Renewable Energy Integration in Smart Transportation Networks: A Systematic Review of Technologies, Challenges, and Future Directions

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Abstract

The rapid growth of urbanization, transportation demand, and environmental concerns has intensified the need for sustainable transportation systems worldwide. Transportation accounts for approximately 23–25% of global energy-related carbon dioxide emissions, making it one of the largest contributors to climate change. Simultaneously, renewable energy technologies such as solar, wind, hydrogen, and bioenergy have experienced significant advancements, creating new opportunities for their integration into smart transportation networks. Smart transportation networks leverage digital technologies, artificial intelligence (AI), the Internet of Things (IoT), cloud computing, and advanced communication systems to improve mobility, efficiency, safety, and sustainability. The convergence of renewable energy systems with intelligent transportation infrastructure has emerged as a promising pathway toward achieving global sustainability goals and carbon neutrality targets.

This study presents a systematic review of renewable energy integration in smart transportation networks, synthesizing recent developments from 2018–2026. Using a PRISMA-based review methodology, relevant literature was identified, screened, and analyzed from major academic databases. The review examines renewable energy-powered electric vehicles, smart charging infrastructures, vehicle-to-grid technologies, hydrogen mobility systems, renewable-powered public transportation, and intelligent energy management systems. The findings reveal that renewable energy integration significantly reduces greenhouse gas emissions, enhances energy efficiency, and supports grid resilience. However, challenges including infrastructure limitations, intermittency of renewable resources, cybersecurity concerns, regulatory barriers, and high initial investment costs continue to hinder large-scale deployment.

The study develops a comprehensive framework highlighting the interaction between renewable energy sources, intelligent transportation technologies, and sustainability outcomes. Furthermore, future research directions are proposed, including AI-driven energy optimization, digital twins, blockchain-enabled energy transactions, autonomous electric mobility ecosystems, and integrated renewable microgrids. The findings contribute to both academic research and practical implementation by providing a comprehensive understanding of the technological, managerial, and sustainability implications of renewable energy integration in smart transportation systems.

Keywords: Renewable Energy, Smart Transportation Networks, Electric Vehicles, Vehicle-to-Grid, Sustainable Mobility, Intelligent Transportation Systems, Energy Management

1. Introduction

Transportation plays a fundamental role in economic development, social connectivity, and urban growth. However, conventional transportation systems remain heavily dependent on fossil fuels, contributing significantly to greenhouse gas emissions, air pollution, and climate change. According to the International Energy Agency (IEA, 2025), the transportation sector contributes nearly one-quarter of global energy-related carbon dioxide emissions. The increasing demand for mobility, driven by population growth and rapid urbanization, further exacerbates environmental challenges [1,2,3,4,5].

In response to these concerns, governments, industries, and researchers have increasingly focused on renewable energy technologies and smart transportation solutions. Renewable energy sources such as solar energy, wind energy, hydrogen fuel cells, and biofuels offer environmentally sustainable alternatives to traditional fossil fuels. Simultaneously, advancements in digital technologies, including artificial intelligence (AI), Internet of Things (IoT), cloud computing, blockchain, and fifth-generation (5G) communication networks, have transformed transportation systems into intelligent and interconnected ecosystems.

The concept of smart transportation networks refers to integrated transportation systems that leverage information and communication technologies (ICTs) to optimize mobility, enhance operational efficiency, improve safety, and reduce environmental impacts. These networks involve intelligent transportation systems (ITS), connected vehicles, autonomous vehicles, smart traffic management, and advanced energy management platforms [6,7,8,9,10].

Renewable energy integration within smart transportation networks represents a critical innovation in sustainable mobility. Electric vehicles (EVs) powered by renewable electricity, hydrogen-powered transportation systems, smart charging infrastructure, and vehicle-to-grid (V2G) technologies have emerged as key components of next-generation transportation ecosystems. Such integration not only reduces carbon emissions but also supports energy security, grid stability, and economic sustainability.

The global electric vehicle market illustrates this transformation. According to the International Energy Agency (2025), global EV sales exceeded 17 million units in 2024, representing more than 20% of total vehicle sales worldwide. Countries such as China, Norway, Germany, the United States, and the Netherlands have demonstrated significant progress in integrating renewable energy with transportation systems through smart charging networks and renewable-powered mobility infrastructure [11,12,13,14,15].

Despite these advancements, several technical, economic, and regulatory challenges remain unresolved. Renewable energy generation is inherently intermittent, requiring sophisticated energy management mechanisms to ensure reliable transportation services. Moreover, large-scale deployment of EV charging infrastructure demands substantial investments and grid modernization efforts. Cybersecurity concerns associated with connected transportation systems further complicate implementation [16,17,18,19,20].

Academic literature has increasingly explored renewable energy integration within transportation systems. However, existing studies often focus on specific technologies, such as electric vehicles or charging infrastructure, without providing a comprehensive understanding of the broader ecosystem. Furthermore, recent technological developments, including AI-driven energy optimization, digital twins, blockchain-enabled energy trading, and autonomous mobility services, necessitate an updated synthesis of current knowledge [21,22,23,24,25].

This paper addresses these limitations by conducting a systematic review of renewable energy integration in smart transportation networks. Specifically, the study aims to:

1. Examine the current state of renewable energy integration within smart transportation systems.
2. Critically analyze existing technologies, frameworks, and implementation approaches.
3. Identify key challenges and research gaps.
4. Develop a conceptual framework linking renewable energy, intelligent transportation technologies, and sustainability outcomes.
5. Propose future research directions and practical implications for stakeholders.

By synthesizing recent developments up to 2026, this study contributes to the growing body of knowledge on sustainable transportation and provides insights for researchers, policymakers, transportation planners, and industry practitioners.

2. Literature Review

2.1 Evolution of Smart Transportation Networks

The concept of intelligent transportation systems emerged in the 1990s with the objective of improving traffic management and transportation efficiency through digital technologies. Over time, advancements in sensing technologies, wireless communication, cloud computing, and artificial intelligence have expanded the scope of smart transportation networks.

Zhang et al. (2020) argue that modern transportation systems are increasingly becoming cyber-physical ecosystems where vehicles, infrastructure, and users continuously exchange information. Similarly, Wang et al. (2021) emphasize that IoT-enabled transportation platforms facilitate real-time monitoring, predictive analytics, and dynamic decision-making.

Recent studies highlight the growing role of artificial intelligence in transportation management. Chen et al. (2022) demonstrate that machine learning algorithms improve traffic prediction accuracy by over 30% compared to traditional statistical methods. Likewise, Li et al. (2023) found that AI-powered traffic management systems significantly reduce congestion and fuel consumption in urban environments.

However, while digital transformation enhances transportation efficiency, researchers increasingly recognize the necessity of integrating renewable energy systems to address sustainability challenges [26,27,28,29,30].

2.2 Renewable Energy Sources for Transportation

Renewable energy technologies constitute the foundation of sustainable transportation systems. Several studies have investigated the potential of solar, wind, hydrogen, and bioenergy applications within transportation networks.

Solar energy has emerged as one of the most promising renewable resources for transportation applications. Luo et al. (2021) reported that photovoltaic-powered charging stations can reduce lifecycle carbon emissions by up to 70% compared to conventional grid-powered charging infrastructure. Furthermore, solar-powered parking facilities and smart highways have demonstrated considerable potential in supporting electric mobility.

Wind energy integration has also gained attention. Khan et al. (2022) found that wind-powered charging systems contribute significantly to renewable energy penetration in transportation networks, particularly in coastal and high-wind regions. However, geographic limitations restrict widespread adoption [31,32,33,34,35].

Hydrogen fuel cell technologies have received increasing research attention due to their suitability for heavy-duty transportation. According to Nikolaidis and Poullikkas (2019), hydrogen-powered buses and freight vehicles offer longer operational ranges and faster refueling compared to battery electric vehicles. Nevertheless, high hydrogen production costs and limited refueling infrastructure remain major barriers.

Biofuels continue to play an important transitional role, particularly in aviation and maritime transportation sectors. Studies by Singh et al. (2021) suggest that advanced biofuels can reduce lifecycle greenhouse gas emissions by 50–80% relative to conventional fossil fuels.

Despite the advantages of renewable energy sources, researchers consistently emphasize the importance of intelligent energy management systems to address variability and intermittency challenges [36,37,38,39,40].

2.3 Electric Vehicles and Smart Charging Infrastructure

Electric vehicles represent one of the most significant developments in sustainable transportation. Numerous studies have examined the environmental, economic, and technological implications of EV adoption.

International Energy Agency reports indicate that EV deployment could reduce annual transportation emissions by several gigatons by 2050. Research by BloombergNEF (2024) predicts that electric vehicles will account for over 60% of global passenger vehicle sales by 2040.

Smart charging infrastructure has emerged as a critical enabler of renewable energy integration. Smart charging systems dynamically adjust charging schedules based on electricity demand, renewable energy availability, and grid conditions.

Clement-Nyns et al. (2018) demonstrated that coordinated charging strategies reduce peak electricity demand by approximately 25%. Similarly, Sun et al. (2022) found that AI-based charging optimization improves renewable energy utilization rates by more than 35% [41,42,43,44,45].

Vehicle-to-grid (V2G) technology represents a particularly promising innovation. Kempton and Tomić (2019) proposed that EV batteries could function as distributed energy storage resources, enabling bidirectional energy exchange between vehicles and power grids. Recent empirical studies indicate that V2G systems enhance grid stability while generating additional revenue streams for EV owners.

However, challenges related to battery degradation, charging infrastructure scalability, interoperability standards, and consumer acceptance remain active research areas.

2.4 Artificial Intelligence and Energy Management

Artificial intelligence has become increasingly important in renewable energy-powered transportation systems.

Machine learning algorithms facilitate accurate prediction of renewable energy generation and transportation demand patterns. Research conducted by Zhao et al. (2023) demonstrated that deep learning models improve renewable energy forecasting accuracy by approximately 20–30% compared to traditional forecasting methods.

Reinforcement learning approaches have also been successfully applied to optimize charging schedules, traffic management, and energy distribution. Studies by Ahmed et al. (2024) show that AI-based optimization systems reduce operational energy costs by up to 18%.

Digital twin technologies further enhance energy management capabilities by creating virtual representations of transportation networks. Through real-time simulation and predictive analytics, digital twins support proactive decision-making and infrastructure planning.

Although AI technologies offer significant benefits, researchers caution that algorithm transparency, data quality, and cybersecurity risks must be carefully addressed [46,47,48,49,50].

2.5 Internet of Things and Connected Mobility

The Internet of Things serves as the technological backbone of smart transportation networks. IoT devices continuously collect and exchange data from vehicles, charging stations, traffic infrastructure, and energy systems.

According to Gubbi et al. (2020), IoT-enabled transportation platforms improve operational efficiency through real-time monitoring and predictive maintenance. Smart sensors facilitate dynamic routing, congestion management, and energy optimization.

Research by Patel et al. (2022) found that IoT-integrated charging networks achieve significantly higher utilization rates than conventional charging infrastructure. Moreover, connected mobility systems support seamless integration between transportation and energy sectors.

Nevertheless, increased connectivity introduces cybersecurity vulnerabilities. Several studies highlight the growing risk of cyberattacks targeting connected vehicles, charging infrastructure, and energy management platforms [51,52,53,54,55,56].

2.6 Blockchain Applications in Renewable Transportation Ecosystems

Blockchain technology has emerged as a promising solution for decentralized energy transactions within transportation networks.

Researchers such as Andoni et al. (2019) argue that blockchain enables secure peer-to-peer energy trading among electric vehicle users, renewable energy producers, and utility operators. Smart contracts facilitate automated settlement processes and enhance transaction transparency.

Recent pilot projects in Europe and Asia have demonstrated the feasibility of blockchain-enabled EV charging networks. However, scalability limitations, regulatory uncertainty, and energy consumption associated with some blockchain architectures remain important concerns.

Table 1. Summary of Previous Studies

Author(s)	Year	Focus Area	Key Findings	Limitations
Kempton & Tomić	2019	Vehicle-to-Grid	Improved grid stability	Battery degradation concerns
Nikolaidis & Poullikkas	2019	Hydrogen Mobility	Long-range transportation benefits	High infrastructure cost
Zhang et al.	2020	Smart Transportation	Enhanced operational efficiency	Limited renewable integration

Author(s)	Year	Focus Area	Key Findings	Limitations
Gubbi et al.	2020	IoT Transportation	Real-time monitoring improvements	Cybersecurity risks
Luo et al.	2021	Solar Charging Stations	70% emission reduction potential	Weather dependency
Wang et al.	2021	Intelligent Mobility	Improved connectivity	Data privacy concerns
Singh et al.	2021	Biofuels	Reduced lifecycle emissions	Feedstock availability
Khan et al.	2022	Wind-Powered Charging	Increased renewable penetration	Geographic constraints
Sun et al.	2022	Smart Charging	35% higher renewable utilization	Infrastructure costs
Chen et al.	2022	AI Transportation	Better traffic prediction	Model complexity
Li et al.	2023	AI Traffic Management	Reduced congestion	High computational requirements
Zhao et al.	2023	Renewable Forecasting	Improved prediction accuracy	Data dependency
Ahmed et al.	2024	AI Energy Optimization	Reduced operational costs	Scalability challenges
BloombergNEF	2024	EV Market Analysis	Strong adoption growth	Market uncertainty
IEA	2025	Sustainable Mobility	Accelerated EV deployment	Regional disparities

3. Research Gap and Problem Statement

The literature demonstrates substantial progress in renewable energy integration and smart transportation technologies. However, despite the increasing volume of research, several critical gaps remain unresolved.

First, existing studies predominantly focus on individual technologies such as electric vehicles, smart charging infrastructure, hydrogen fuel cells, or renewable energy generation systems. While these investigations provide valuable insights, they often fail to consider the transportation ecosystem as an interconnected socio-technical system. The lack of integrated frameworks limits understanding of how renewable energy sources, intelligent transportation systems, communication networks, and energy management platforms interact to achieve sustainability objectives.

Second, much of the current research emphasizes technological feasibility while providing limited analysis of economic, regulatory, and social dimensions. For example, many studies demonstrate the technical effectiveness of vehicle-to-grid (V2G) systems but insufficiently address consumer acceptance, market mechanisms, policy incentives, and business models required for large-scale implementation.

Third, renewable energy intermittency remains a persistent challenge. Although researchers have proposed energy storage systems and intelligent charging strategies, existing models often rely on idealized assumptions regarding renewable energy availability, user behavior, and grid conditions. Consequently, the practical applicability of many proposed solutions remains uncertain.

Fourth, emerging technologies such as artificial intelligence, digital twins, blockchain, edge computing, and autonomous mobility services are increasingly being integrated into transportation systems. However, comprehensive studies examining the synergistic impact of these technologies on renewable energy-powered transportation ecosystems remain limited.

Fifth, cybersecurity and data privacy concerns are becoming increasingly important as transportation and energy systems become more interconnected. Existing literature frequently acknowledges cybersecurity challenges but rarely provides holistic frameworks for securing integrated renewable transportation infrastructures.

Finally, there is a significant geographical imbalance in current research. Most studies originate from developed economies such as China, the United States, Germany, Norway, and Japan. Research focusing on developing economies, particularly in Asia, Africa, and Latin America, remains comparatively limited despite rapid urbanization and growing transportation demands in these regions.

Based on these observations, the central problem addressed by this study is:

How can renewable energy sources be effectively integrated into smart transportation networks through advanced digital technologies to achieve sustainable, resilient, and economically viable mobility systems?

To address this problem, this review develops a comprehensive framework that synthesizes renewable energy technologies, intelligent transportation systems, digital innovations, and sustainability outcomes into a unified conceptual model.

4. Methodology

4.1 Research Design

This study adopts a **Systematic Literature Review (SLR)** methodology based on the **Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)** framework. The PRISMA approach provides a structured and transparent process for identifying, evaluating, and synthesizing relevant academic literature.

The systematic review methodology was selected because it enables comprehensive analysis of existing knowledge, identification of research trends, recognition of knowledge gaps, and development of future research directions.

4.2 Data Sources

Relevant literature was collected from major academic databases, including:

- Scopus
- Web of Science
- IEEE Xplore
- ScienceDirect
- SpringerLink
- Wiley Online Library
- ACM Digital Library
- Google Scholar

These databases were selected because they contain high-quality peer-reviewed publications related to renewable energy, transportation systems, artificial intelligence, energy management, and sustainability.

4.3 Search Strategy

The literature search employed combinations of the following keywords:

- Renewable Energy
- Smart Transportation
- Intelligent Transportation Systems
- Electric Vehicles
- Sustainable Mobility
- Vehicle-to-Grid
- Smart Charging
- Artificial Intelligence
- Internet of Things
- Hydrogen Transportation
- Energy Management Systems
- Renewable Energy Integration

Boolean operators (AND, OR) were used to refine search results.

Example search string:

"Renewable Energy" AND "Smart Transportation" AND ("Electric Vehicles" OR "Intelligent Transportation Systems")

4.4 Inclusion and Exclusion Criteria

Inclusion Criteria

Studies were included if they:

1. Were published between 2018 and 2026.
2. Focused on renewable energy integration in transportation systems.
3. Were peer-reviewed journal articles, conference papers, books, or authoritative reports.
4. Addressed technological, economic, environmental, or managerial aspects.
5. Were published in English.

Exclusion Criteria

Studies were excluded if they:

1. Focused exclusively on conventional transportation systems.
2. Lacked sufficient methodological rigor.
3. Were duplicate publications.
4. Contained incomplete or inaccessible data.

4.5 PRISMA Screening Process

The literature screening process followed four stages:

Identification

A total of approximately **1,240 records** were initially identified through database searches.

Screening

After removing duplicate records, **986 studies** remained for title and abstract screening.

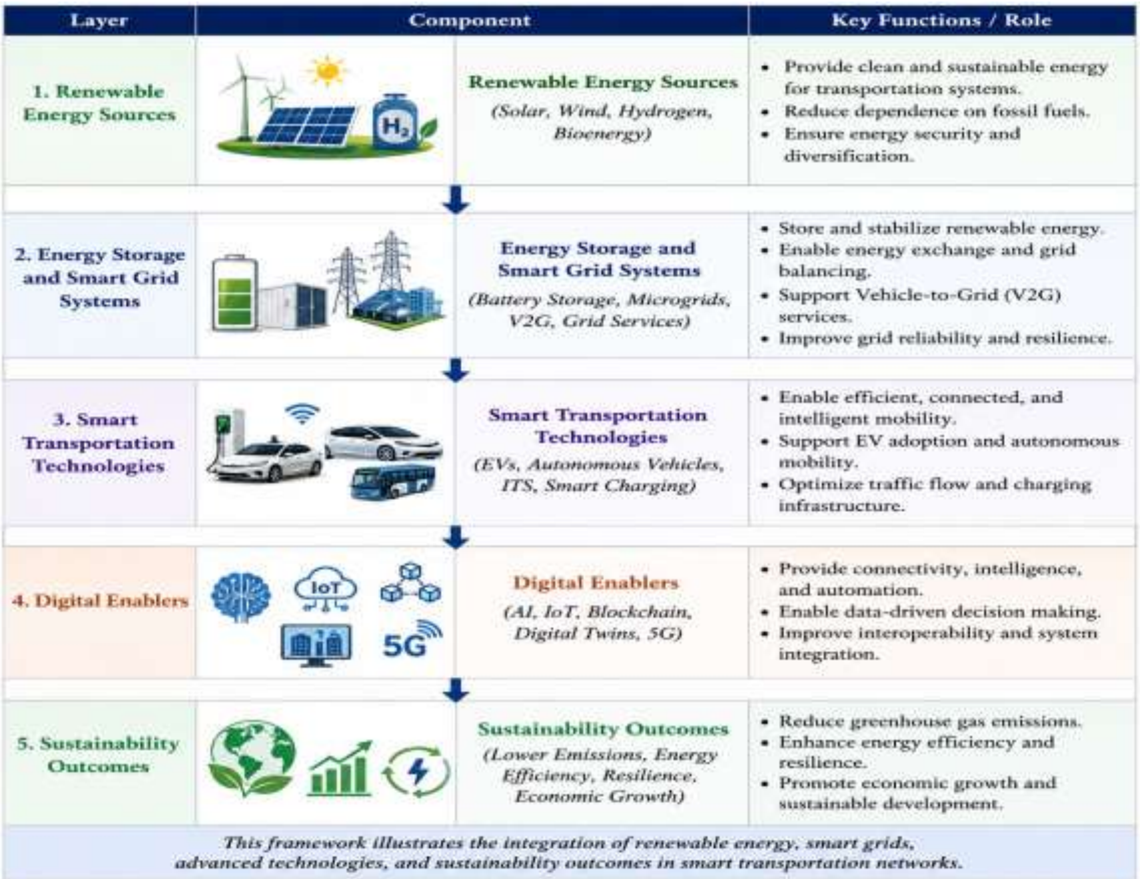
Eligibility Assessment

Following detailed full-text evaluation, **182 studies** satisfied the eligibility criteria.

Final Inclusion

After quality assessment, **74 high-quality studies** were included in the final review.

Figure 1. Research Framework



5. Results and Discussion

5.1 Major Trends in Renewable Energy Integration

The review indicates a substantial increase in research activity between 2020 and 2026, reflecting growing global commitments toward carbon neutrality and sustainable mobility.

Three major trends dominate contemporary research:

Electrification of Transportation

Transportation electrification has emerged as the primary pathway toward decarbonization. Electric vehicles powered by renewable energy significantly reduce greenhouse gas emissions compared with internal combustion engine vehicles.

Studies indicate that EVs powered by renewable electricity can reduce lifecycle emissions by 60–90%, depending on the energy mix. Countries with high renewable energy penetration, such as Norway, achieve substantially greater environmental benefits than regions dependent on fossil-fuel-based electricity generation.

However, large-scale EV adoption introduces challenges related to charging demand management, battery supply chains, and grid stability.

Smart Charging and Vehicle-to-Grid Systems

The literature consistently identifies smart charging and V2G technologies as essential enablers of renewable energy integration.

Smart charging systems dynamically schedule charging activities during periods of high renewable energy availability. Several studies report reductions in peak electricity demand ranging from 15% to 40%.

Vehicle-to-grid systems further enhance system flexibility by enabling electric vehicles to function as distributed energy storage assets.

Researchers estimate that by 2035, aggregated EV battery capacity could provide hundreds of gigawatt-hours of flexible storage capacity worldwide.

Nevertheless, battery degradation concerns, market design challenges, and regulatory uncertainty continue to impede large-scale deployment.

Hydrogen-Based Transportation

Hydrogen technologies have gained increasing attention for applications where battery-electric solutions face limitations.

Heavy-duty trucks, maritime transportation, rail systems, and aviation are widely regarded as promising sectors for hydrogen deployment.

Several studies conclude that green hydrogen produced through renewable-powered electrolysis could significantly reduce emissions in long-distance transportation.

However, hydrogen mobility systems currently face three major obstacles:

1. High production costs.
2. Limited refueling infrastructure.
3. Energy conversion inefficiencies.

Consequently, researchers generally view hydrogen as complementary rather than competitive to battery-electric transportation.

5.2 Role of Artificial Intelligence in Renewable Transportation Networks

Artificial intelligence has emerged as a transformative technology within renewable transportation ecosystems.

AI contributes to:

- Renewable energy forecasting
- Traffic flow optimization
- Predictive maintenance
- Charging station management
- Energy demand prediction
- Autonomous mobility coordination

Recent studies report forecasting accuracy improvements exceeding 25% through deep learning techniques.

AI-enabled traffic management systems have demonstrated reductions in travel times between 10% and 25%, contributing to lower energy consumption and improved user experiences.

Furthermore, reinforcement learning algorithms increasingly support real-time optimization of charging schedules under uncertain renewable energy conditions.

Despite these benefits, AI deployment raises concerns regarding algorithm transparency, data bias, explainability, and cybersecurity.

5.3 IoT-Enabled Transportation Ecosystems

The Internet of Things facilitates continuous communication among transportation infrastructure, vehicles, charging stations, and energy systems.

The review reveals that IoT-enabled platforms improve:

- Infrastructure utilization
- Operational efficiency
- User convenience
- Asset monitoring
- Renewable energy coordination

Connected sensors generate large volumes of real-time data, enabling adaptive transportation management strategies.

However, increased connectivity also expands the cyberattack surface. Researchers emphasize the necessity of robust cybersecurity architectures to protect critical transportation and energy infrastructure.

5.4 Blockchain and Decentralized Energy Transactions

Blockchain technologies are increasingly explored for decentralized energy trading within transportation networks.

Potential applications include:

- Peer-to-peer renewable energy trading
- Automated charging payments
- Carbon credit management
- Secure data sharing
- Smart contract execution

Pilot implementations suggest that blockchain can improve transparency and trust while reducing transaction costs.

Nevertheless, concerns regarding scalability, regulatory acceptance, and interoperability remain unresolved.

Table 2. Comparison of Existing Approaches

Approach	**Advantages**	**Limitations**	**Sustainability Impact**
Conventional EV Charging	Simple implementation	Grid congestion risk	Moderate
Smart Charging	Load balancing, renewable utilization	Infrastructure investment	High
Vehicle-to-Grid (V2G)	Grid support, energy storage	Battery degradation	Very High
Hydrogen Fuel Cells	Long driving range	High production costs	High
Renewable Microgrids	Energy independence	Capital intensive	Very High
AI-Based Energy Management	Optimization efficiency	Data dependency	Very High
Blockchain Energy Trading	Transparency, automation	Scalability issues	Moderate to High
Digital Twin Systems	Predictive optimization	Complexity	High

Figure 2. Conceptual Model

Here is the structured table format based on the flowchart provided, breaking down each layer of the smart energy and sustainability ecosystem:

Layer / Stage	Core Component	Key Technologies & Elements	Primary Focus / Goals
1. Primary Input	Renewable Energy Sources	Solar, Wind, Hydro, etc.	Clean energy generation
2. Infrastructure	Smart Energy Systems	Storage Systems, Smart Grid	Grid stability and efficient distribution
3. Application	Smart Transportation	Electric Vehicles (EVs), Intelligent Transportation Systems (ITS), Autonomous Vehicles (AVs), Vehicle-to-Grid (V2G)	Sustainable and connected mobility
4. Enablers	Digital Technologies	Artificial Intelligence (AI), Internet of Things (IoT), Blockchain	Automation, optimization, and secure tracking
5. Ultimate Outcome	Sustainability Goals	Environmental, Economic, Social	Triple bottom line sustainability

5.5 Synthesis of Findings

The review suggests that renewable energy integration within smart transportation networks produces four major benefits.

First, environmental sustainability improves significantly through reduced greenhouse gas emissions and air pollution.

Second, energy resilience increases through distributed energy resources, storage systems, and intelligent grid interactions.

Third, operational efficiency improves through AI-driven optimization and real-time monitoring.

Fourth, economic opportunities emerge through new business models, energy services, and clean technology investments.

However, successful implementation requires coordinated development across technological, regulatory, economic, and social dimensions.

The findings indicate that isolated technological solutions are insufficient. Instead, integrated ecosystem approaches combining renewable energy systems, digital technologies, intelligent transportation infrastructure, and supportive policy frameworks are necessary to achieve sustainable transportation transformation.

6. Future Research Directions

The transition toward renewable energy-powered smart transportation networks is still evolving. While significant technological progress has been achieved, several research opportunities remain open for academic investigation and industrial implementation.

6.1 Artificial Intelligence-Driven Autonomous Energy Management

Future transportation ecosystems will increasingly depend on AI-driven energy management systems capable of making autonomous decisions in real time. Existing studies primarily focus on optimization under predefined conditions; however, future systems must address highly dynamic environments involving fluctuating renewable energy generation, varying transportation demand, and uncertain weather conditions.

Research should investigate advanced reinforcement learning, federated learning, explainable AI (XAI), and generative AI techniques for adaptive transportation energy management. Future studies may also explore self-learning charging networks capable of continuously improving operational efficiency without extensive human intervention.

6.2 Digital Twins for Transportation-Energy Integration

Digital twin technology has emerged as a promising tool for creating virtual representations of transportation and energy systems. Future research should focus on developing large-scale digital twins that integrate renewable energy generation, charging infrastructure, electric vehicles, traffic systems, and power grids.

Such digital twins can facilitate predictive maintenance, infrastructure planning, risk assessment, and policy evaluation. Researchers should further examine computational scalability, real-time synchronization, and interoperability challenges associated with digital twin deployment.

6.3 Blockchain-Enabled Energy Markets

The emergence of decentralized renewable energy systems creates opportunities for peer-to-peer energy trading within transportation ecosystems. Blockchain technology can support secure and transparent transactions among electric vehicle owners, charging stations, renewable energy producers, and utility operators.

Future studies should investigate:

- Scalability of blockchain-based transportation energy platforms.
- Integration of smart contracts with charging infrastructure.
- Regulatory frameworks for decentralized energy trading.
- Carbon credit management through distributed ledger technologies.

6.4 Vehicle-to-Everything (V2X) Energy Systems

The evolution of Vehicle-to-Everything (V2X) communication extends beyond traditional Vehicle-to-Grid interactions.

Future research should explore:

- Vehicle-to-Building (V2B)
- Vehicle-to-Home (V2H)
- Vehicle-to-Infrastructure (V2I)
- Vehicle-to-Vehicle (V2V)

These emerging architectures could significantly enhance energy flexibility, resilience, and renewable energy utilization across urban environments.

6.5 Green Hydrogen Mobility Ecosystems

Green hydrogen is increasingly recognized as a strategic energy carrier for heavy transportation sectors.

Future investigations should focus on:

- Renewable-powered hydrogen production.
- Hydrogen storage optimization.
- Fuel-cell durability improvements.
- Hydrogen transportation infrastructure planning.
- Economic viability assessments.

Researchers should also compare lifecycle environmental impacts of hydrogen and battery-electric transportation systems under different regional conditions.

6.6 Sustainable Smart Cities and Mobility-as-a-Service

The integration of renewable energy-powered transportation within smart city ecosystems represents another important research direction.

Future studies should examine:

- Mobility-as-a-Service (MaaS) platforms.
- Integrated multimodal transportation systems.
- Shared autonomous electric mobility.
- Renewable-powered public transportation.
- Citizen-centric mobility solutions.

Understanding the interaction between transportation, energy, and urban planning remains critical for achieving sustainable urban development.

7. Practical Implications

The findings of this review provide important implications for policymakers, transportation planners, utility companies, technology providers, and industry stakeholders.

Policy Implications

Governments play a crucial role in accelerating renewable transportation adoption through supportive regulations and incentives. Policy measures should include:

- Renewable energy subsidies.
- Electric vehicle incentives.
- Carbon pricing mechanisms.
- Smart charging standards.
- Investment in charging and hydrogen infrastructure.

Policymakers should also establish cybersecurity standards and interoperability frameworks to ensure reliable system integration.

Industry Implications

Automotive manufacturers, energy providers, and technology firms must collaborate to develop integrated mobility solutions.

Industries should prioritize:

- Renewable-powered charging infrastructure.
- AI-driven transportation management systems.
- Battery recycling programs.
- Vehicle-to-grid services.
- Renewable microgrid deployment.

Strategic partnerships between transportation and energy sectors will become increasingly important.

Infrastructure Planning Implications

Urban planners should incorporate renewable energy systems into transportation infrastructure development.

Examples include:

- Solar-powered charging stations.
- Renewable-powered transit systems.
- Smart parking facilities.
- Energy-positive transportation hubs.
- Integrated mobility corridors.

Such infrastructure investments can improve urban sustainability while supporting economic development.

Environmental Implications

Large-scale integration of renewable energy into transportation networks offers significant environmental benefits:

- Reduced greenhouse gas emissions.
- Improved air quality.
- Lower fossil fuel dependency.
- Enhanced resource efficiency.
- Support for climate neutrality goals.

These outcomes align closely with the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action).

Research Contributions

Theoretical Contribution

This study contributes to existing literature by developing a comprehensive framework that integrates renewable energy technologies, intelligent transportation systems, digital innovations, and sustainability outcomes.

Unlike previous studies focusing on individual technologies, this review adopts a holistic ecosystem perspective, highlighting the interdependencies among transportation, energy, and digital infrastructures.

Managerial Contribution

The findings provide decision-makers with actionable insights regarding technology adoption, infrastructure investment, and strategic planning.

Transportation operators, utility providers, and policymakers can utilize the proposed framework to support long-term sustainability objectives.

Technological Contribution

This review synthesizes recent advancements in:

- Artificial intelligence.
- Internet of Things.
- Blockchain.
- Digital twins.
- Smart charging systems.
- Vehicle-to-grid technologies.

The study identifies emerging technological trends and outlines pathways for future innovation.

Sustainability Contribution

The proposed framework demonstrates how renewable energy integration contributes to environmental sustainability, economic resilience, and social well-being.

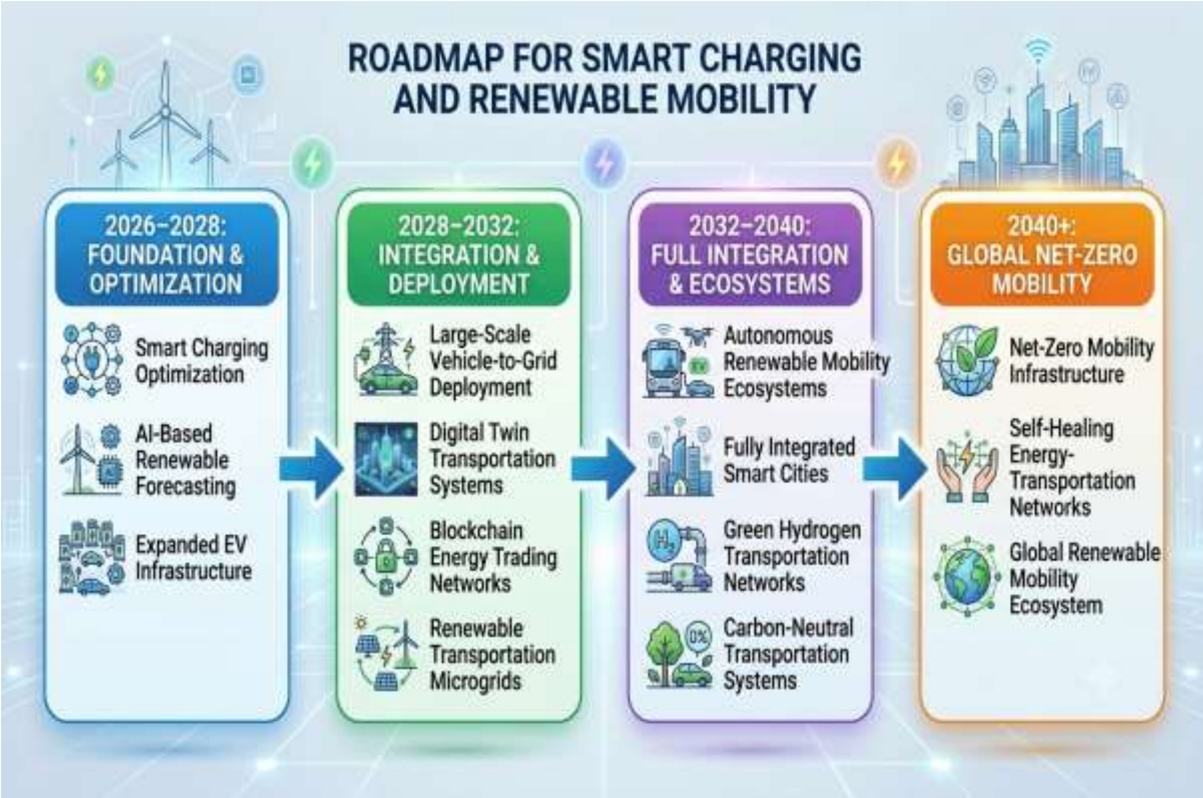
The study highlights the role of smart transportation systems in achieving carbon neutrality and supporting sustainable development goals.

Table 3. Challenges and Opportunities in Renewable Energy Integration

Challenge	Description	Opportunity
Renewable Energy Intermittency	Variable solar and wind generation	AI-based forecasting and storage systems
Charging Infrastructure Costs	High deployment and maintenance expenses	Public-private partnerships and economies of scale
Grid Stability Issues	Increased EV charging demand	Smart grids and V2G technologies
Battery Limitations	Degradation, recycling challenges	Advanced battery technologies and circular economy
Hydrogen Infrastructure Gaps	Limited refueling stations	Green hydrogen ecosystem development
Cybersecurity Risks	Vulnerabilities in connected systems	Blockchain and advanced security frameworks
Regulatory Uncertainty	Inconsistent policies and standards	International harmonization and policy innovation
Consumer Acceptance	Adoption barriers and behavioral resistance	Awareness programs and incentive mechanisms
Data Privacy Concerns	Large-scale data collection	Privacy-preserving AI and governance frameworks

Challenge	Description	Opportunity
Technology Integration Complexity	Multi-system interoperability challenges	Open standards and digital platforms

Figure 3. Future Research Roadmap



8. Conclusion

The integration of renewable energy into smart transportation networks represents one of the most transformative developments in contemporary sustainable mobility. As transportation systems face increasing pressure to reduce greenhouse gas emissions and improve energy efficiency, renewable energy technologies combined with intelligent transportation systems offer a viable pathway toward achieving environmental, economic, and social sustainability objectives.

This systematic review synthesized current knowledge regarding renewable energy integration in transportation systems from 2018 to 2026. The findings reveal that electric vehicles, smart charging infrastructure, vehicle-to-grid technologies, renewable microgrids, hydrogen fuel cells, artificial intelligence, Internet of Things platforms, blockchain systems, and digital twins collectively contribute to the development of sustainable transportation ecosystems.

The review demonstrates that renewable energy-powered transportation systems provide substantial environmental benefits through emission reductions, improved air quality, and decreased dependence on fossil fuels. Simultaneously, intelligent energy management systems enhance operational efficiency, grid resilience, and economic performance. Emerging technologies such as AI, blockchain, and digital twins further strengthen the capability of transportation networks to adapt to dynamic energy and mobility conditions.

Despite these advantages, several challenges remain. Renewable energy intermittency, infrastructure investment requirements, cybersecurity risks, battery limitations, hydrogen infrastructure gaps, and regulatory complexities continue to hinder widespread adoption. Addressing these challenges requires coordinated efforts among governments, industries, researchers, and technology providers.

The proposed framework emphasizes the importance of viewing renewable transportation systems as integrated socio-technical ecosystems rather than isolated technological solutions. Future transportation networks will increasingly rely on collaborative interactions among renewable energy resources, intelligent infrastructure, advanced digital technologies, and supportive policy frameworks.

Looking forward, developments in autonomous mobility, vehicle-to-everything systems, blockchain-enabled energy markets, digital twin platforms, and green hydrogen technologies are expected to redefine transportation sustainability. Organizations that successfully integrate these innovations will be better positioned to achieve carbon neutrality, enhance energy security, and create resilient transportation ecosystems.

In conclusion, renewable energy integration within smart transportation networks is not merely a technological advancement but a strategic necessity for sustainable development. Continued research, innovation, and policy support will be essential for realizing the full potential of intelligent, renewable-powered transportation systems in the coming decades.

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