed as well as developing countries. Electric vehicles include various types from passenger cars, commercial trucks, and public transport vehicles such as city buses, and more recently, two-wheeler and three-wheeler vehicles which account for most transport in developing countries of Asia, Africa, and South America. Micro-mobility solutions such as e-bikes, e-scooters, and e-motorcycles have shown immense importance in urban settings with regards to energy efficiency, minimal infrastructure compared to cars, use for short distances in place of fossil-fuel vehicles, and accessibility in economic disadvantaged sections of society **[10].** Studies have shown the effectiveness of light electric vehicles in serving the purpose of last/first mile connectivity, relieving traffic congestion due to reduced use of private vehicles, minimizing pollution in urban environments due to use of renewable energy, and promoting active living with non-motorized transport infrastructure **[11].**

Table 1: Pakistan's Electric two-wheeler Companies and E2Ws model details

Brand	Model	Battery Type & Capacity	Charging Input	Charger Type / Rating	Fast-Charge Support	Charging Time
Vlektra	Velocity 180	Lithium-ion 60 V 30 Ah	AC 220 V	10 A company charger	No	3.5 hours
	V180 SE	Lithium-ion 60 V 30 Ah	AC 220 V	10 A company charger	No	3.5 hours
	Bolt	Lithium-ion 60 V 30 Ah	AC 220 V	10 A company charger	No	3.5 hours
Evee	S1	Lithium-ion 60 V 20-25 Ah	AC 220 V	5-6 A portable charger	No	5-7 hours
	S1 Pro	Lithium-ion 60 V 20-25 Ah	AC 220 V	5-6 A portable charger	No	5-7 hours
	S1 Air	Lithium-ion 60 V 20-25 Ah	AC 220 V	5-6 A portable charger	No	5-7 hours
United Motors	Classy Pro	Graphene / Li-ion 48-72 V 22-40 Ah	AC 220 V	Standard wall charger	No	4-5 hours
	Smart Pro	Graphene / Li-ion 48-72 V 22-40 Ah	AC 220 V	Standard wall charger	No	4-5 hours
	Sharp Pro	Graphene / Li-ion 48-72 V 22-40 Ah	AC 220 V	Standard wall charger	No	4-5 hours
Jolta Electric	JE-70D	Dry Gel / Li-ion 60 V 20-30 Ah	AC 220 V	5 A smart charger	No	3-6 hours

	JE-70 Li (Eco)	Dry Gel / Li-ion 60 V 20-30 Ah	AC 220 V	5 A smart charger	No	3-6 hours
	JE Scooty	Dry Gel / Li-ion 60 V 20-30 Ah	AC 220 V	5 A smart charger	No	3-6 hours
Pakzon	PE-70L	LiFePO4 60 V 30-50 Ah	AC 220 V	6 A charger	No	3-4 hours
	PE-100L	LiFePO4 60 V 30-50 Ah	AC 220 V	6 A charger	No	3-4 hours
Road Prince	E-GO	Lithium-ion 60 V 30 Ah	AC 220 V	Company charger	No	4-5 hours
	RP E-70	Lithium-ion 60 V 30 Ah	AC 220 V	Company charger	No	4-5 hours
Hi-Speed	RM-1500	Lithium-ion 60 V 35-38 Ah	AC 220 V	Standard AC charger	No	4-6 hours
	RM-1700	Lithium-ion 60 V 35-38 Ah	AC 220 V	Standard AC charger	No	4-6 hours
	RM-1900	Lithium-ion 60 V 35-38 Ah	AC 220 V	Standard AC charger	No	4-6 hours
Metro EV	T9 Pro	Graphene / Li-ion 60 V 38 Ah	AC 220 V	Optional fast module	Partial	30 min (fast)
	E8S	Graphene / Li-ion 60 V 38 Ah	AC 220 V	Optional fast module	Partial	30 min (fast)
	M6 Lithium	Graphene / Li-ion 60 V 38 Ah	AC 220 V	Optional fast module	Partial	30 min (fast)
Yadea	T5	Lithium-ion 72 V 26-32 Ah	AC 220 V	4 A charger	No	6-8 hours
	GT30	Lithium-ion 72 V 26-32 Ah	AC 220 V	4 A charger	No	6-8 hours
Crown	EV-800	Lithium-ion 60 V 20-25 Ah	AC 220 V	Wall charger	No	5-6 hours
	EV-1000W	Lithium-ion 60 V 20-25 Ah	AC 220 V	Wall charger	No	5-6 hours
Road King	Eagle-i	Graphene 72 V 32 Ah	AC 220 V	Company charger	No	5-6 hours
	RX-9	Graphene 72 V 32 Ah	AC 220 V	Company charger	No	5-6 hours

Table 1 presents a comparative technology review for the electric two-wheeler (E2W) industry in the Pakistani market, segmented on the basis of automobile manufacturers and models. It lists important details necessary for a well-integrated charging system, like battery types (Lithium Ion, Graphene, & LiFePO4), voltages from 48 Volts to 72 Volts, and battery capacities from 20 Ah to 50 Ah. Moreover, to emphasize the current charging system deficiency within each manufacturer's models, most models are coupled with a standard AC 220V charging interface and charging times up to eight hours with a current limit between 4A and a maximum of 10A charging current, but only a few models from Metro EV support partial-fast charging.

Table 2: Electric Two-wheeler Registered Companies in Pakistan

Company / Brand	Activity	Source
Vlektra	Produces and sells premium electric motorcycles in Pakistan	Official site shows models & sales presence in Pakistan Vlektra
Jolta Electric	Electric motorcycle / scooter brand	Listed among top EV motorcycle makers in Pakistan Pakwheels+2TYCORUN Battery Swap+2
MS Jaguar	Expanded into electric scooter / motorcycle lineup	Their site mentions electric scooters & PAVE scheme participation msjaguarmotorcycles.com
Pakzon Electric	Electric motorcycles & scooters	Listed among leading EV motorcycle manufacturers in Pakistan TYCORUN Battery Swap+1
Metro E-Vehicle	Electric motorcycle / scooter models	Included in "top" lists of EV makers in Pakistan TYCORUN Battery Swap
Okla Pakistan	EV bikes / scooters brand	Named in lists of Pakistani EV motorcycle manufacturers TYCORUN Battery Swap+1
United Auto Industries	Listed as assembler / seller of electric motorcycles / scooters	On EDB's "Main Assemblers – 2/3 Wheelers" list: "Electric Motorcycles, Scooters" included in their vehicle types engineeringpakistan.com
Pak Star Automobile (Pvt) Ltd.	Assembler / seller of electric scooters & motorcycles	On EDB's assembler list including "Electric Scooters & etc" engineeringpakistan.com
Siwa Industries (Pvt) Ltd.	Listed to produce electric motorcycles among other types	On EDB assembler list including "Electric Motorcycles" engineeringpakistan.com
Treet Holding Ltd.	Listed as assembler including electric motorcycles / scooters	In EDB list under "Electric Motorcycles & Electric" types engineeringpakistan.com
Crown Motor Company Ltd.	Listed with electric motorcycle and scooter capabilities	Included in EDB list with "Electric Motorcycles, Electric Scooties" engineeringpakistan.com
Nova Mobility (Pvt) Ltd.	Electric motorcycles / electric loaders	Listed in assembler list under "Electric Motorcycles & Electric Loaders" engineeringpakistan.com
Pakzon Electric Motors (Pvt) Ltd.	Specifically "Electric Motorcycles & Electric Scooties"	In EDB main assemblers list engineeringpakistan.com

Inner Z Automotive (Pvt) Ltd.	Listed as "Electric Motorcycles" assembler	In EDB main assemblers list engineeringpakistan.com
E-Turbo Motors (Pvt) Ltd.	Listed as "Electric Motorcycles" assembler	In EDB list engineeringpakistan.com

Table 2 shows Pakistan's electric two-wheeler market by a mix of pure EV players and established assemblers. Firms that are very actively offering electric motorcycles and scooters include Vlektra, Jolta Electric, MS Jaguar, Pakzon Electric, Metro E-Vehicle, and Okla Pakistan, while various automotive firms are officially listed by the Engineering Development Board (EDB) as assemblers of electric two-wheelers. Such a fact reflects a gradually growing and officially known EV manufacturing and assembly ecosystem in the country.

Planning of Charging Infrastructure: The problem of planning of charging infrastructure arises due to the need to maximize more than one conflicting criteria simultaneously under a large number of constraints **[12].** There has been a proliferation of research work related to the planning of location of charging stations in the past few years using a wide range of methods, right from using traditional location problems to machine learning algorithms and stochastic optimization methods.

Typically, basic location planning algorithms involve means to resolve variants of the Maximum Covering Location Problem or p-median formulations, which are optimized to maximize service coverage for a given dataset of distance constraints, minimum costs of installation and operation, and in other situations a combination of maximizing service coverage and economic viability to meet location requirements **[13].** Basically, these conventional models allow efficiencies in location planning and development by assuming complex parameters within demand behavior and traffic flow, which in actual situations might be excessively rigid in practice to accurately meet desired and expected objectives in location development and allocation. The new methods would allow geospatial systems to take into account a number of parameters, such as accessibility to transportation hubs, residential areas, and business points, along with land use and infrastructure parameters.

Recent studies have been incorporating more machine learning techniques for demand forecasted calculations as well as the identification of the best locations. Here, the concepts make use of intensive data sets based on past charging behaviors, demographics, mobility patterns, traffic flow, and climate factors, allowing for the identification of the non-linear connection that would enable the forecast of charging demands for a particular location and time. Data-driven methods, such as the aforementioned, would be beneficial in cases where little past information exists about the charging infrastructure.

One of the important steps that would be involved in designing the infrastructure would be the use of integrated modeling of transportation and power infrastructure networks as it had been observed that provision of charge infrastructure could influence not only transportation systems but also electric power distribution networks as well **[14].** Multi-objective optimization strategies would aim to optimize different objectives such as the reduction in overall infrastructure costs, improvement incoverage, and improvement in usage of renewable power.

Charging Infrastructure and Integration with Renewable Energy: Electric vehicle charging is highly dependent on the source of electricity that feeds into charging facilities for its sustainability profile. Maximum environmental benefits through a reduction in emissions across the full lifecycle of the vehicle come from renewable-powered charging, while charging provided by electrically generated electricity from fossil fuel sources yields modest emission benefits compared to internal combustion.

This has brought serious impacts on vehicles and grid stability, especially in periods of high demand for charging conditions. Such understanding has stimulated serious research into integrating renewable energy sources, especially solar photovoltaic systems, directly linked to the EV charging infrastructure.

Solar-powered charging stations bring several advantages in relation to South Asian developing nations: high solar irradiance in tropical and subtropical climates, very little operational expenditure post-installation, techno-feasibility of decentralized power production requiring less dependence on the main grid infrastructure, complimenting the energy independence policies and climate agreements, and the ability to utilize land constructively, such as roofs of buildings, parking lots, and dedicated land areas for solar installations. Available research illustrates the capability of a PV system in meeting/reducing the daily charging requirements of electric vehicles by as much as 30-60% in real urban sites, and requiring the requisite grid supply during times of lower solar outputs **[15].** Battery Energy Storage Systems maximize the potential of renewable energy in conjunction with solar energy by storing the excess solar energy produced during times of reduced energy demand and can provide energy during peak vehicle-charging hours, lessening the strain on the grid and enhancing the system's economic viability.

These are the technical challenges that need to be overcome for integrating renewable sources in a grid: integrating varying sources with varying demands, voltage regulation in distributed Renewable Energy Sources, inverter harmonics, and complexity in controls. On the other end, smart grid solutions, power electronic devices, and sophisticated controls have ensured that integrating renewable sources in charging systems is less of a challenge these days. The vehicle-to-grid technology ensures that power is also supplied back into the grid from the charged batteries in cars when there is peak demand, and hence, these systems enhance grid flexibility and make further utilization of renewable sources in charging systems. It has been interpreted from different researches that efficiently designed solar-powered charging infrastructure reduces grid electricity consumption expenses by 40-70% while producing substantial benefits in terms of being environmentally friendly.

User Behavior, Demand Patterns, and Adoption Dynamics: Analyzing the user behaviour, and actual demand pattern of charging remains a very important step before setting up any charging infrastructure because, for high usage and a sustainable system to take place, it is highly important that it serves their needs and desires. It may perhaps be acknowledged that although models of actual EV demand based on details of vehicle specifications and drive cycles could serve as a very useful starting point, actual user behavior may sometimes differ considerably from it due to reasons related to psychological needs, social pressures, and convenience requirements and restrictions related to resources and facilitation **[16].**

The findings of studies on EV users' behavior include: Firstly, there are variations in the preferred charging points, which tend to be influenced by user type, with fleet and private car owners showing a preference for home charging; while others prefer workplace and public charging; Secondly, there exists a peak hour in terms of EV charging, which tends to be in the early morning and evening hours, thereby posing challenges in the level of engagement with the grid; Thirdly, the factors of range anxiety and rate of waiting time at the charging points have continued to influence users' level of satisfaction and use of EVs despite the level of use of the charging points; Fourthly, there exists a relationship between individual characteristics of users, such as age, income level, level of education, and gender of users, which influence the level of use of the preferred charging points; Lastly, there exists a relationship between users' perceptions of the level of accessibility of the charging points and use, irrespective of the level of use of the said facilities.

Research work carried out within South Asia provides evidence of the need for the identification of more behaviors that are unique for developing economy environments, including: A deficiency in dedicated residential area parking that limits the options for the charging strategy; Mixed commercial and residential land use that generates varying demands compared to those of developed environments; Employment patterns with commute distances longer than those of the developed world that stipulate dissimilar demands for the daily charging strategy; High variability of ownership rates of vehicles, income, and user class diversity resulting in varying demands for diversified supporting infrastructure provision.

User Behavior, Demand Patterns, and Adoption Dynamics: Analyzing the user behaviour, and actual demand pattern of charging remains a very important step before setting up any charging infrastructure because, for high usage and a sustainable system to take place, it is highly important that it serves their needs and desires **[17]**. For transportation infrastructure projects, there are a number of dimensions of equity that are analyzed in planning, including Geographic Accessibility, Economic Accessibility, Demographic Accessibility, or how it serves differing demographics such as women, elders, people with disabilities, in addition to procedural accessibility. Such dimensions are aimed at ensuring that rail infrastructure planning projects are carried out in accordance with consideration of its effect on equitably accessing transport services.

It has been found that location plans primarily oriented towards optimizing the cost efficiency of the private owner could result in a concentration of charging points in upmarket business areas, overlooking the middle classes, to say nothing of low-income areas. This perpetuates inequities in mobility and reduces sustainable transport benefits to already privileged populations while excluding those who stand to benefit more from low-cost electric mobility. Equitable infrastructure would need to be planned with explicit consideration of accessibility across neighborhoods, deliberate identification of underserved areas, and strategic investment ensuring geographic distribution of facilities even where commercial viability may be lower**[18].**

Gender differences in access to charging infrastructure appear to be a crucial issue in South Asian situations in which there are large gaps in mobility access based on gender. Women have security risks when accessing shared facilities in general, especially in late evening peaks, have limitations in vehicle ownership and personal mobility, and are likely to depend on shared mobility systems**[19]**. Designing charging infrastructure based on gender factors includes designing safe and lighted facilities, social communications through social media in order to eliminate information gaps, and actively engaging women in planning to gain from their perspective and requirements.

Although there is substantial literature on the subject of EV charging infrastructure development, there remain several knowledge gaps, especially in the context of developing South Asian countries. Current literature largely focuses on the developed world situation that has well-established electric power infrastructure that is generously funded, has established regulatory environments, and has urban structures that would be radically different for South Asian nations**[20]**. Developed country models include the assumption of generously available grid capacity margins, advanced power distribution control, easy accessibility to funds, and urban structures that would vary significantly for South Asian countries.

3. METHODOLOGY

The methodology used in this study is structured in a way that helps fill the gap that exists between the requirements and the technical implementation process in the EV industry. In a comprehensive approach to building an integrated charging system for two-wheeler EVs, the methodology used in this topic involves the use of a mixed-methods approach to the research process that aims to balance the results gained qualitatively with those acquired quantitatively. This approach is helpful in ensuring that the final outcome is not only technical but is feasible economically and socially for the daily commuter. The methodology follows a logical process to address the complex issues that come with electric mobility in an urban setting.

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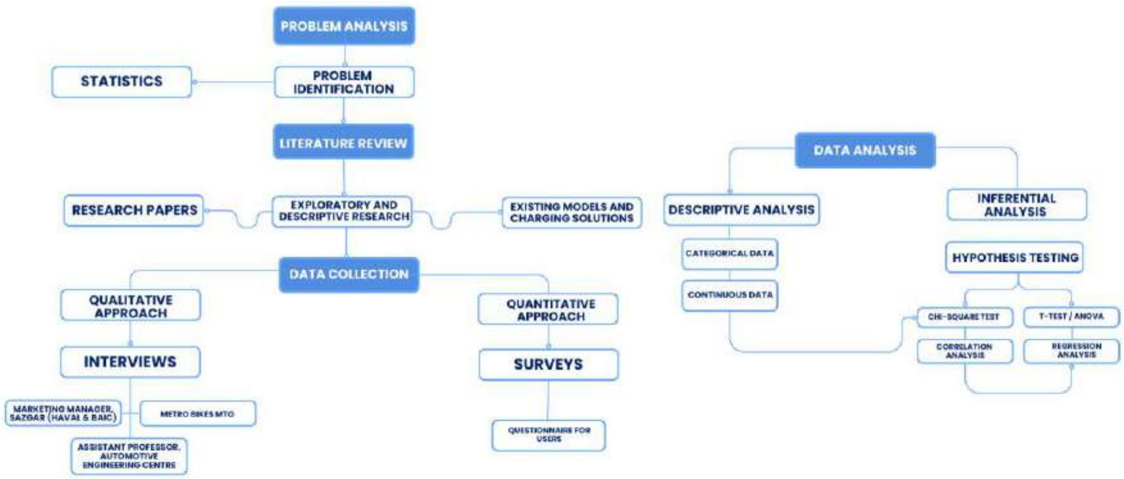

Figure 3: Research Methodology for Electric Two-Wheeler Charging Infrastructure

The flow chart, Figure 6, summarizes the processes involved in undertaking research work, starting from identifying the problem right through to a literature review and finally to exploratory and descriptive forms of research. The processes entail both qualitative and quantitative study methods.

4. RESULTS AND ANALYSIS:

To get a general idea of the technical and structural needs of the ecosystem, qualitative interviews were done with industry experts and stakeholders. These sessions were about getting expert opinions from people who work in battery technology, urban planning, and EV infrastructure design about the problems with charging networks and new trends in energy management. The qualitative feedback from these sessions was a key piece of information about how possible it is to combine smart-grid technologies with the rules for public charging interfaces. To be competitive in today's world, the proposed two-wheeler EV and its charging ecosystem needed to be designed and built with the right technical limits and performance metrics in mind. This required input from experts.

Table 3: Thematic Analysis of Expert Interviews for Charging Infrastructure

Theme	Dr. Muhammad Ali Shahbaz (Academic/Technical - UET)	Ali Hassan Maqsood (Trainee Engineer - Metro)	Arslan Jamil (Marketing - Sazgar/Industry)
Primary Perspective	Focus on engine diagnostics, alternative fuels, and thermal optimization of energy systems.	Technical implementation of EV adoption and the transition from ICE to E2W in the local market.	Market strategy, infrastructure scalability, and consumer trust in new EV brands.
Technical Constraint	Emphasizes the need for performance optimization and the challenges of waste-to-energy for local contexts.	Identifies infrastructure barriers and perceived technical risks as major negative drivers for consumer purchase intention.	Highlights the high upfront cost driven by imported battery components and the lack of supply chain localization.

Infrastructure Gap	Highlights the role of energy engineering in overcoming environmental hazards and fossil fuel dependency.	Points to the inadequacy of current charging networks to directly influence consumer attitudes toward EV adoption.	Cites "Range Anxiety" as a critical barrier intensified by the lack of visible, reliable public charging stations.
Policy & Ecosystem	Views innovation through the lens of socio-environmental responsibility and ethical engineering.	Notes that government non-monetary policies (incentives) have a significant positive influence on purchase intent.	Discusses the National EV Policy (NEVP) targets (30% by 2030) and the need for standardized technical protocols for interoperability.
Future Recommendation	Integration of disruptive technologies like blockchain for sustainable supply chains.	Recommends localized, affect-filled communication strategies to overcome psychological barriers.	Calls for strategic interventions in financing, battery swapping, and leveraging surplus grid capacity.

Table 3 shows a thematic analysis of expert interviews that looks at technical, infrastructural, and market-driven barriers to E2W adoption and ecosystem development across sectors. The quantitative component of the data collection process occurred simultaneously with the expert analysis, involving the distribution of structured surveys to a diverse range of daily commuters. The goal of these surveys was to find out what potential users need by asking about things like how far they travel each day, how they currently charge their devices, and what is the most important reason people don't want to switch to EVs. The research was able to identify the specific "pain points," such as range anxiety and the lack of easily accessible charging stations at work, among other things, by analyzing data that covered a larger population of users. Additionally, this data serves as the main source of information during the development phase, guaranteeing that the final combined charging solution takes into account the actual requirements of the contemporary daily commuter.

Demographic and Behavioural Analysis: Based on data collected from 200 participants, the 18–30 age group, which makes up the majority of users, has a significant need for more stable charging stations. Incorporating the frequency distribution variable (n) and the measures of central tendency of these data, namely Mean, Median, and Mode, in this project is integral for the successful transfer of the conceptual design into an engineering design solution for the project. Though the frequency measures the extent of the market and the severity of the charging problems that commuters experience, the measures of central tendency indicate the mathematical limitations required for design creation.

Table 4: Frequency Distribution of Key Variables (N=200)

Variable	n (Frequency)	Percentage (%)	Mode
Age Group: 18–30	182	75.8%	18–30
Primary Charging: At Home	158	65.8%	At Home
Daily Travel: 20–40 km	112	46.7%	20–40 km
Charging Satisfaction: Unsatisfied	124	51.7%	Unsatisfied

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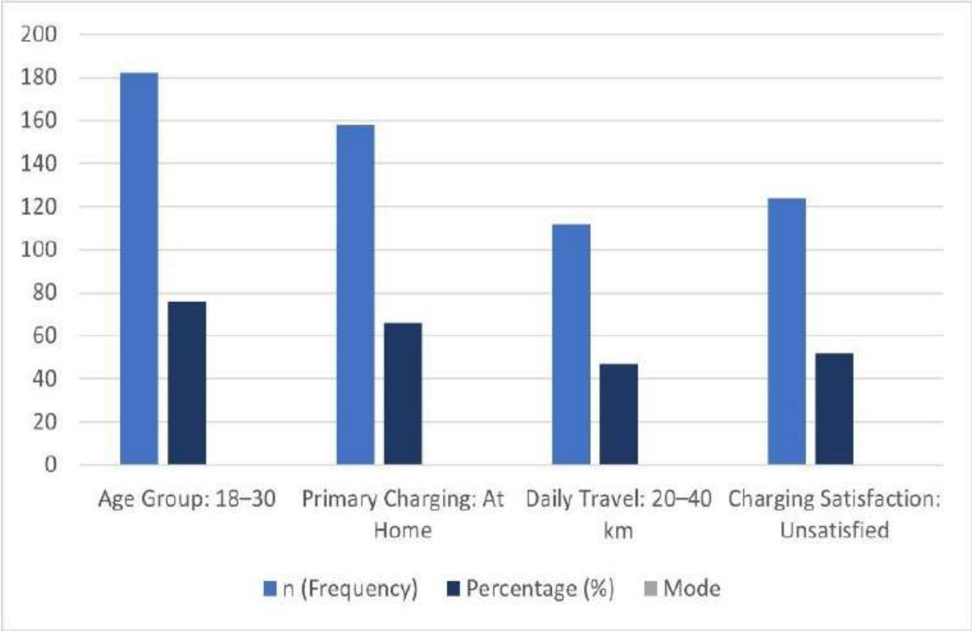

Figure 4: Frequency Distribution Chart

Figure 4 illustrates the age distribution of survey respondents across three categories: 18–30, 31–45, and Under 18. The 18–30 age group represents the largest number of participants, while those Under 18 constitute the smallest group.

Descriptive Statistics for the Performance Parameters: Average Range Expectation is an important parameter in this case. This defines the benchmark for the consumer expectation with respect to the extent of the journey the consumer wishes to undertake in one go, which would require the development of the energy capacity needed for the integrated charging system. To derive the parameters for the battery characteristics, the Mean, Median, and Mode have been calculated by using the mid-point classification. To obtain the Mean, the mid-point for the categories you have described, such as "30-50 km," would be 40.

Table 5: Average Range Expectation Calculation

Range Category	Midpoint (x)	Frequency (f)	x·f
30–50 km	40	85	3400
51–70 km	60	92	5520
71–90 km	80	45	3600
91+ km	100	18	1800
Total (N)		**240**	**14,320**

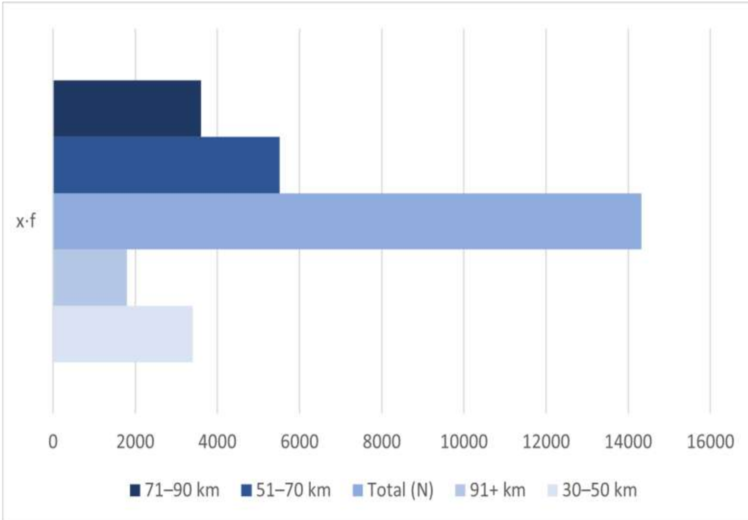

Figure 5 Electric Two-Wheeler Average Range Results

Table 5 results shows Mean: 59.6 km, Median: The 120th value falls in the 51–70 km category, Mode: 51–70 km (Highest frequency of 92). The data suggests that the majority of the sampled units fall within the 51–70 km range, indicating this is the most common performance level for the group.

Relationship Between Distance and Range Anxiety: The following tests were carried out to prove the relationship between the behavior of the customer and the system requirement. Chi-Square Test for Independence was employed to establish the effect that daily distance through commuting may have on range anxiety experienced by commuters. Chi-Square Statistic x^2 = 153.94, Degrees of Freedom (df)= 12, $p < 0.001$. The result is highly significant. As commuters travel longer distances (particularly the 61–80 km group), the intensity of range anxiety increases significantly. This proves that an integrated ecosystem must provide "on-the-go" charging to make long commutes viable.

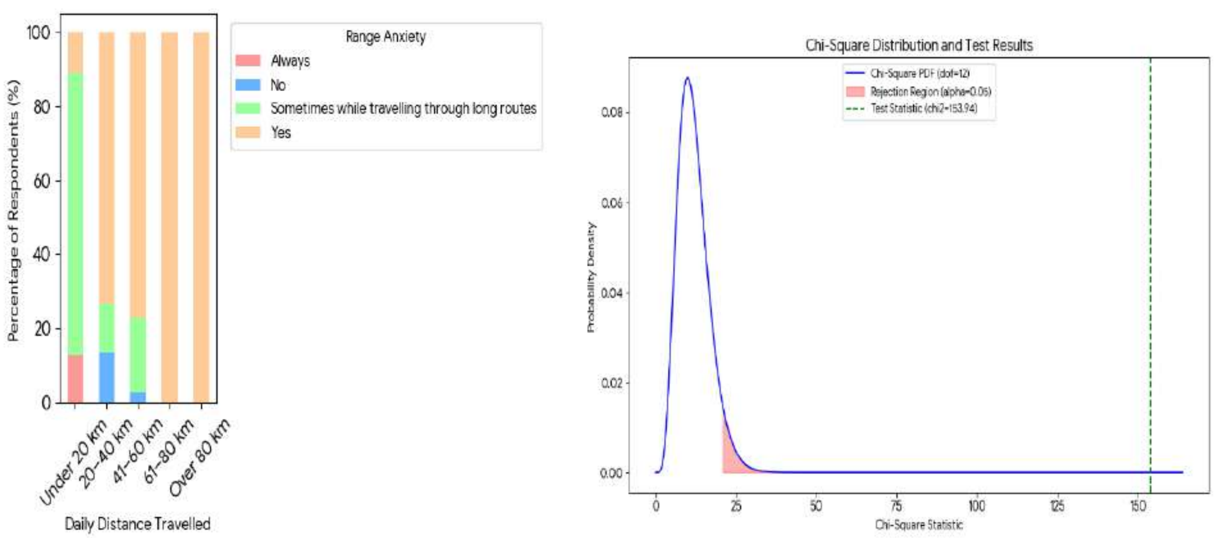

Figure 6 Chi-Square Distribution and Test Results (Distance Travelled)

The current "Home-Only" charging model is inadequate, according to the descriptive analysis and the Distance vs. Range Anxiety Chi-Square test (x^2 = 153.94). The data demonstrates that a secondary, mid-commute charging layer is a biological requirement for the ecosystem's survival, with 70.8% of users reporting range anxiety and a distinct "Range Gap" where daily travel (61–80 km mode) frequently exceeds the expected battery range (54.91 km mean).

Relationship Between Age and Infrastructure Preference: A second test was conducted to see if different age groups prefer different charging technologies. Chi-Square Statistic x^2= 36.95, Degrees of Freedom (df) = 4, p < 0.001. There is a strong correlation between age and preference. Younger users are significantly more likely to prefer Battery Swapping and Public Charging than older demographics.

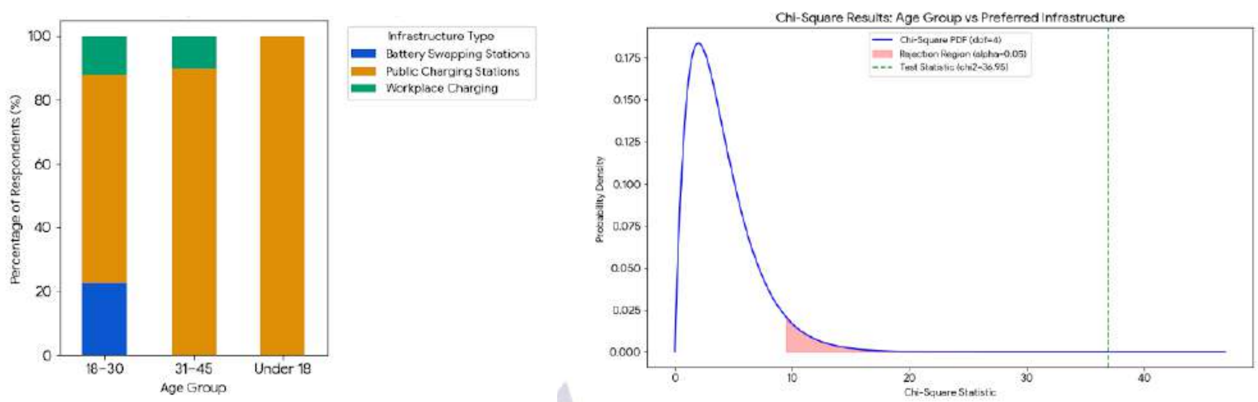

Figure 7 Chi-Square Results Age Group vs. Preferred Infrastructure

The Age Group vs. Preferred Infrastructure test finally did away with design guesswork, where the x^2 = 36.95. This study proved that a modular vehicle design would be justified because the dominant user demographic overwhelmingly prefers Battery Swapping and Public Charging, thus assuring that the ecosystem allows for rapid replenishment of energy to directly address the 4.28 hours downtime by users.

Relationship between Age Group vs. Daily Travel Distance: To determine if travel patterns are influenced by the age of the commuter, a Chi-Square test of independence was performed. Chi-Square Statistic x^2: 119.07, Degrees of Freedom (df): 8, P-value: 5.16 x 10^{-22} (Highly Significant, p < 0.05). The test shows a very high Chi-Square value and a P-value approaching zero. This indicates that we reject the null hypothesis that Age and Daily Distance are independent. Instead, there is a statistically significant correlation between a user's age and how far they travel daily on their EV.

Table 6: Observed and Expected Counts

Category	Observed	Test Proportion	Expected	Contribution to Chi-Square
20-40 km	44	0.2	35.8	1.8782
41-60 km	21	0.2	35.8	6.1184
61-80 km	57	0.2	35.8	12.5542
Over 80 km	4	0.2	35.8	28.2469
Under 20 km	53	0.2	35.8	8.2637

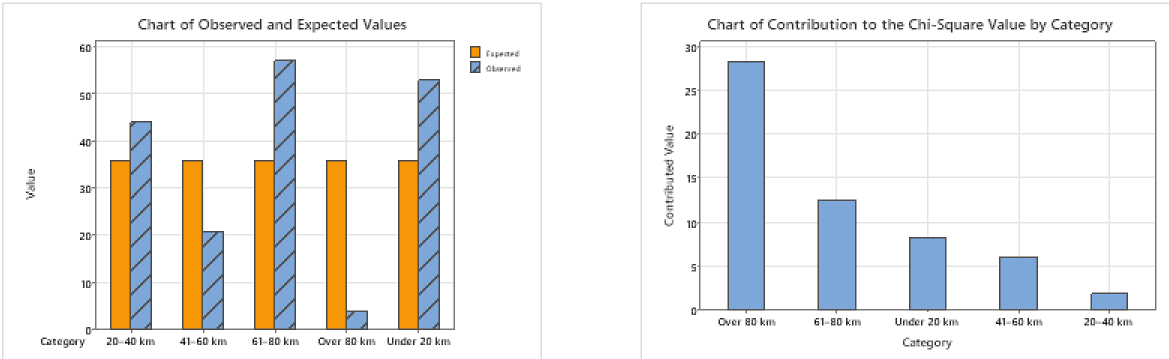

Figure 8 Chi-Square Results (Age Group vs Distance Travelled)

Table 7: Chi-Sq Test Summary

N	N*	DF	Chi-Sq	P-Value
179	0	4	57.0615	0

Relationship of Age Group vs. Occupation: To determine if there is a significant relationship between the demographic age and the professional status of potential EV users, a Chi-Square test of independence was performed. Chi-Square Statistic $\mathbf{x^2}$**:** 137.93, Degrees of Freedom (df): 6, P-value: 2.74 x 10^{-27}(Highly Significant, $p < 0.05$). The results indicate that we reject the null hypothesis. There is a very strong, statistically significant association between the age of the respondent and their occupation. This suggests that certain age groups are clustered within specific professional roles that dictate their daily commuting needs.

Table 7: Observed and Expected Counts

Category	Observed	Test Proportion	Expected	Contribution to Chi-Square
20-40 km	44	0.2	35.8	1.8782
41-60 km	21	0.2	35.8	6.1184
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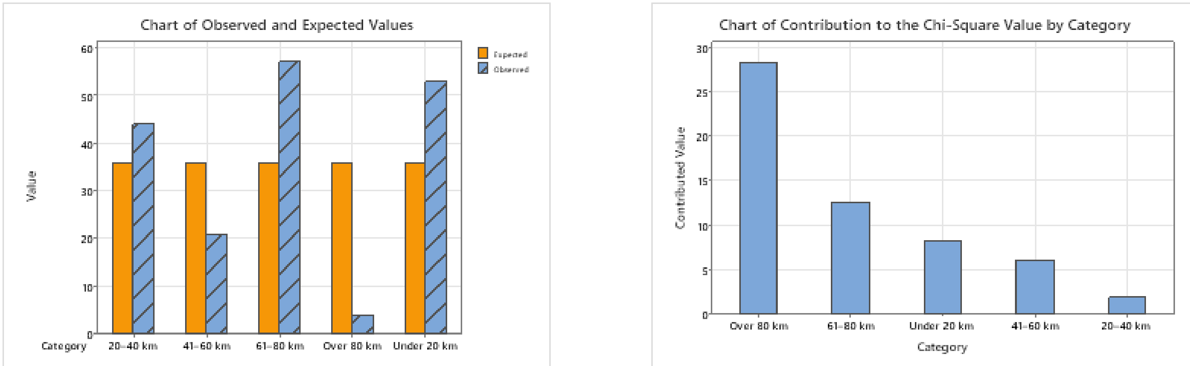

Figure 9 Chi-Square Test (Age Group vs Occupation)

Identification of User and Geographic Distribution "Where": The research using the Age Group vs. Occupation test (x^2 = 137.93) and the Age Group vs. Distance test (x^2 = 119.07) determined the "Primary Commuter Persona." From the findings, the age group that travels the longest distance consists of people aged 18 to 30 years, which includes students and young professionals. This is the scientific basis to incorporate charging points exclusively in universities and Corporate environments to ensure the infrastructure is located in the "where" the demand is greatest and the "when" the downtime is most frequent. The statistical evidence verifies the need for the Integrated Charging Ecosystem to be multi-modal, strategically localized, and user-centered. This renders the project design a factually verified engineering solution for the modern city of today.

5. CCONCLUSION

The need and motive to conduct this study are the understandings of the dynamic nature of the user and the related psychological challenges associated with the adoption process of electric two-wheelers. The results of the mentioned study state the definite outcome in one place, and that outcome is the existing paradigm of "Isolated and Home-Based Charging" is ineffective in meeting the requirements of the 'Commuter of Today' and further quote as: "For electric mobility to be successful, the paradigm shift 'needs to be Infrastructure-centric,'"

Developing a sustainable charging infrastructure system for electric two-wheelers is a big challenge and at the same time a big opportunity that could facilitate faster transformation toward environmentally sustainable mobility in urban areas. The issue has been scrutinized by this study with analysis of infrastructure needs and possibilities of development on various aspects of optimization and sustainable use of options of sustainable mobility.

The Failure of Home-Charging Paradigm: One of the most important observations from this analysis is the concept called "Range Anxiety." Even though the average daily travel distance covered by users has been recorded as 45.28 km, the users have been expected to maintain a minimum range-buffer zone of 54.91 km with their vehicles. On the surface, this looks sufficient, as users can easily recharge their batteries when connected at home, but paradoxically, 70.8% of users experience "range anxiety" when 98.1% users have access to home charging facilities.

This disparity points to the idea that range anxiety is not driven by the range of the battery, but the absence of the "safety net." Without the public infrastructure to serve as the "mid-journey" emergency option, people are forced to live a "range-limited" lifestyle where "any change from the regular route becomes an adventure." Thus, the first point is that home charging cannot exist in isolation and that there has to be a public infrastructure to fill the gap between the range of the car and the needs of the daily commute.

The Paradigm Shift from Private to Public Demand: The study reveals that a staggering 81.2% of people would rather have access to Public Charging Stations than any sort of private or business-based facility. A paradigm shift of this nature reveals that the "early adopter" of this new innovation—the driver prone to taking on their own charging duties themselves—has passed. The new breed of driver equates electric charging facilities with gas stations. Such a high level of preference for public accessibility shows that the market is no longer satisfied with the private charging cycles that require seclusion of the vehicle for 5-6 hours. As such, the market is in need of a shared network that would serve the mobility purpose in the urban setting. This presents a clear mandate in that the success of the electric vehicle market is dependent on the development of public-facing charging points. It became apparent in the study that the development of infrastructure should not be assessed in the absence of frameworks that address the matter of policy, finance, institutional frameworks of governance, among other frameworks that have to deal with the equity of development in that it should be beneficial to the disadvantaged members of society.

It is among the many contributors to the international knowledge base on sustainable urban mobility infrastructure in developing South Asian contexts, highlighting the fact that evidence-based planning proper for local conditions can enable infrastructure development capable of supporting rapid electric vehicle market growth while meeting environmental, economic, and social sustainability objectives. The methodology and findings of this report prove to be useful as actionable guidance for Pakistan's decision-makers through frameworks that shall also have relevance in other South Asian cities facing similar transportation challenges and imperatives related to sustainability. Future research needs to realize implementation issues and monitoring performances of infrastructure whenever the systems become operational and refine the planning framework based on empirical experiences and evolving technological capabilities.

Therefore, the final destination of sustainable two-wheeler transportation on a larger scale is dependent on the unsatisfied demand for energy nodes that are conveniently accessible. This paper not only confirms the relevance of the infrastructure being the missing piece, as defined, but that by providing a decentralized charging infrastructure, the freedom of mobility the younger generation of high-mileage drivers require is possible.

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