Electric Vehicle Charging Infrastructure in Türkiye: An Integrated Socio-Technical Framework for Network Readiness, Standards and Energy Justice

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Abstract*—Electric vehicle charging infrastructure is a component of low-carbon mobility, smart grid development and energy transition. However, its evaluation often remains limited to station numbers, market expansion or technical parameters. This study develops an integrated socio-technical framework for assessing electric vehicle charging infrastructure in Türkiye by linking network readiness, technical standards, institutional coordination, digital transparency and energy justice. A qualitative exploratory research design based on thematic document analysis was adopted. Purposively selected academic studies, regulatory documents, technical standards and policy reports published between 2010 and 2026 were coded to identify recurring themes related to grid capacity, transformer adequacy, load management, certification, interoperability, pricing transparency, spatial access, home-charging inequality, user trust and procedural fairness. The findings show that charging infrastructure should be understood as grid-embedded social infrastructure rather than a purely technical or commercial system. Distribution network readiness determines the feasibility, reliability and regional equity of charging deployment. Technical standards, testing, inspection and certification strengthen safety, interoperability, consistency and public trust. Energy justice reveals how charging access may differ across regions, housing types, income groups, disabled users, rural users and digitally disadvantaged users. Digital governance shapes user confidence through real-time availability, price transparency, payment diversity, complaint mechanisms and platform reliability. The proposed framework shifts charging infrastructure evaluation from expansion-oriented metrics to a multidimensional assessment of technical reliability, institutional legitimacy and inclusive access. The study offers practical implications for regulators, distribution system operators, municipalities, charging network operators, testing institutions and policymakers seeking a reliable, transparent and justice-oriented electric mobility transition in Türkiye.

Keywords—*electric vehicle charging infrastructure, distribution network readiness, technical standards, energy justice, Türkiye*.

I. Introduction

A. Background and Context

Electric vehicle charging infrastructure has become a strategic component of energy transition, transport electrification, smart grid development, and low-carbon mobility policy. In Türkiye, the rapid growth of electric mobility requires more than the numerical expansion of charging stations. It also requires distribution network readiness, reliable charging equipment, standardized installation and inspection procedures, institutional coordination, transparent service provision, and equitable access across regions and user groups [1], [2]. For this reason, charging infrastructure should be evaluated not only as a technical investment, but also as a socio-technical infrastructure regime shaped by grid capacity, standard compliance, institutional governance, digital service quality, and energy justice.

One of the factors that will require changes to the distribution network is the increase in electric vehicle charging stations. Electric vehicle charging stations and other electrification applications connected at the distribution level will increase both the load and bidirectional energy flows [3]. Therefore, the successful development of charging infrastructure depends on the interaction between electricity distribution networks, technical standards, regulatory institutions, service providers, municipalities, and users.

Türkiye provides an important context for this discussion because electric vehicle adoption and charging infrastructure expansion are occurring within a developing regulatory, technical and institutional environment [4]. Distribution system operators, charging network operators, municipalities, regulatory authorities, technical standard-setting bodies, testing laboratories, manufacturers and users all shape the quality and direction of this transition. The coordination among these actors is central to ensuring that charging infrastructure is technically reliable, socially inclusive and institutionally legitimate [5].

B. Theoretical Positioning: Charging Infrastructure as a Socio-Technical and Justice-Oriented System

Electric vehicle charging infrastructure cannot be understood only through the physical presence of charging points. It is embedded in electricity networks, governed through institutional rules, standardized through technical specifications, operated through digital platforms, and experienced by users through accessibility, affordability, reliability, and trust. This makes charging infrastructure a socio-technical transition field in which technology, regulation, market actors, user practices, and public expectations interact.

A socio-technical perspective shifts the analytical focus from infrastructure availability to infrastructure quality, reliability, inclusiveness and legitimacy. In this view, station

numbers alone cannot indicate whether charging infrastructure is resilient, interoperable, accessible or socially acceptable. A region may have a growing number of charging stations yet still experience grid constraints, unreliable service quality, fragmented digital platforms, uneven spatial distribution, or limited access for users without home-charging options.

Energy justice provides a second theoretical lens for evaluating charging infrastructure. Distributional justice concerns the spatial and economic distribution of charging services. Procedural justice concerns transparency, accountability, and participation in infrastructure planning and regulation. Recognition justice concerns the differentiated needs of user groups whose mobility and charging conditions are shaped by income, housing type, location, disability status, digital capacity, and access to private parking [6], [7]. These dimensions are directly relevant to Türkiye's transition to charging infrastructure because charging access may differ substantially across metropolitan areas, smaller cities, rural regions, apartment-dense neighborhoods, and lower-income districts.

Infrastructure justice further extends this perspective by emphasizing that public-facing infrastructure systems should be evaluated in terms of access, usability, reliability, affordability, and inclusion. In the case of electric vehicle charging, this includes regional coverage, home-charging inequality, apartment residents, users without private parking, low-income users, rural users, disabled users, elderly users, and digitally disadvantaged groups. Therefore, charging infrastructure should be assessed as both an energy infrastructure and a mobility infrastructure that may either reduce or reproduce existing inequalities.

C. Problem Statement and Literature Gap

Existing studies on electric vehicle charging infrastructure generally focus on technical optimization, charging station location, grid impacts, battery technologies, demand forecasting, smart charging, consumer adoption, and market development. Although these studies provide important insights, they often examine technical infrastructure, regulation, user access, and energy justice as separate areas [6]. This separation limits the understanding of charging infrastructure as an integrated system that combines grid capacity, technical compliance, institutional governance, digital service transparency, and social equity [7].

In Türkiye the research on charging infrastructure focuses on the discussion about additional investment requirements for electric vehicle charging stations, smart charging solutions to mitigate potential impacts on the distribution grid and policy recommendations. Energy justice is generally considered within broader energy transition debates, but it is less frequently connected to electric vehicle charging infrastructure [8], [9]. As a result, there remains a need for an integrated analytical framework that links distribution network readiness, technical standardization, institutional coordination, digital service transparency, and energy justice in the Turkish context.

This gap is important because charging infrastructure can create new forms of inequality. Regions with stronger grid capacity and higher investment potential may receive better charging services, while underserved areas may remain disadvantaged. Users living in detached houses may access home charging more easily, whereas apartment residents, renters, and users without private parking may depend heavily on public charging networks. Rural users, low-income groups, disabled users, digitally disadvantaged users, and people with limited access to reliable public charging may face additional barriers. These issues show that charging infrastructure is both a technical matter and a question of spatial, economic, digital and procedural justice.

D. Aim and Original Contribution

This study aims to develop a socio-technical framework for evaluating electric vehicle charging infrastructure in Türkiye by linking distribution network readiness, technical standards, institutional coordination, digital transparency and energy justice. The study conceptualizes charging infrastructure as grid-embedded social infrastructure. In this view, charging systems are not only electrical assets but also public-facing service infrastructure that affects user trust, accessibility, mobility practices, and public acceptance.

The article's original contribution lies in its integrated approach. Technical standards, testing, inspection, interoperability, and certification are examined not only as engineering and compliance mechanisms but also as factors shaping infrastructure legitimacy, user trust, and procedural fairness. Safe installation, reliable equipment, transparent operation and interoperable access can improve user confidence and strengthen the perceived legitimacy of the charging ecosystem. Thus, technical reliability has a broader social meaning because it influences how users experience, evaluate, and trust the charging system.

The study also contributes by integrating energy justice into the analysis of electric vehicle charging infrastructure. Energy justice is addressed through distributional, procedural, and recognition-based dimensions. Distributional justice concerns the spatial and economic distribution of charging services. Procedural justice concerns transparent planning, regulatory accountability, and institutional coordination. Recognition justice concerns the needs of different user groups, including apartment residents, users without home charging opportunities, rural users, digitally disadvantaged users, disabled users, and those who primarily rely on public charging.

E. Research Questions

The study is guided by the following research questions:

RQ1. Through which technical, institutional and social components can electric vehicle charging infrastructure in Türkiye be conceptualized as a socio-technical transition field?

RQ2. How does distribution network readiness shape the reliability, regional deployment and equitable accessibility of electric vehicle charging infrastructure?

RQ3. How do technical standards, testing, inspection, certification and interoperability mechanisms function as sources of infrastructure reliability, user trust and institutional legitimacy?

RQ4. How does an energy justice perspective require the reassessment of electric vehicle charging infrastructure in Türkiye in terms of spatial access, pricing, home-charging inequality, digital inclusion and user diversity?

RQ5. What integrated socio-technical framework can be proposed to evaluate reliable, inclusive, and justice-oriented electric vehicle charging infrastructure in Türkiye?

F. Scope and Research Direction

The study focuses on electric vehicle charging infrastructure in Türkiye, with particular attention to distribution networks, charging station expansion, technical standards, institutional arrangements, digital service transparency and justice-oriented access. It covers public and semi-public charging infrastructure, home-charging implications, fast and slow charging systems, technical specification requirements, regulatory governance and user-facing digital service dimensions.

The study develops a conceptual and analytical framework based on qualitative thematic document analysis. This approach is suitable because the main purpose is to explain how technical, institutional and justice-related dimensions interact in the planning and governance of charging infrastructure. The article therefore examines charging infrastructure as an integrated socio-technical system rather than as a narrow technical, commercial or behavioral issue.

G. Expected Outcomes and Practical Implications

The expected outcome of the study is an integrated framework for assessing electric vehicle charging infrastructure in Türkiye beyond station numbers and market growth indicators. The framework identifies the interactions among distribution network readiness, technical standards, institutional coordination, digital transparency, and energy justice. It emphasizes that the success of charging infrastructure should be evaluated through grid adequacy, service reliability, interoperability, pricing transparency, regional coverage, user accessibility, digital usability and public trust.

The practical implications are relevant for several stakeholders. Regulators may use the framework to develop equity-sensitive charging policies. Distribution system operators may align grid reinforcement with charging demand and regional access needs. Municipalities may use it for inclusive location planning. Charging network operators may improve service transparency, reliability, interoperability, and user trust. Testing and certification institutions may also recognize the broader social relevance of technical reliability. Overall, the study argues that Türkiye's transition to charging infrastructure requires the integration of technical readiness, standardization, governance, and justice-oriented planning.

II. METHODOLOGY

This study adopts a qualitative exploratory research design based on thematic document analysis. This approach is appropriate because the study aims to synthesize the technical, institutional and social dimensions of electric vehicle charging infrastructure in Türkiye and to develop an integrated socio-technical framework for its evaluation. Rather than focusing on a single technical parameter or market indicator, the analysis brings together selected academic, regulatory, policy and technical sources that directly address the governance, reliability, accessibility and justice dimensions of charging infrastructure.

The data sources consist of regulatory documents, technical standards and specifications, policy reports, and academic literature. Regulatory documents are used to examine governance of charging services, licensing, pricing, user information, platform operations, and institutional responsibilities. Technical standards and specification documents are reviewed with respect to installation, testing, certification, safety, inspection, interoperability, metering, and service reliability. Policy reports and academic studies are used to evaluate Türkiye's electric vehicle charging development, distribution network readiness, smart charging, grid integration, energy justice, user trust, spatial access and socio-technical transition processes.

The source selection followed a purposive logic. Documents were included when they provided direct analytical relevance to at least one of the following dimensions: electric vehicle charging infrastructure, distribution grid impacts, technical standards, institutional governance, pricing transparency, digital platforms, spatial access, home-charging inequality, user trust or inclusive infrastructure planning. Sources focusing only on battery chemistry, vehicle design, automotive manufacturing, or company-level marketing were not included unless they directly addressed charging infrastructure governance, technical compliance, or user access. The reviewed material covers the period from 2010 to 2026, as debates on electric mobility, smart grid development, renewable energy integration, digitalized infrastructure, and energy justice have become increasingly prominent during this period.

The analysis was conducted through thematic coding. In the first stage, the selected documents were reviewed to identify recurring concepts, problem areas, and governance concerns related to electric vehicle charging infrastructure. Initial codes included grid capacity, transformer adequacy, voltage quality, connection procedures, peak load management, smart charging, technical standards, testing, inspection, certification, interoperability, licensing, pricing, digital transparency, regional access, home-charging inequality, user trust, accessibility, and procedural fairness.

In the second stage, these initial codes were grouped into broader analytical categories. Four main categories were developed: distribution network readiness; technical standards and institutional coordination; energy justice and inclusive access; and digital governance and service transparency. These categories reflect the main dimensions through which charging infrastructure reliability, legitimacy and inclusiveness can be evaluated.

In the final stage, the analytical categories were synthesized into a socio-technical framework for evaluating electric vehicle charging infrastructure in Türkiye. The framework links technical readiness, standardization, institutional governance, digital service quality, and energy justice. It is intended to support a broader evaluation of charging infrastructure beyond station numbers by emphasizing grid adequacy, service reliability, interoperability, price transparency, regional coverage, user accessibility, and public trust.

III. FINDINGS

A. EV Charging Infrastructure as a Socio-Technical Transition Field in Türkiye

Electric vehicle charging infrastructure in Türkiye can be conceptualized as a socio-technical transition field because it connects electrical networks, regulatory institutions, market actors, technical standards, digital platforms, and diverse user groups. Charging infrastructure is not limited to the physical installation of charging stations. It is embedded in distribution networks, shaped by public regulation, operated by charging network providers, and experienced by users through access, pricing, reliability, and digital service interfaces. Therefore, its development should be evaluated as part of a broader infrastructure transition rather than a narrow technological expansion [10], [11]. The socio-technical character of charging infrastructure becomes visible in several ways. First, charging stations create new electricity demand patterns that must be coordinated with local grid capacity and network conditions [12]. Second, the quality of charging services depends on technical specifications, installation procedures, testing, inspection, certification, and maintenance [13]. Third, user adoption is influenced by accessibility, price transparency, payment convenience, station reliability, digital information, and trust [14]. Fourth, infrastructure planning may either reduce or reproduce inequalities depending on station locations, pricing structures, home-charging opportunities, and the inclusion of different user groups [15]. In this respect, the Turkish charging ecosystem should not be assessed only through the number of stations. Numerical growth may coexist with uneven spatial distribution, regional grid constraints, limited interoperability or insufficient service transparency. A socio-technical perspective shifts the focus from infrastructure availability to infrastructure quality, reliability, inclusiveness and legitimacy.

B. Distribution Network Readiness and Grid-Embedded Charging Infrastructure

Distribution network readiness is a foundational condition for the sustainable expansion of EV charging infrastructure. It includes local grid capacity, transformer adequacy, voltage stability, peak-demand management, connection procedures, power quality, demand forecasting, smart-charging capability, renewable-energy integration, and operational resilience under high-load conditions. Since charging stations are directly connected to distribution systems, their technical performance depends on the capacity and flexibility of local networks [16]. Different charging types create different load impacts. Home charging may increase evening residential demand, particularly when users charge vehicles after work. Public alternating-current charging may create moderate but geographically dispersed demand [17]. Direct-current fast charging and high-power charging may produce concentrated peak loads in commercial zones, highway corridors, fleet depots, and urban mobility centers. These differences require differentiated planning strategies from distribution system operators. Grid readiness also has a justice dimension. Regions with stronger distribution infrastructure may attract charging investment more easily, while areas with weaker grid capacity may experience delayed deployment, reduced service reliability, or limited access to charging [18]. This may create mobility-energy exclusion, especially in regions where electric mobility is expected to expand but grid reinforcement remains insufficient. Therefore, distribution network readiness should be understood as a technical planning issue and precondition for equitable access to electric mobility. Smart charging, demand-side management, local storage, renewable energy integration, time-sensitive pricing, and grid reinforcement can reduce the pressure on the grid from EV charging loads. However, these mechanisms should be designed with user diversity in mind [19], [20]. Flexible charging and dynamic tariffs may benefit users with private parking, home-charging access, and adaptable schedules. In contrast, users who depend on public fast charging may face higher costs and reduced flexibility.

C. Technical Standards, Testing, Inspection and Infrastructure Legitimacy

Technical standards and specifications play a central role in shaping the reliability, safety, interoperability and institutional legitimacy of EV charging infrastructure. Standards define how charging equipment is designed, installed, connected, tested, operated and maintained. They influence electrical safety, connector compatibility, communication protocols, metering accuracy, grounding systems, protection mechanisms, power quality and service consistency. Testing, inspection and certification mechanisms translate technical standards into public trust [21]. Users cannot directly evaluate grounding quality, protection coordination, interoperability protocols or power quality performance. Instead, they rely on the assumption that charging systems are properly specified, installed, tested, certified, inspected and maintained. In this sense, technical compliance functions as a trust-building mechanism. Interoperability is also important for service equity [22]. If charging infrastructure becomes fragmented across incompatible connectors, payment systems, platforms or operator-specific access conditions, users may experience unequal service quality. Interoperability, therefore, has a justice dimension because it affects whether users can access charging services across different regions, operators, and digital platforms without unnecessary barriers [23]. In Türkiye, IEC-based standards and national technical specifications can support reliable and internationally aligned charging infrastructure. However, standardization should be interpreted as an engineering requirement and mechanism that strengthens safety, predictability, user confidence and infrastructure legitimacy.

D. Energy Justice, Spatial Access, Affordability and User Inclusion

Energy justice provides a critical analytical view for evaluating EV charging infrastructure in Türkiye. Distributional justice concerns the spatial and social distribution of charging services. Procedural justice concerns transparency, participation, regulation and accountability in infrastructure planning. Recognition justice concerns the differentiated needs of users with different housing conditions, income levels, mobility patterns, digital capacities, regional locations and accessibility requirements [6]. Spatial access is one of the most visible justice issues. Charging infrastructure concentrated in metropolitan areas, high-income districts, commercial zones and highway

corridors may support early adopters but leave smaller cities, rural areas, apartment-dense neighborhoods and low-income regions behind [7]. A station-expansion model based only on market demand may therefore reproduce existing regional and urban inequalities unless it is supported by equity-sensitive planning. Affordability is another central issue. Pricing strategies, dynamic tariffs, service fees, membership systems, roaming costs, and payment models influence whether EV use remains accessible to different user groups. Users with home-charging access may benefit from lower, more predictable charging costs, while apartment residents, renters, and users without private parking may rely more heavily on public charging [24]. This creates a potential inequality between users with private charging options and those who depend on public infrastructure. Recognition justice requires charging policy to consider diverse user profiles, including apartment residents, long-distance travelers, taxi and fleet operators, disabled users, elderly users, digitally disadvantaged users, low-income groups, and residents of underserved regions [25]. Inclusive charging infrastructure requires accessible locations, transparent prices, reliable digital information, multiple payment options, physical accessibility standards, and clear complaint mechanisms.

E. Integrated Socio-Technical Framework: Digital Governance, Service Transparency and User Trust as Cross-Cutting Dimensions

Digital governance is central to the practical operation of EV charging infrastructure. Charging services increasingly depend on mobile applications, real-time station availability data, digital payments, user accounts, navigation systems, remote monitoring and data exchange between operators and regulators. These digital layers directly shape user experience and service trust. Service transparency requires accurate information on station availability, operating status, connector type, charging speed, price, payment method, waiting time, malfunction status, and service interruptions [26], [27]. Users need reliable information before reaching a charging station. Incomplete or inaccurate information may increase range anxiety, reduce user confidence, and weaken public acceptance of electric mobility. However, digitalization can also create exclusion risks [28]. Users with limited digital literacy, limited smartphone access, language barriers, payment restrictions, or accessibility needs may face difficulties if charging services become overly app-dependent. Therefore, platform design should be considered part of energy justice. Transparent, accessible, multilingual, user-friendly, and interoperable digital systems can support procedural fairness and user trust [29]. An integrated socio-technical framework for Türkiye should combine distribution network readiness, technical standardization, institutional coordination, energy justice and digital transparency. Charging infrastructure should be evaluated using indicators such as grid adequacy, compliance with standards, station uptime, price transparency, regional coverage, payment diversity, user accessibility, complaint resolution, interoperability, and platform reliability.

Taken together, the findings suggest that EV charging infrastructure in Türkiye should be evaluated through an integrated socio-technical framework composed of five interrelated dimensions: distribution network readiness, technical standards and compliance, institutional coordination, energy justice and inclusive access, and digital governance and service transparency. These dimensions are mutually reinforcing. Grid readiness determines the technical feasibility and regional reliability of charging services; standards and certification strengthen safety, interoperability and legitimacy; institutional coordination aligns regulatory, municipal and operator responsibilities; energy justice ensures that access, affordability and recognition are embedded in planning; and digital transparency shapes user trust, procedural fairness and service accountability. Therefore, the proposed framework shifts the evaluation of charging infrastructure from station numbers to the combined assessment of technical reliability, institutional legitimacy and inclusive access.

Figure 1 visually summarizes the proposed integrated socio-technical framework for evaluating justice-oriented EV charging infrastructure in Türkiye, highlighting the interrelated roles of distribution network readiness, technical standards and compliance, institutional coordination, energy justice and inclusive access, and digital governance and service transparency.

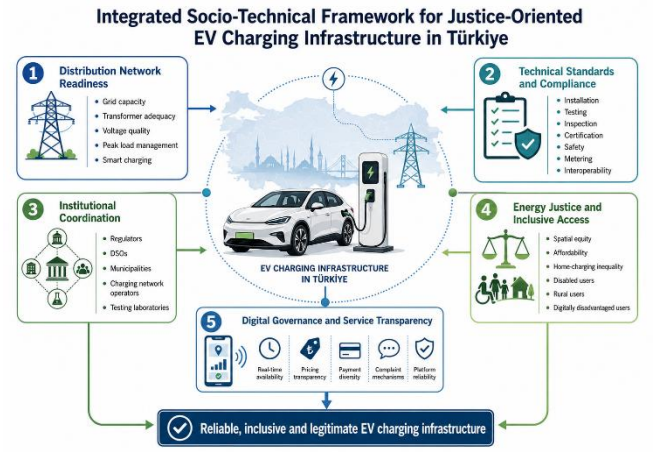

Fig. 1. Integrated Socio-Technical Framework for Justice-Oriented EV Charging Infrastructure in Türkiye.

IV. DISCUSSION

The findings indicate that electric vehicle charging infrastructure in Türkiye should be understood as a socio-technical system rather than a purely technical or market-based development. In response to RQ1, the analysis shows that charging infrastructure is shaped by the interaction of distribution networks, regulatory institutions, technical standards, digital platforms, market actors, and user practices. This perspective is consistent with socio-technical transition approaches, which emphasize that energy transitions depend on technological change, institutional coordination, user acceptance, service reliability, and social legitimacy [30]. The main implication is that charging infrastructure cannot be adequately evaluated through station numbers alone. Its performance also depends on whether charging services are technically reliable, institutionally coordinated, digitally transparent and socially inclusive.

Regarding RQ2, the study identifies distribution network readiness as the technical foundation of charging infrastructure expansion. Grid capacity, transformer adequacy, voltage stability, power quality, demand forecasting, smart charging and load management directly

affect the reliability and feasibility of charging services. However, the discussion also shows that grid readiness has a social dimension. Regions with limited distribution capacity may experience slower infrastructure deployment, lower service quality and weaker access to electric mobility [17], [18]. Therefore, grid planning should be linked with equity-sensitive infrastructure development. This is particularly important for Türkiye, where regional differences in infrastructure capacity, urban density, housing patterns and charging demand may shape the uneven distribution of electric mobility benefits.

In relation to RQ3, technical standards, testing, inspection, certification, and maintenance are understood as more than mere compliance mechanisms. They function as instruments of reliability, safety, interoperability and institutional legitimacy. Since users cannot directly observe the technical quality of charging equipment, trust depends on the assumption that systems are properly installed, tested, inspected and maintained [21], [30], [22]. In this respect, technical standardization contributes to operational performance and public confidence in charging infrastructure. This finding also suggests that technical reliability has a social meaning: safe, interoperable and consistently functioning charging systems support user trust, reduce uncertainty and strengthen the legitimacy of the charging ecosystem.

RQ4 is addressed by demonstrating the importance of energy justice in charging infrastructure planning. Spatial access, affordability, home-charging inequality, digital inclusion, physical accessibility and user diversity are central issues for Türkiye's EV transition. Charging infrastructure may reproduce inequality if it is concentrated in metropolitan, high-income, or commercially attractive areas, while underserved regions, apartment residents, low-income users, and digitally disadvantaged groups receive less support [10], [24], [7]. Therefore, EV charging policy should consider who benefits from infrastructure expansion and whose needs are recognized in planning and service design. In this context, energy justice should not be treated as an external ethical concern, but as an internal planning criterion for charging infrastructure development.

RQ5 is addressed through the proposed socio-technical framework, which connects distribution network readiness, technical standards, institutional coordination, energy justice and digital transparency. This framework enables the evaluation of charging infrastructure beyond station numbers or market growth indicators. It emphasizes service reliability, regional coverage, interoperability, price transparency, user trust and inclusive access as core evaluation dimensions [10], [17], [30]. The framework also clarifies that these dimensions are mutually reinforcing. Grid readiness determines the technical feasibility and regional reliability of charging services; standards and certification strengthen safety, interoperability, and legitimacy; institutional coordination aligns regulatory, municipal, and operator responsibilities; energy justice embeds access, affordability, and recognition into planning; and digital transparency shapes user trust, procedural fairness, and service accountability.

The study shows that the academic and practical value of the proposed framework lies in integrating technical reliability and social justice into a single analytical model. For Türkiye, this means that charging infrastructure policy should shift from a station-expansion logic toward a quality-, reliability-, and justice-oriented infrastructure governance approach. Such an approach can support a more resilient and inclusive electric mobility transition by aligning grid planning, technical standardization, institutional coordination, digital service quality and user-centered access.

V. Conclusion and Implications

This study concludes that electric vehicle charging infrastructure in Türkiye should be understood as a socio-technical transition field rather than solely a technical investment area or market expansion issue. The findings show that reliable, inclusive, and legitimate charging infrastructure depends on the interaction of distribution network readiness, technical standards and compliance, institutional coordination, digital governance, and energy justice. In this respect, the success of charging infrastructure cannot be assessed solely by the number of charging points, market growth indicators, or station availability. It should also be evaluated based on grid adequacy, service reliability, interoperability, pricing transparency, regional coverage, accessibility, digital usability, and user trust.

The first key finding is that distribution network readiness is a foundational condition for the development of sustainable charging infrastructure. Grid capacity, transformer adequacy, voltage quality, load forecasting, peak demand management, smart charging and system resilience are central to the technical reliability of charging services. However, the study also shows that grid readiness has a justice dimension. Regions with stronger distribution infrastructure may attract investment more quickly, while areas with weaker grid capacity may experience delayed deployment, lower service quality, or limited access to charging. Therefore, grid reinforcement and charging infrastructure planning should be coordinated with regional equity concerns.

The second key finding is that technical standards, testing, inspection, certification and interoperability are not merely engineering or compliance requirements. They also function as mechanisms of infrastructure legitimacy and public trust. Since users cannot directly observe grounding quality, protection mechanisms, metering accuracy, communication protocols or power quality, they rely on the assumption that charging systems are properly installed, tested, inspected, certified and maintained. In this sense, technical compliance contributes to safety, reliability, service consistency, interoperability and user confidence.

The third key finding is that energy justice should be treated as a core planning principle in electric vehicle charging infrastructure. Charging infrastructure may create or reproduce inequalities if spatial access, affordability, home-charging opportunities, digital inclusion, physical accessibility and user diversity are not considered together. Apartment residents, renters, users without private parking, rural users, low-income groups, disabled users, elderly users and digitally disadvantaged users may experience different forms of charging vulnerability. For this reason, EV charging policy should integrate distributional, procedural and recognition-based justice into infrastructure planning and service governance.

The fourth key finding is that digital governance and service transparency directly shape user trust and public acceptance. Real-time station availability, pricing information, payment

options, malfunction status, wait times, connector types, charging speeds, and complaint mechanisms are not secondary service details. They are part of the public-facing quality of charging infrastructure. Inaccurate, fragmented, or inaccessible digital information may increase range anxiety and reduce confidence in electric mobility. Therefore, digital transparency should be evaluated as a procedural justice and service accountability issue.

The study makes a theoretical contribution by conceptualizing EV charging infrastructure as grid-embedded social infrastructure. This perspective connects socio-technical transition theory, energy justice and infrastructure justice. It shows that technical reliability and social inclusion should not be treated as separate evaluation domains. Instead, grid readiness, standard compliance, institutional coordination, digital transparency and inclusive access jointly determine whether charging infrastructure becomes reliable, legitimate and socially acceptable.

The proposed framework also has practical implications for key stakeholders. Regulators can use the framework to develop equity-sensitive charging policies, define minimum service transparency requirements and monitor infrastructure quality beyond station numbers. Distribution system operators can align grid reinforcement, transformer planning, load forecasting and smart charging strategies with regional charging demand and access needs. Municipalities can use the framework for inclusive location planning by considering apartment-dense neighborhoods, underserved districts, rural connections, disabled users and public-space accessibility. Charging network operators can improve service reliability, price transparency, payment diversity, interoperability and complaint resolution mechanisms. Testing, inspection and certification institutions can contribute to public trust by ensuring that technical compliance is connected to safety, reliability and service consistency. Policymakers can use the framework to align electric mobility, smart grid development, urban planning, consumer protection and energy justice objectives.

For implementation, EV charging infrastructure in Türkiye should be monitored using a multidimensional set of indicators. These indicators may include grid adequacy, transformer capacity, connection time, voltage quality, station uptime, fault frequency, repair time, price transparency, payment diversity, interoperability, regional distribution, accessibility for disabled users, public versus home-charging dependence, complaint resolution time, digital platform reliability and user satisfaction. Such indicators would allow policymakers and regulators to move beyond expansion-oriented metrics and evaluate whether charging infrastructure is technically reliable, spatially balanced, affordable, transparent and inclusive.

This study has several limitations. It is based on qualitative thematic document analysis and does not include station-level technical measurements, user surveys, interviews, econometric modeling or power system simulations. The framework is conceptual and analytical; therefore, it should be tested through empirical studies in different regional and user contexts. The study also focuses on Türkiye, which provides a relevant case for examining charging infrastructure in a developing regulatory and institutional environment. However, the findings may require adaptation when applied to countries with different grid structures, housing patterns, charging markets and regulatory systems.

Future research can extend this framework in several directions. First, regional access mapping can be used to examine whether charging infrastructure is equitably distributed across metropolitan areas, smaller cities, rural regions and underserved districts. Second, user surveys and interviews can assess how apartment residents, renters, fleet operators, disabled users, elderly users, and digitally disadvantaged groups experience charging access, pricing, and service reliability. Third, grid impact simulations can evaluate how fast charging, high-power charging, smart charging, storage systems and dynamic tariffs affect distribution networks under different demand scenarios. Fourth, comparative studies can examine the differences among home, workplace, public, and highway charging in terms of cost, reliability, and justice outcomes. Fifth, future research can investigate artificial intelligence, data governance, platform interoperability and algorithmic pricing in EV charging services from an energy justice perspective.

In conclusion, the transition to electric mobility in Türkiye requires a broader understanding of charging infrastructure. Expanding the number of charging stations is necessary but insufficient. A reliable and inclusive charging ecosystem also requires prepared distribution networks, robust technical standards, effective institutional coordination, transparent digital services and justice-oriented planning. The proposed socio-technical framework provides a basis for evaluating and governing EV charging infrastructure as a public-facing system that must be technically reliable, institutionally legitimate, and socially inclusive.

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