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Diagnosis and Foresight in the Design of Smart Charging Systems for Autonomous Electric Vehicle Fleets in Megacities

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ABSTRACT

The rapid growth of electric transportation and the increasing adoption of autonomous vehicles have made the development of smart charging systems a necessity. Megacities in Iran face challenges such as the depletion of fossil fuel resources, rising air pollution, and infrastructural constraints, which further emphasize the need for advanced and optimized charging systems. This study examines the necessity of developing smart charging infrastructures for autonomous electric vehicles in megacities, analyzing the associated challenges and opportunities. The research focuses on evaluating the macro-environmental dimensions influencing this technology using the PESTEL framework, encompassing political, economic, social, technological, environmental, and legal factors. A descriptive-analytical methodology was employed, with data collected from secondary sources including scientific articles, industry reports, policy documents, and successful global case studies. The findings indicate that the development of smart charging systems requires coordinated planning among government entities, the private sector, and society. Economically, the high costs of installation and maintenance, along with currency fluctuations, are key challenges that call for financial incentives and foreign investment. From a technological perspective, integrating charging systems with smart grids, the Internet of Things (IoT), and artificial intelligence (AI) can enhance overall efficiency. Environmentally, the use of renewable energy sources and optimization of power consumption at charging stations are crucial strategies for mitigating environmental impact. Legally, the need for new regulations governing charging standards, cybersecurity, and data ownership poses significant challenges. This research

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provides a comprehensive analysis of the multifaceted development of smart charging systems and offers actionable insights for policymakers, urban managers, and investors to optimize charging infrastructure and advance toward sustainable urban mobility. The study underscores that for this technology to succeed in Iran, legal, economic, and social challenges must be meticulously managed, while technological and environmental solutions must align with broader sustainable development goals.

Keywords: Autonomous vehicles, smart charging systems, sustainable transportation, megacities

1. Introduction

Over time, cities have undergone tremendous transformations, with transportation systems and technologies serving as integral components of these changes. In the past two decades, remarkable advances in wireless communication, computational power, and sensing systems have significantly reshaped traffic management systems. These developments have been driven by the goals of enhancing mobility, sustainability, safety, and system reliability. The new generation of technological innovations, particularly in the domain of vehicles, is aimed at influencing these systems. Among such innovations are connected and autonomous vehicles, which, through advanced technologies in sensing, pattern recognition, and intelligent control, have revolutionized the transportation industry (Sepehri et al., 2021).

In defining autonomous vehicles, the state of Nevada introduced a legal definition in 2011, describing them as "vehicles capable of operating without human intervention using artificial intelligence, sensors, and global positioning systems." In this context, the Society of Automotive Engineers (SAE) has established a set of standards for classifying various levels of driving automation. These levels range from Level 0, where the human driver performs all driving tasks, to Level 5, where the vehicle is fully autonomous and capable of executing all driving functions without any human input (Nahid Parsa, 2023).

Connected and Autonomous Vehicles (CAVs) are rapidly becoming a reality in modern transportation, offering considerable advantages such as enhanced safety. These technologies are designed to make instantaneous decisions in various situations, often reacting more quickly than human drivers. As a result, these vehicles can help reduce accidents, facilitate efficient route planning, and alleviate traffic congestion—leading to lower fuel consumption and fewer emissions. Moreover, CAVs can significantly improve mobility for individuals with physical limitations and contribute to the reduction of greenhouse gas emissions (HamidHanifi et al., 2022). However, despite their many benefits, these emerging technologies face several challenges. High production and maintenance costs of the associated hardware and software, data security concerns, the need for control centers and supporting infrastructure, and complex socio-legal and regulatory issues are among the most critical obstacles. In particular, if autonomous vehicles are electric, they not only contribute to energy efficiency but also pave the way toward achieving sustainable transportation goals. One of the key challenges in this context is the provision of electricity for these vehicles, which necessitates the development and deployment of smart charging systems in urban environments.[4]

Therefore, intelligent transportation is considered a critical component of sustainable development. This concept emphasizes the sustainable protection, maintenance, and utilization of natural resources to meet present human needs while ensuring that future generations can access environmental, economic, and social resources. In this regard, smart transportation, serving as a tool for social equity seeks to offer more inclusive access across different social groups, reduce economic costs, and effectively minimize environmental pollution (Ibrahim Abaker, 2023).

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The development of sustainable transportation requires the establishment of appropriate organizational and technical infrastructure. The integration of software and hardware in intelligent transportation systems can address various challenges in productive sectors such as agriculture, industry, services, and tourism, while also promoting social equity. Ensuring road safety, improving road communications, and reducing operational costs, considered prerequisites for sustainable development will contribute to expanded trade and enhanced quality of life in communities (Alireza Haggoo, 2023). Autonomous electric vehicles, as an emerging technology within smart systems, play a vital role in achieving sustainable development. These vehicles, by utilizing renewable energy sources, contribute to reducing greenhouse gas emissions and are expected to aid in environmental restoration and quality-of-life improvement, particularly in Iran's major cities. The expansion of this technology and its related infrastructure can foster urban circular economies (e.g., automotive waste recycling) and social connectivity, steering cities toward sustainable development. Additionally, smart charging systems are among the critical technologies required to realize these objectives.

On the other hand, the depletion of fossil fuel resources and the increase in environmental pollution have driven the widespread adoption of electric vehicles (EVs) within the transportation sector (Saeed Zolfaghari Moghaddam, 2022). Globally, the transportation system is one of the largest energy consumers, accounting for nearly one-third of total energy usage. Moreover, transportation systems based on internal combustion engines (ICEs) are the primary source of air pollution and greenhouse gas emissions. In recent years, the electrification of transportation systems has garnered significant attention as a means to minimize these adverse effects and reduce dependence on fossil fuels. In this context, research into electric vehicles (EVs) as a safe and sustainable alternative has gained considerable importance. Despite this, the development of EVs has been slow due to high costs and a lack of sufficient charging infrastructure. Consequently, many countries have implemented policies and regulations to overcome these barriers and promote the large-scale adoption of EVs (Parsa Parhizgar, 2022). Therefore, the development of electric vehicles in Iran’s megacities appears to be inevitable, especially in pursuit of sustainable transportation objectives. Meeting the energy demands of this transition necessitates the deployment of smart charging systems. These systems, powered by advanced algorithms, can determine the optimal time for vehicle charging and can also leverage renewable energy sources. They employ specific standards such as wireless and automated charging. The algorithms embedded within these systems are designed to continuously monitor battery health, ultimately contributing to extended battery lifespan and improved system efficiency.

Therefore, in this study, the PESTEL framework is employed as an analytical tool to assess the necessity and challenges associated with the development of smart charging systems in Iran’s megacities. PESTEL is a strategic analysis method that enables researchers to identify and evaluate Political (P), Economic (E), Social (S), Technological (T), Environmental (E), and Legal (L) factors that influence a specific phenomenon. In this research, the PESTEL framework is utilized to examine the various dimensions affecting the development of smart charging systems in Iran, focusing on both existing challenges and potential opportunities in this domain.

The main objective of this study is to identify and analyze the key dimensions influencing the development of smart charging systems for electric vehicles in Iranian metropolitan areas. Through the PESTEL methodology, the study offers an in-depth evaluation of political and economic aspects such as government policies, legislation, and associated costs, as well as social and cultural factors impacting public acceptance of these technologies. Moreover, the research addresses technical and environmental challenges, including infrastructure development for electric vehicle charging and the mitigation of negative environmental impacts stemming from fossil fuel consumption.

This research seeks to uncover the barriers and constraints hindering the development of smart charging systems and to propose effective strategies to overcome them and accelerate progress in this area. One of the key innovations of this study lies in the application of the PESTEL framework for a comprehensive analysis of this issue within the Iranian context. Given the country’s unique social,

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economic, and technical characteristics, the research aims to offer deeper insights into local needs and the specific features of the electric vehicle and smart charging market.

In addition, the study identifies technological and policy-driven solutions that can facilitate the acceptance and deployment of electric vehicles and associated smart infrastructure in Iran. Particular attention is also given to the potential integration of renewable energy sources and modern technologies within smart charging systems. While most previous studies have focused on analyzing the challenges and opportunities of these technologies in developed countries, this research considers the unique conditions and constraints of Iran's megacities, offering a localized analysis of the environmental and economic impacts of smart charging infrastructure. Specifically, the study emphasizes how clean energy sources and energy-efficient management systems can be utilized in the smart charging of electric vehicles.

Theoretical Foundations and Literature Review

Electric and autonomous vehicles, as emerging technologies, have been proposed not only for reducing traffic congestion through the use of clean energy but also as a solution to environmental challenges and the reduction of fossil fuel consumption. One of the primary challenges associated with the deployment of these technologies lies in the charging methods, related algorithms, and infrastructure requirements, necessitating the adoption of smart charging systems by specialists and practitioners.

The simultaneous integration of smart charging technology and autonomous electric vehicles has the potential to revolutionize both urban and interurban transportation. Leveraging sensors, intelligent equipment, and real-time data, these systems enable improved traffic management, optimized route selection, and more efficient vehicle charging strategies, which in turn help reduce overall transportation costs.

A smart charging system refers to an infrastructure that utilizes advanced technologies to charge electric vehicles or equipment while considering specific features such as intelligent energy consumption management, predictive algorithms for estimating charging time, and automated control of the charging process via both software and hardware platforms. These systems monitor energy usage in real time and allow for dynamic adjustments based on demand and availability.

Among the notable capabilities of smart charging systems are the issuance of real-time alerts in the event of technical failures, as well as battery charge time management to prevent overcharging and prolong battery life. Such systems play a pivotal role in enhancing the operational reliability and energy efficiency of electric vehicle ecosystems. Today, the deployment of autonomous electric vehicles requires intelligent charging infrastructure, and such technology is increasingly being made available to drivers through mobile phones and tablet applications. Smart charging refers to an ecosystem for electric vehicle (EV) charging, in which the electric vehicle and the charging device form a standardized network that shares essential information with a charging operator. Unlike conventional chargers, smart charging stations are connected to the cloud, allowing station owners to monitor and manage usage limitations of their equipment for optimized energy distribution. The flexibility to add or remove features and create a system tailored to user needs is enabled through intelligent infrastructure. Electric vehicles that are intelligently charged and grid-connected can collaborate with the power grid to facilitate uniform and low-loss energy distribution. This symbiotic relationship is not possible without smart charging, since under normal circumstances, a high volume of simultaneously charging EVs could place excessive strain on the power grid, turning them into disruptive loads. A complex end-to-back virtual power plant system that supports smart EV charging allows charging station operators to monitor connected EVs and their charging events in real time. Due to cloud connectivity, smart stations can respond dynamically to a variety of input signals, including variable energy production, local electricity consumption, and the number of online EVs, by leveraging advanced electrical equipment.

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Moreover, this system is capable of aggregating heterogeneous distributed energy resources, such as solar panels, batteries, electric vehicles, wind turbines, and more (E-Amrit, 2023).

Electric vehicles (EVs) are increasingly gaining popularity as a sustainable mode of transportation due to their low environmental impact and high energy efficiency. However, range limitations and long battery charging times continue to pose major challenges. Smart chargers address these issues by considering multiple factors such as battery chemistry, ambient temperature, state of charge, and infrastructure capacity, to determine the optimal charging rate. Furthermore, smart chargers can communicate with the grid to adjust charging rates and utilize renewable energy sources when available. They are also equipped with safety features such as over-voltage and over-current protection to ensure the safety of both the EV and the charging infrastructure (Ramesh P. et al., 2024).

Smart charging is a method of actively monitoring and controlling EV chargers to optimize energy distribution and consumption while preventing peak load issues. The architectural design and functional blocks of a Smart Charging System (SCS) have been implemented through an iterative development process as part of the open-source “Open e-Mobility” solution. Details about the core charging algorithm used in SCS show how the system integrates various data sources to enhance the safety and efficiency of the EV charging process (Tobias Fleck et al., 2023).

The rapid adoption of EVs necessitates the development of advanced and efficient charging management systems. One such system, based on artificial intelligence (AI), emphasizes load management, equitable energy distribution, and anomaly detection. This proposed system aims to enhance the user experience by providing accurate cost predictions and proactive detection of charging issues (Raphael Cruz Alves et al., 2023).

Globally, the number of EVs continues to rise due to their zero CO_2 emissions and environmentally friendly characteristics. Nevertheless, energy storage and charging infrastructure remain key challenges that must be fully addressed. The integration of Internet of Things (IoT) and AI technologies has been discussed as a way to monitor the performance of both the charging system and fully autonomous driving systems, using various connected sensors. A fully automated charging system can be implemented to enable real-time data exchange between the vehicle and its surrounding environment, with AI driving the EV ecosystem toward complete automation (Aaqib Raza et al., 2022). In another study, fleet operators and electric vehicles are modeled as interactive agents equipped with advanced decision-making tools. The focus is on learning smart charging policies (i.e., where and when to charge vehicles) under uncertain future demand conditions. These models are designed to accommodate long charging times, limited infrastructure, and time-varying electricity prices, making them well-suited for real-world deployment (Ramin Ahadi et al., 2022). Furthermore, shared autonomous electric vehicle (AEV) fleet systems have recently attracted significant attention for their potential to reduce oil dependency, lower carbon emissions, and alleviate traffic congestion in urban environments.

The additional daily electrical demand introduced by electric vehicles poses significant operational challenges for existing power distribution networks (H. Ali et al., 2023). In response to current issues related to EV charging, a smart parking system has been proposed, leveraging license plate recognition technology to identify vehicles and implement an intelligent control system. The primary objective of this system is to prevent fossil-fuel vehicles from occupying EV charging spots and to address the issue of "short charging, long parking" by promoting responsible parking behaviors. This solution enhances the utilization efficiency of charging stations and reduces operational inefficiencies in EV infrastructure (Zihan Gao et al., 2023).

Given recent advancements in vehicle and battery technologies, electric vehicles (EVs) are rapidly establishing themselves as a sustainable alternative to traditional fossil-fueled cars. This progress has made large-scale electrification of ride-hailing and fleet operations a feasible solution, offering new opportunities for accelerating urban sustainability goals. While EVs now offer driving ranges comparable to internal combustion engine vehicles, they still suffer from long charging times, which

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reduce the overall service availability of fleets. Efficient fleet management requires operators to optimize charging schedules as part of their dispatch strategy. During the technological transition toward autonomous mobility, it is also important to account for the stochastic behavior of drivers in mobility models. Since drivers may either comply with or reject charging instructions due to extra costs, contrary to the assumption of full autonomy, one proposed solution introduces an incentive-based model (e.g., charging discounts) to increase driver compliance and realize the planned benefits of coordinated charging behavior (Linji Chen et al., 2023).

Research Methodology

This study adopts a descriptive-analytical approach and is conducted based on qualitative research methods. To investigate the challenges and opportunities related to the development of smart charging systems for autonomous electric vehicle fleets in Iranian megacities, the PESTEL analytical framework has been employed. PESTEL serves as a comprehensive tool for analyzing macro-environmental factors that significantly influence the acceptance and development of emerging technologies.

In this research, the six main dimensions of the PESTEL framework are systematically examined as follows:

1. **Political Factors**:

   Analyzing the overarching government policies in Iran regarding intelligent transportation, legal frameworks related to autonomous electric vehicles, and public sector support for smart charging infrastructure.

2. **Economic Factors**:

   Evaluating the costs associated with developing and maintaining charging stations, the impact of currency fluctuations, financial incentives, and both domestic and foreign investment dynamics.

3. **Social Factors**:

   Investigating public acceptance levels of autonomous electric vehicles, cultural perceptions surrounding clean transportation, and social challenges linked to shifts in lifestyle and commuting habits.

4. **Technological Factors**:

   Examining recent technical advancements in smart charging systems, the role of artificial intelligence (AI) and the Internet of Things (IoT) in optimizing the charging process, and the capabilities of smart grid integration.

5. **Environmental Factors**:

   Assessing the role of smart charging in reducing greenhouse gas emissions, the use of renewable energy in EV charging infrastructure, and the development of sustainable urban energy ecosystems.

6. **Legal Factors**:

   Reviewing national and international regulations related to smart charging standards, data ownership of vehicle charging sessions, and cybersecurity challenges.

For data analysis, the study utilizes content analysis and comparative review methods. Insights drawn from global case studies are systematically compared with the context of Iranian megacities to identify strengths, weaknesses, opportunities, and threats (SWOT analysis) relevant to local implementation.

Furthermore, the study proposes practical recommendations aimed at assisting policymakers, urban managers, and private-sector stakeholders in decision-making processes related to the planning and development of smart charging infrastructure.

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Data Analysis

In this study, the collected data were analyzed using content analysis and comparative review methods. First, relevant information regarding the development of smart charging systems in leading countries, as well as regulatory documents and policies in Iran, were reviewed. Then, the findings were categorized according to the PESTEL framework into six dimensions, Political, Economic, Social, Technological, Environmental, and Legal, to evaluate how each of these factors affects the development of such systems in Iranian megacities.

Analysis of Political Factors

The overarching governmental policies in Iran concerning sustainable transportation play a significant role in the advancement of smart charging infrastructure. Currently, the country is in the process of formulating regulations aimed at expanding its electric mobility infrastructure. However, several obstacles persist, including lack of coordination among government bodies, absence of clear standards for smart charging, and restrictions on foreign investment. These challenges remain major barriers to the full deployment of smart charging systems.

Analysis of Economic Factors

The high costs of establishing and maintaining smart charging stations represent one of the primary constraints hindering the widespread adoption of this technology in Iran. Currency fluctuations and broader economic instability further complicate the integration of new technologies. Nevertheless, policy tools such as tax incentives, government subsidies, and preferential banking loans could play a vital role in encouraging private sector investment and accelerating the development of smart charging infrastructure.

Analysis of Social Factors

The level of public acceptance of electric vehicles (EVs) and smart charging systems in Iran remains relatively low. A lack of awareness, concerns about battery performance, and the absence of widespread infrastructure have limited public enthusiasm for these technologies. Expanding educational campaigns, raising public awareness, offering financial incentives for EV purchases, and developing charging stations in key urban locations can significantly boost societal acceptance and adoption.

Analysis of Technological Factors

Global advancements in wireless charging, fast-charging stations, and the digitalization of the charging process present numerous opportunities for the growth of smart charging technologies in Iran. However, the absence of modern infrastructure and reliance on imported technologies remain serious obstacles. Investing in domestic research and development, as well as fostering international collaboration, can help mitigate these technological challenges and promote local innovation.

Analysis of Environmental Factors

The expansion of smart charging systems could have a substantial impact on reducing greenhouse gas emissions and improving air quality, especially in Iranian megacities. However, a key environmental concern lies in the source of energy used by these stations. Integrating solar and wind energy sources,

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alongside smart energy management systems, can significantly enhance the environmental sustainability of this technology and support broader climate goals.

Analysis of Legal Factors

The lack of comprehensive legal frameworks regarding data ownership, cybersecurity, and smart charging standards poses a major barrier to the development of such systems in Iran. Formulating clear data governance policies, regulations for secure smart charging communications, and legal guidelines for international collaboration will be crucial in overcoming these challenges and enabling secure and scalable implementation.

Table 1. Content Analysis of PESTEL Dimensions for Smart Charging Systems

PESTEL Dimension	Key Components	Code
Political (P)	Government policies on EV development	P1
	Government incentives for charging stations	P2
	Regulations on importing charging technologies	P3
	Impact of sanctions on equipment supply	P4
	Coordination between public and private sectors	P5
	Challenges in foreign investment	P6
	Environmental pollution reduction policies	P7
	National programs for renewable energy development	P8
	Government support for electricity infrastructure	P9
	Impact of urban planning laws on station location	P10
	Role of parliament in passing EV-supportive legislation	P11
	Electricity tariff policies for charging stations	P12
	Role of municipalities in station expansion	P13
	Licensing challenges for station installation	P14
	Government funding for innovative charging startups	P15
Economic (E)	Cost of developing charging stations	E1
	Currency exchange rate impact on equipment	E2
	Electricity costs for EV users	E3
	Business models for charging stations	E4
	Economic volatility and investment risks	E5
	Consumer-level cost-effectiveness	E6

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PESTEL Dimension	Key Components	Code
	Impact of financial incentives on EV adoption	E7
	International investment in Iran's EV sector	E8
	Supply chain and component sourcing issues	E9
	EV pricing and its influence on smart charging expansion	E10
	Profitability of high-traffic charging stations	E11
	Maintenance costs of charging systems	E12
	Cost comparison: gasoline vs electric vehicles	E13
	Role of banks in financing this industry	E14
	Investor interest in smart charging technologies	E15
	Public attitudes toward EV adoption	S1
	Awareness of smart charging benefits	S2
	Lifestyle shifts and sustainable transport	S3
	Public concerns over EV performance	S4
	Role of education and media campaigns	S5
	Impact of social media on public information	S6
	Shift in public transit models toward autonomy	S7
Social (S)	Accessibility of charging stations	S8
	Public perception of clean energy	S9
	Social impacts of reduced gasoline dependence	S10
	Government efforts in EV culture promotion	S11
	Socioeconomic impacts of EV-related employment	S12
	Consumer willingness to switch to EVs	S13
	Public safety concerns with electric vehicles	S14
	Media's role in promoting smart charging awareness	S15
	Development of wireless charging infrastructure	T1
	Integration of IoT in charging stations	T2
Technological (T)	Role of AI in energy optimization	T3
	International charging standards for EVs	T4
	Connectivity issues between AVs and charging stations	T5

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PESTEL Dimension	Key Components	Code
	Ultra-fast charging technologies	T6
	Smart grid integration for power supply	T7
	Energy management algorithm development	T8
	System integration with autonomous vehicles	T9
	Maintenance challenges for charging stations	T10
	Compatibility with current infrastructure	T11
	Access to advanced charging equipment in Iran	T12
	Cloud-based smart charging management	T13
	Interoperability with public transport	T14
	Technical cost-reduction solutions	T15
	Impact of smart charging on air pollution reduction	E1
	Reduction of greenhouse gas emissions	E2
	Use of renewable energy in charging stations	E3
	Lithium battery recycling	E4
	Urban noise pollution reduction	E5
	Fossil fuel reduction and its environmental benefits	E6
	Impact of charging station expansion on green space	E7
Environmental (E)	Environmental policies in infrastructure development	E8
	Role of modern tech in battery waste management	E9
	Challenges in securing stable electricity for charging stations	E10
	Lifecycle analysis of EVs	E11
	Impact of climate change on station efficiency	E12
	Pollution reduction in urban transportation	E13
	Carbon footprint reduction from smart charging	E14
	Energy efficiency analysis of charging stations	E15
	Data ownership regulations for EV charging	L1
Legal (L)	Cybersecurity standards for charging stations	L2
	National standards for EV charging infrastructure	L3
	Legal challenges in equipment import	L4

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PESTEL Dimension	Key Components	Code
	Electricity tariff regulations for EV charging	L5
	Legal use of public space for charging infrastructure	L6
	User rights regarding vehicle energy consumption data	L7
	Rules for installing chargers in residential complexes	L8
	Insurance-related legal issues for EVs	L9
	Legal responsibilities in case of station malfunction	L10
	Harmonization of domestic laws with international standards	L11
	Legal support for startups in the smart charging domain	L12
	Judiciary's role in resolving charging station disputes	L13
	Consumer protection policies for smart charging	L14
	Legal concerns over sharing private chargers	L15

Based on the coded identified components, the next step will involve formulating the main and sub-concepts.

Table 2. Main and Sub-Concepts in PESTEL Analysis for Smart Charging Systems in Megacities

PESTEL Dimension	Main Concepts	Sub-Concepts
Political (P)	Government policies on electric transport	National EV development plans, government support for charging infrastructure
	National and international regulations	EV standards, technology import requirements
	Impact of sanctions and economic restrictions	Barriers to equipment supply, challenges in foreign investment
	Urban regulations and station site selection	Municipal policies, impact of urban planning on charger development
	Government financial support	Tax incentives, energy subsidies
Economic (E)	Cost of charging infrastructure development	Charging station financing, maintenance and repair costs
	Private and foreign investment	Attracting investors, influence of economic policies on industry growth

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PESTEL Dimension	Main Concepts	Sub-Concepts
	Pricing and electricity tariffs	Electricity rate-setting, impact of energy costs on station operation
	Economic viability of electric vehicles	Cost comparison of electric vs gasoline vehicles, consumer cost justification
	Business models for charging stations	Revenue generation potential, financial sustainability of smart charging projects
Social (S)	Public acceptance of electric vehicles	Social attitudes toward EVs, cultural factors in clean energy adoption
	Public awareness and education	Campaigns on smart charging benefits, role of social media
	Access to charging infrastructure	Geographical distribution of stations, equity in service accessibility
	Lifestyle shifts toward electric transport	Decline in use of traditional vehicles, interest in smart mobility
	Social concerns and safety	Theft and misuse of chargers, public trust in the technology
Technological (T)	Advances in smart charging technologies	Wireless charging, use of IoT in energy management
	Smart grid development	Role of AI in energy optimization, grid integration with charging stations
	Technical standards for EV charging	Compliance with international standards, interoperability challenges
	Infrastructure maintenance and sustainability	Equipment wear and breakdowns, spare part availability
	Digitalization of mobility and charging systems	Connectivity between AVs and chargers, use of big data in network management
Environmental (E)	Emission reduction	Impact of smart charging on air pollution, EV role in CO_2 mitigation
	Use of renewable energy sources	Integration of solar and wind power into charging stations
	Battery waste management	Lithium battery recycling, chemical disposal challenges
	Reducing fossil fuel dependency	Gasoline consumption reduction, sustainable energy in transportation
	Improving urban quality of life	Noise pollution reduction, effects of traffic decongestion on public health
Legal (L)	National regulations on smart charging	Requirements for installation and operation, national EV standards

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PESTEL Dimension	Main Concepts	Sub-Concepts
	Legal challenges in data ownership	User privacy concerns, government access to consumption data
	Cybersecurity regulations for charging stations	Prevention of cyberattacks, protection of vehicle-to-station communication data
	Innovation and startup support policies	Legal support for smart charging startups
	International regulations and standard alignment	Integration with global protocols, facilitation of international collaboration

The analysis of smart charging system development in Iranian megacities, using the PESTEL framework, reveals that political, economic, social, technological, environmental, and legal factors all play a critical role in shaping and advancing this emerging technology. From a political perspective, key influences include government policies supporting electric vehicles, legislation related to the development of charging infrastructure, the impact of international sanctions on technology imports, and urban policies regarding the siting of charging stations.

In the economic domain, factors such as the costs of developing and maintaining charging stations, exchange rate fluctuations, electricity tariffs, business models for smart charging deployment, and the overall investment attractiveness of this sector are considered essential components of feasibility and scalability. From a social standpoint, public acceptance of electric vehicles, the level of citizen awareness, the role of advertising and media, security concerns, and accessibility to infrastructure are all crucial determinants of adoption and expansion of these systems.

In terms of technology, important concepts include the development of wireless charging infrastructure, the use of artificial intelligence (AI) and the Internet of Things (IoT) for energy management, global standards for charging technology, and the integration of smart charging systems with autonomous vehicles. Challenges related to maintenance, equipment repair, and the role of smart power grids in optimizing the charging process also significantly influence the trajectory of development. From an environmental perspective, the adoption of smart charging systems has the potential to significantly reduce greenhouse gas emissions, particularly in densely populated cities. The use of renewable energy sources (e.g., solar and wind), recycling of lithium batteries, and reduced dependence on fossil fuels are key topics in this context. Additionally, smart charging contributes to urban quality of life through noise reduction and improved transportation efficiency.

Lastly, legal factors are highly influential in enabling or hindering progress. These include regulations on data ownership, cybersecurity standards for charging stations, national and international compliance for deployment and operation, legal protections for startups, and tariff and access rules for electricity distribution. Harmonizing domestic legal frameworks with international standards plays a pivotal role in facilitating broader adoption. Overall, the findings indicate that the development of smart charging systems requires a holistic and interdisciplinary approach, one that integrates effective policymaking with economic support mechanisms, public engagement, technological innovation, environmental considerations, and robust legal frameworks. This research offers valuable insights for urban planners, policymakers, and industry stakeholders seeking to establish the necessary infrastructure to support the transition to autonomous electric vehicles and smart charging ecosystems in Iran's urban centers.

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Discussion and Conclusion

The development of smart charging systems for autonomous electric vehicles in Iranian megacities requires a comprehensive analysis of political, economic, social, technological, environmental, and legal (PESTEL) dimensions. The findings from this study indicate that government support policies, financial incentives, and national standards for infrastructure development play a pivotal role in accelerating the growth of this technology. However, lack of coordination among governmental institutions, absence of comprehensive legislation, and the impact of international sanctions on technology imports remain major obstacles. From an economic standpoint, the high costs of installing and maintaining charging stations, currency fluctuations, and the limited investment appeal of the sector necessitate stronger support policies and mechanisms to facilitate both domestic and foreign investment.

In the social dimension, the public's acceptance of emerging technologies, such as electric vehicles and smart charging systems—continues to face resistance. Lack of awareness, concerns over battery performance, and limited charging infrastructure are key factors influencing citizens' adoption behavior. Educational initiatives, widespread media campaigns, and the deployment of dense charging networks in strategic urban areas can significantly enhance public acceptance and change consumer behavior. From a technological perspective, recent advancements in wireless charging, Internet of Things (IoT) integration, and artificial intelligence (AI) present promising opportunities for the growth of smart charging systems. Nonetheless, inadequate electricity infrastructure, dependence on imported technologies, and the high cost of implementation highlight the need for increased investment in domestic research and development (R&D).

In the environmental domain, the expansion of smart charging infrastructure has the potential to significantly reduce air pollution, decrease fossil fuel dependency, and enable greater use of renewable energy sources. However, challenges such as lithium battery waste management, securing stable electricity supply, and limited access to renewables must be addressed in future policy frameworks. Integrating smart charging with clean energy systems and optimizing power consumption through smart grids will be key to ensuring the sustainable development of this technology.

From a legal perspective, the absence of clear legal frameworks surrounding data ownership, cybersecurity, and national standards for charging stations presents considerable barriers. Addressing these issues will require the formulation of new legislation and alignment with international legal standards. Enhanced coordination among domestic policymakers and global standardization efforts is essential for driving growth in this sector. The results of this study underscore that the successful development of smart charging systems for autonomous electric vehicles in Iran requires a holistic and interdisciplinary strategy, one that incorporates effective policymaking, economic development, public engagement, technological innovation, environmental protection, and legal reform. To achieve this, actions such as supportive policy design, investment facilitation, infrastructure enhancement, public education, energy optimization, and the drafting of comprehensive legal frameworks are critical. This research offers valuable guidance for policymakers, urban planners, and investors, serving as a foundation for more informed decision-making toward the development of smart charging infrastructure and the broader transition to sustainable and green transportation systems in Iran.

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