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MECHANISMS FOR SUPPORT AND EFFECTIVE INTERACTION BETWEEN THE ENERGY AND TRANSPORT SECTORS IN AZERBAIJAN

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Abstract. *This article examines the concept of «green» transport, based on three interrelated theoretical approaches: decarbonization and energy transition; sustainable mobility; and energy synergy and systems integration. Key areas of energy–transport integration are analyzed, including transport electrification, development of charging infrastructure integrated with the power grid, management of transport energy consumption aligned with renewable generation schedules, and utilization of vehicle battery systems as distributed energy storage. The integration of the transport and energy sectors is highlighted as particularly important for Azerbaijan, providing a transition from a petroleum-based energy model to a framework of coordinated management of renewable energy distribution and storage, transforming transport into an instrument of national energy strategy. The study examines global experience to identify critical factors for successful sectoral transformation and to formulate recommendations applicable to countries with diverse economic structures and energy infrastructures. The research emphasizes that increasing the number of electric vehicles without integrated load management can strain existing power grid infrastructure, causing peak loads and reducing system stability. The article develops and substantiates an Evolutionary Multi-Level Systemic Model of Energy–Transport Coupling, which integrates renewable energy expansion, transport electrification, digital coordination mechanisms, institutional regulation, and transnational integration into a unified architecture. The model demonstrates that quantitative growth in electric mobility alone is insufficient for systemic sustainability: coordinated load management, smart charging, Vehicle-to-Grid integration, and alignment with renewable generation are essential. The findings provide both conceptual and practical guidance for advancing low-carbon mobility, enhancing energy security, improving economic efficiency, and supporting environmental sustainability in a hydrocarbon-dependent transition economy.*

Key words**:** *renewable energy, green transport, energy system, transport system, integration, decarbonization, e-mobility.*

Introduction. The accelerating global energy transition necessitates a fundamental shift from the traditional one-directional model of electricity consumption toward cross-sectoral interaction between energy generation and end-use systems. In this context, the integration of renewable energy sources (RES) into the transport sector should be understood not merely as a decarbonization measure, but as a systemic transformation of energy–mobility relations. Electrified transport, particularly electric vehicles (EVs) and electric public transit, possesses the potential to operate not only as a consumer of electricity but also as an active component of load management, contributing to grid flexibility, peak smoothing, and enhanced integration of variable renewable generation.

This systemic perspective is especially relevant for Azerbaijan. The country's renewable energy profile is characterized by pronounced temporal variability, with peak solar output occurring during daytime hours and elevated wind generation typically observed at night. Under such conditions, the transport sector can perform balancing functions within the national power system. Managed charging strategies, demand response mechanisms, and prospective Vehicle-to-Grid (V2G) applications enable electric vehicles to serve as distributed storage assets, reducing peak load pressure and minimizing system imbalances. Consequently, transport electrification contributes not only to emission reduction but also to improved economic efficiency and operational stability of renewable energy integration.

Recognizing these opportunities, Azerbaijan has progressively strengthened its public policy framework aimed at sustainable energy and transport transformation. A notable milestone was the Presidential Decree of March 7, 2024, № 42 "On Stimulating the Use of Electric Vehicles", which positions electric mobility as a driver of carbon reduction, energy efficiency enhancement, technological innovation, and the development of a new environmentally oriented market segment [1]. This decree reflects a strategic shift toward aligning transport modernization with broader energy transition objectives.

A central instrument in this strategy is the National Electric Vehicle Plan, designed to ensure systematic development of the EV market and charging infrastructure. The plan encompasses the expansion of charging networks, stabilization measures for distribution grid loads associated with charging integration, and the gradual incorporation of electric vehicles into the broader energy system architecture, taking into account the expanding role of renewable generation. This approach reflects a

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movement from isolated electrification measures toward coordinated sector coupling.

The successful promotion of green transport and effective RES integration requires coherent public policy ensuring coordinated interaction among financial, regulatory, and infrastructural mechanisms [2]. In Azerbaijan, these support instruments are increasingly implemented in an integrated manner.

Financial mechanisms include tax exemptions for the import of electric vehicles and charging equipment, subsidies for electric public transport procurement, and support schemes for battery storage systems. Regulatory measures focus on establishing technical standards for charging infrastructure, defining energy efficiency requirements, and introducing environmental criteria for public sector vehicle fleets. Infrastructure modernization programs promote the deployment of charging stations in urban areas and along major transport corridors, as well as the modernization of transport depots through the integration of solar and wind installations.

These instruments collectively reduce investment risks, lower entry costs for private actors, and enhance the attractiveness of the emerging low-carbon mobility market [2–4].

International empirical evidence confirms that the coordinated application of financial, regulatory, and infrastructural measures constitutes the most effective mechanism for accelerating transport electrification and renewable integration [5–7]. However, global experience also demonstrates that the mere presence of isolated support instruments is insufficient. Their effectiveness depends critically on systemic coherence, institutional coordination, and alignment with long-term energy transformation strategies.

In Azerbaijan's case, the integration of renewable expansion with transport electrification occurs within the structural context of a hydrocarbon-dependent economy undergoing gradual diversification. This creates both opportunities and structural complexities. On the one hand, expanding renewable generation enhances export potential and energy security; on the other hand, variability of RES output and grid constraints require new balancing mechanisms and institutional adaptation. The transport sector, therefore, emerges as a strategic interface capable of synchronizing supply variability with demand flexibility.

Accordingly, the central analytical question of this study is how mechanisms of support and cross-sectoral coordination between energy and transport can be structured to ensure synchronized development, institutional coherence, grid stability, and long-term system resilience. Addressing this question requires examination of theoretical and empirical approaches to decarbonization, sustainable mobility, and sector coupling, which provide the conceptual foundation for understanding the mechanisms enabling effective energy–transport interaction.

Analysis of recent researches and publications. The literature review follows a thematic and analytical approach, focusing on three core dimensions: decarbonization theory, sustainable mobility frameworks, and sector coupling models. Conceptually, the analysis is informed by socio-technical transition theory and multi-level transformation perspectives [8], which interpret energy–transport interaction as a systemic reconfiguration process rather than isolated sectoral modernization.

Evolution of the «Green Transport» Concept: From Environmental Instrument to Systemic Infrastructure Element

The concept of green transport has evolved from a narrowly defined environmental objective–primarily focused on reducing emissions – to a systemic and interdisciplinary construct embedded within sustainable development and energy transition paradigms. Early interpretations emphasized atmospheric pollutant reduction; however, contemporary scholarship conceptualizes transport as an active structural component of an integrated energy infrastructure.

Within socio-technical transition theory [9], transport electrification is understood not merely as technological substitution but as regime transformation involving infrastructure, markets, institutions, and user practices. This systemic understanding aligns with the growing recognition that mobility systems must be analyzed as embedded within broader energy regimes.

In this context, Rifkin [32] argues that transport assets are transforming into nodal elements of distributed energy systems characteristic of the "third industrial revolution", where electrified mobility interacts with decentralized renewable generation. While this perspective offers a compelling techno-economic vision, it tends to assume institutional and infrastructural readiness that is often absent in hydrocarbon-dependent economies. The literature frequently extrapolates advanced integration models without sufficiently addressing structural constraints in resource-based states such as Azerbaijan.

Similarly, reports by the International Energy Agency (IEA) [10–12] stress that genuine decarbonization of transport is achievable only through full life-cycle integration–linking vehicle electrification to clean electricity generation. However, although these analyses provide macro-level policy guidance, they largely remain normative and insufficiently systematize the mechanisms of interaction between energy supply transformation and transport demand restructuring.

Studies on energy transitions emphasize that structural change requires alignment between niche innovations and regime-level institutions [9; 13]. For countries in transition, the absence of an operational framework that aligns generation expansion, grid modernization, and transport electrification creates implementation gaps.

Thus, while the literature establishes the strategic importance of decarbonization, it does not fully articulate how sectoral coordination mechanisms should be structured in hydrocarbon-exporting national contexts characterized by centralized governance, fossil-based generation, and export-oriented energy models.

Sustainable Mobility Theory: Institutional Incentives and Structural Limitations

The «Avoid–Shift–Improve» paradigm [14] offers a structured framework for reducing transport emissions through demand management, modal restructuring, and technological improvement. Empirical studies [15-17] demonstrate that fiscal incentives, urban planning reforms, and infrastructure investment accelerate the adoption of electric mobility.

However, critical evaluation reveals two structural limitations. First, much of the research concentrates on municipal or micro-level policy instruments, without embedding them within national energy system constraints. Second, sustainable mobility frameworks often treat electricity supply as exogenous and implicitly decarbonized. This assumption becomes analytically problematic in fossil-fuel-dominated systems.

From an institutional economics perspective [18], policy instruments cannot be effective without congruent regulatory frameworks, market design, and investment incentives. In hydrocarbon-dependent economies, the electricity sector frequently operates under vertically integrated or state-dominated structures, limiting flexibility for decentralized renewable integration.

For Azerbaijan, where the energy system historically relies on hydrocarbons, the application of sustainable mobility policies without parallel transformation of generation capacity risks producing "electrified but carbon-intensive" transport. Empirical studies on life-cycle emissions confirm that the carbon intensity of electricity significantly determines the net environmental benefits of EV adoption [19].

Therefore, although the literature highlights effective instruments, it lacks a systemic integration logic that synchronizes transport electrification with energy sector restructuring at the macroeconomic and institutional level.

This analytical gap justifies the need for a coordinated support mechanism aligning regulatory, infrastructural, technological, and investment domains within a unified transformation strategy.

Sector Coupling and Energy Synergy: Conceptual Strengths and Operational Gaps

The concept of sector coupling represents one of the most theoretically advanced approaches in recent research. It proposes the integration of electricity, transport, and heating systems to increase renewable penetration and system flexibility [20].

Studies [6; 7] emphasize Vehicle-to-Grid (V2G) technologies and smart grid architectures as tools for transforming electric vehicles into distributed storage assets capable of stabilizing electricity systems.

Empirical evidence from technologically advanced countries demonstrates that unmanaged charging can increase peak loads, potentially offsetting environmental benefits. Conversely, integrated load management and bidirectional energy flows can reduce peak demand by approximately 10–12 % and enhance renewable utilization efficiency.

Nevertheless, sector coupling literature frequently assumes:

- high digitalization levels;
- advanced regulatory environments;
- liberalized electricity markets;
- substantial financial capacity.

There is limited attention to transitional economies where infrastructure modernization, institutional reform, and market liberalization occur simultaneously. Moreover, existing research often analyzes V2G or smart grids as technological solutions rather than as components of an evolutionary socio-technical transformation requiring staged institutional adaptation.

From a multi-level transition perspective [9], successful coupling requires alignment across technological niches, regulatory regimes, and macro-level landscape pressures. In hydrocarbon-exporting economies, regime inertia and fossil-fuel rent structures may slow this alignment.

Consequently, while sector coupling provides a robust conceptual foundation, it lacks a structured evolutionary framework explaining staged development, institutional sequencing, and coordinated investment planning – particularly relevant for Azerbaijan.

International Experience: Transferability and Contextual Constraints

The European Union's strategy [12] integrates transport electrify-cation with renewable expansion, industrial modernization, and regulatory harmonization. Scandinavian countries demonstrate effective coupling between electric vehicles and renewable electricity (hydropower and wind), ensuring substantial life-cycle emission reductions. Simultaneously, smart grid deployment and long-term planning underpin system resilience [10].

However, the European model is characterized by:

- high institutional maturity;
- diversified energy portfolios;
- strong supranational coordination;
- liberalized electricity markets.

Direct replication in Azerbaijan may be constrained by differences in market structure, energy export orientation, and infrastructure legacy.

Asian experience emphasizes rapid public transport electrification driven by urban air quality concerns and state-led industrial policy. North America prioritizes market-driven innovation, private charging networks, and digitalized load management.

While these models illustrate diverse pathways, the literature often analyzes them descriptively rather than comparatively assessing structural preconditions for transferability. Transition studies emphasize that policy transfer must account for regime characteristics and institutional embeddedness [9; 13].

The absence of a generalized, adaptable framework synthesizing these experiences into a context-sensitive model for resource-exporting transition economies highlights a significant research gap.

Smart Grids and V2G Technologies: Technological Emphasis versus Institutional Mechanisms

Recent literature [6; 7] underscores the strategic importance of smart grids and V2G systems in enabling energy–transport synergy. These technologies allow programmable charging aligned with renewable generation schedules and real-time load balancing.

However, technological feasibility does not automatically translate into systemic effectiveness. Research on energy governance demonstrates that institutional alignment, tariff reform, regulatory incentives, and stakeholder coordination are critical for operational integration [13].

In transitional contexts, institutional fragmentation between energy regulators, transport authorities, and municipal planners can impede systemic coherence. Without harmonized regulatory frameworks and investment sequencing, digital and technological innovations remain underutilized.

Thus, current research provides strong technological justification but insufficient institutional modeling.

Unresolved aspects of the general problem. The conducted review demonstrates that although renewable energy expansion, transport electrification, and sector coupling are extensively studied, their interaction is predominantly analyzed within technologically advanced and institutionally mature systems. Existing approaches remain technologically focused, normatively framed, and insufficiently systematized at the level of coordinated transformation mechanisms.

Hydrocarbon-dependent economies constitute a structurally distinct transition regime characterized by fossil-fuel rent dependence, centralized governance structures, export-oriented energy models, and evolving regulatory institutions. In such contexts, renewable expansion and transport electrification cannot evolve as parallel processes; they must be synchronized within a coordinated evolutionary transformation trajectory.

However, the literature does not provide a structured multi-level mechanism capable of aligning generation restructuring, grid modernization, digital load management, regulatory reform, and staged investment allocation under conditions of fossil-fuel dependence.

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Thus, the general unresolved problem lies in the absence of an integrated evolutionary framework that ensures coordinated energy-transport transformation in hydrocarbon-exporting transition economies.

The identified research gap consists in the lack of a systemic multi-level model adapted to resource-dependent regimes that structures sequencing, institutional alignment, and cross-sectoral coordination within a unified transformation architecture.

The formulation of the objectives of the article. The aim of this study is to analyze the structural transformation of the energy and transport sectors in Azerbaijan and to substantiate an evolutionary multi-level systemic model of energy–transport coupling that explains the mechanisms, institutional drivers, and structural constraints shaping the trajectory of low-carbon transition in a hydrocarbon-based economy.

To achieve this aim, the study pursues the following objectives:

1. To assess the current structural state and transformation dynamics of Azerbaijan's energy sector, including renewable energy expansion and diversification trends.

2. To analyze the development trajectory of the transport sector, with particular emphasis on vehicle electrification, import dynamics, and charging infrastructure expansion.

3. To examine strategic interdependencies between national energy and transport policies and identify systemic constraints affecting green mobility development.

4. To evaluate the infrastructural and technological potential for renewable energy integration into the transport sector, including public transport electrification and corridor-based development.

5. To systematize regulatory, infrastructural, digital, and investment mechanisms that enable effective interaction between the energy and transport sectors.

6. To conceptualize and theoretically substantiate an Evolutionary Multi-Level Systemic Model of Energy–Transport Coupling that integrates governance steering, technological adaptation, infrastructure coordination, and structural boundary conditions.

Statement of the main material of the research. The study examines the ongoing transformation of Azerbaijan's energy and transport sectors through a systemic, multi-level lens. Emphasis is placed on the interconnections between infrastructure, governance, and technology, rather than isolated metrics. This perspective allows for a comprehensive understanding of how sectoral changes emerge, interact, and create the conditions for sustainable development. The following analysis explores key patterns, trends, and constraints that shape the evolution of energy and mobility systems in the country.

The state of the energy and transport sectors of Azerbaijan

The empirical analysis of Azerbaijan's energy and transport sectors is conducted through the lens of the proposed multi-level systemic framework. Rather than presenting sectoral statistics as isolated indicators, the data are interpreted as structural signals of an ongoing socio-technical transformation within a hydrocarbon-dependent regime. Historically dominated by oil and natural gas extraction, Azerbaijan's energy architecture represents a centralized, export-oriented fossil-based model.

However, in recent years, there has been a strategic shift in state energy policy aimed at developing renewable energy sources (RES) and reducing the carbon footprint of the national energy system. This transition reflects global decarbonization trends and the desire to integrate environmental goals into the country's economic and infrastructure strategy [15; 21-23].

As of 2025, the share of RES in total installed electricity capacity was approximately 20.2 % (including all hydroelectric power plants), indicating significant growth in both hydropower and solar and wind installations. The total capacity of renewable energy sources reached 1,829.6 MW by the beginning of 2025, compared to 1,748.6 MW in mid-2024. However, the growth trajectory was non-linear. During 2020–2022, average annual expansion did not exceed 1.6 %, indicating relative stagnation.

A structural acceleration occurred in 2023, when renewable capacity increased by 349 MW (+26 % year-on-year), largely due to the commissioning of small hydropower facilities in Karabakh and Eastern Zangezur. These developments demonstrate the gradual expansion of the energy sector beyond traditional hydrocarbon sources and the formation of a foundation for integrating green energy solutions into various sectors, including transport [24] (see Table 1).

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Table 1

Installed capacity and share in the energy system

Indicator	2020	2021	2022	2023	2024	2025	2020–2025 Growth
Total renewable capacity (MW)	1,296	1,316	1,339	1,688	1,748.6	1,829.6	+41.2 %
Annual growth rate, %	-	1.5	1.7	26.1	3.6	4.6	CAGR ≈ 7.1 %
Share of RES in total capacity, %	17.0	17.0	17.3	18.0	20.86	20.2	+3.2 p.p.

Source: compiled by the authors based on data from [25-27]

The share of renewables in total installed capacity increased by 3.2 percentage points over the period, representing a relative structural shift of 18.8 %. Despite measurable growth (see Fig. 1), renewable capacity remains structurally secondary to hydrocarbon-based generation, indicating that Azerbaijan is currently in a diversification stage rather than a systemic decarbonization phase. Estimates of the technical potential of renewable energy in the country suggest significant opportunities for further development.

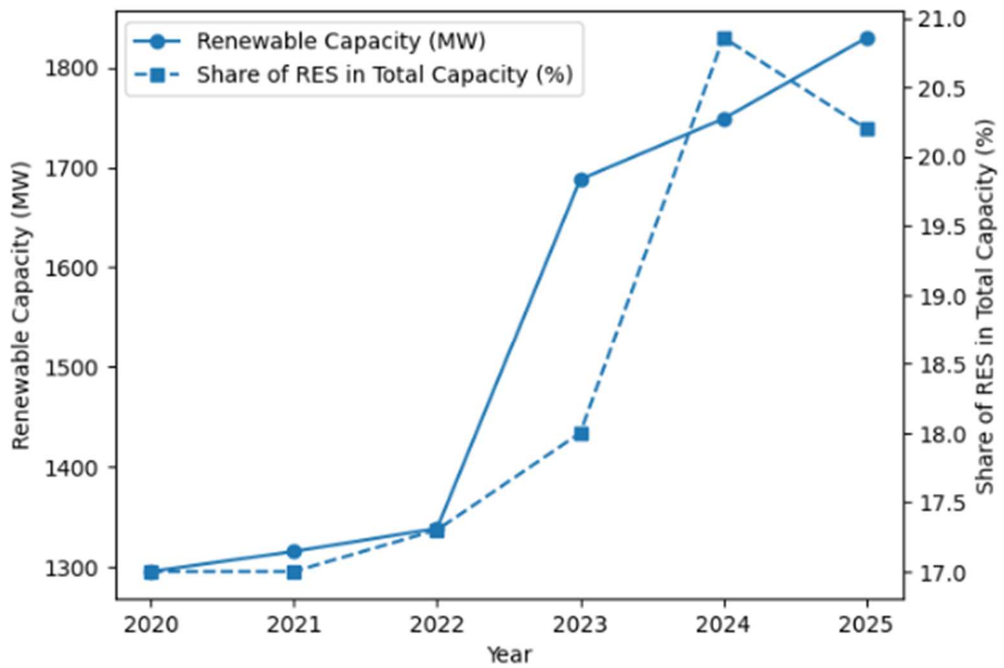

Fig. 1. **Dynamics of renewable capacity and its share in total installed capacity**
Source: compiled by the authors

By 2025, the capacity structure is projected as follows: hydroelectric power plants (HPPs) – 1,443.5 MW; solar power plants (SPPs) – 278.2 MW; wind power plants – 63.5 MW; bioenergy and waste recycling – 37 MW; and hybrid stations – 7.3 MW. These figures highlight that renewable energy resources in Azerbaijan are still at a partial stage of development, which creates broad prospects for the expansion of "clean" generation and the direct use of electricity in the transport sector, including the wider adoption of electric vehicles and the development of public electric transport (see Table 2).

As shown in Table 2, HPPs accounted for 78.9 % of total RES in 2025, although their relative share declined from 88.9 % in 2020 due to the rapid expansion of solar capacity. Solar power grew from a marginal 2.9 % in 2020 to 15.2 % in 2025, reflecting strategic deployment of solar plants in Karabakh and Eastern Zangezur. Wind power remained stable at around 3–5 %, while bio/hybrid installations emerged as small-scale pilot projects, maintaining 2–3 % of the total. A visual representation of this transformation is provided in Fig. 2, which shows the stacked renewable energy capacity by generation type from 2020 to 2025.

Table 2

Structure of installed capacity by type (MW)

Generation Type	Installed Capacity (MW)						Share of generation type in total RES (%)					
	2020	2021	2022	2023	2024	2025	2020	2021	2022	2023	2024	2025
Hydroelectric Power Plants (HPP)	1,152	1,158	1,158	1,301.7	1,443.5	1,443.5	88.9	88.0	86.5	77.1	82.5	78.9
Solar Power Plants (SPP)	38	44	50	278.2	278.2	278.2	2.9	3.3	3.7	16.5	15.9	15.2
Wind Power Plants (WPP)	66	67	67	63.5	63.5	63.5	5.1	5.1	5.0	3.8	3.6	3.5
Bio/Hybrid / Other Power Plants	40	47	64	44.3	44.3	44.3	3.1	3.6	4.8	2.6	2.5	2.4
Total RES	1,296	1,316	1,339	1,688	1,748.6	1,829.6	100	100	100	100	100	100

Source: compiled by the authors based on data from [25-29]

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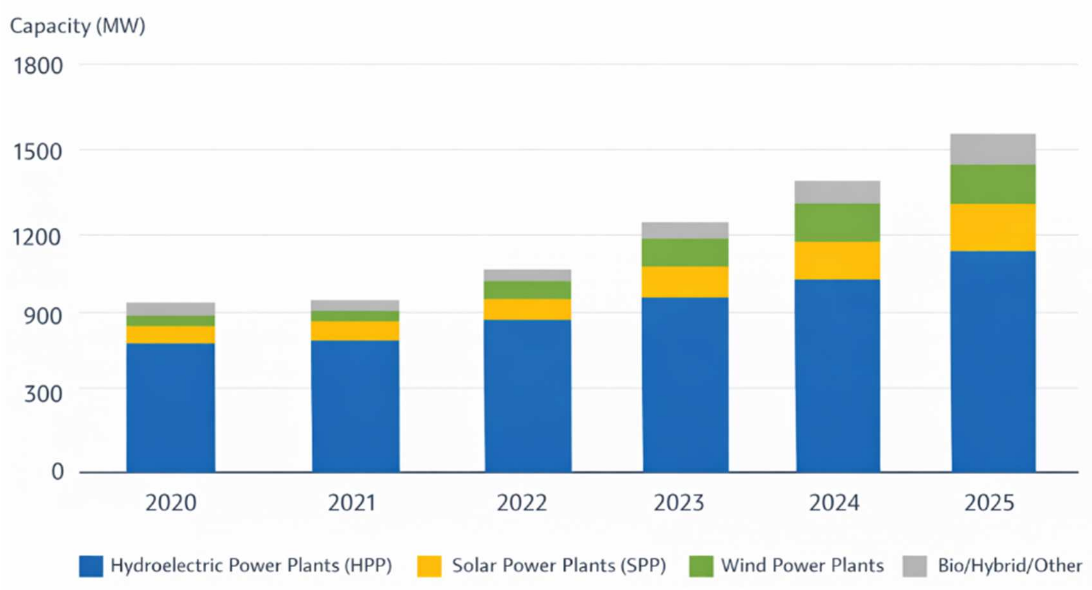

Fig. 2. **Installed Renewable Energy Capacity in Azerbaijan (2020–2025), by generation type**

Source: compiled by the authors

The 2020–2025 trend demonstrates the active implementation of solar and wind projects, alongside the emergence of pilot bioenergy and hybrid installations. These developments indicate a progressive transition toward a more diversified and environmentally friendly energy system, in which each type of renewable energy source is gradually integrated into the overall infrastructure, creating the preconditions for a systemic transformation of the energy sector. Consequently, Azerbaijan's energy balance is gradually shifting from a hydrocarbon-based structure to a multi-component system with an increasing share of renewable energy sources, providing the technological and resource foundation for green transport and aligning strategically with global sustainable energy trends.

Azerbaijan's transport sector remains one of the most energy- and carbon-intensive segments of the economy, playing a key role in shaping the national carbon footprint [30]. Historically, the vehicle fleet has been dominated by internal combustion engine vehicles running on gasoline and diesel, reflecting both hydrocarbon availability and the country's existing infrastructure. In recent years, the gradual emergence of green transport options has begun to reshape the sector, with the number of electric vehicles (EVs) steadily increasing, though their share remains small relative to the total fleet. A significant portion of EVs are imported as used or hybrid models, limiting the potential for a locally driven innovation market and underscoring that the EV segment is still in its early stage of development (see Table 3).

Table 3

Dynamics of imports of electric vehicles in 2020-2025

Indicator	2020	2021	2022	2023	2024	2025
Total imported vehicles						
Quantity, units	53,729	91,194	74,577	95,971	91,838	123,319
Value, US$ million	647.6	935.2	1,057.8	1,680.7	1,844.2	2,386.5
Including electric vehicles (EVs)						
Quantity, units	167	160	486	3,102	3,027	2,028
Share in total imports (%)	0.31%	0.18%	0.65%	3.23%	3.30%	1.64%
Value, US$ million	8.3	3.5	17.7	125.3	121.6	62.5
Average unit value, US$	49,700	21,875	36,400	40,400	40,200	30,800
Yearly growth of EV imports, %	–	-4.2	203.8	538.5	-2.4	-33.0

Source: compiled by the authors based on data from [29; 31-33]

As Table 3 shows, the presented statistical data reflects significant changes in the structure and volume of vehicle imports, with a particular emphasis on the electric vehicle segment. Over the period under review (2020–2025), there has been a steady increase in total vehicle imports in both quantity and value terms. Total imports increased from 53,729 units in 2020 to 123,319 units in 2025 (an increase of approximately 2.3 times). The total value of imports increased even more significantly–from $647.6 million to $2.38 billion (an increase of approximately 3.7 times). This indicates an increase in the average value of imported vehicles.

The sharp increase in EV imports during 2023–2024 represents a niche expansion phase. However, the absence of synchronized renewable scaling and digital load management indicates that electrification is progressing faster than systemic integration. In 2023, the number of imported electric vehicles reached 3,102 units, 18.5 times the 2020 figure. In 2023, EV import spending reached a historic high of $125.27 million, accounting for approximately 7.4 % of the total value of all vehicle imports. Data for 2025 indicate a slight correction, with EV imports declining to 2,028 units and $62.5 million, which may be due to market saturation or changes in government support measures.

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An analysis of the share of EVs in total imports allows us to draw the following conclusions: In 2020-2021, the segment was niche (less than 0.3 % of the total). By 2023, the share of EVs increased to 3.2 % in quantitative terms, indicating a qualitative transformation in consumer demand. The average price of an electric vehicle varied significantly: from ~$50,000 in 2020 to ~$21,600 in 2021, with a subsequent increase to ~$40,000 in 2023-2024.

Trends for 2020-2025 confirm the gradual electrification of the vehicle fleet. Despite a projected slowdown in 2025, the electric vehicle sector has firmly established itself in the import structure, and the overall vehicle market demonstrates high investment attractiveness and expanding capacity.

On the one hand, the implementation of public and private initiatives to stimulate the purchase and operation of electric vehicles is a positive trend, demonstrating growing public interest in environmentally friendly transport. On the other hand, the low share of electric vehicles in the total vehicle fleet indicates the need for systemic government support and the development of a comprehensive incentive policy, including both economic measures and infrastructure development. Public and urban transport are also facing the challenge of modernizing and integrating environmentally friendly solutions. Full electrification of bus depots, tram lines, and commuter rail systems is still in its early stages, but electric and hybrid models are gradually being introduced, as well as municipalities showing interest in developing local projects based on renewable energy sources.

At the same time, current trends in Azerbaijan's transport sector indicate the beginning of a transition from traditional hydrocarbon-based transport to green and digitalized ones. However, full transformation requires systemic integration with the energy sector, the development of charging infrastructure, and the creation of economic and institutional incentives. This process forms the basis for the subsequent large-scale adoption of electric transport and the improvement of the environmental sustainability of urban and national transport systems.

The relationship between strategies and systemic constraints

Azerbaijan's National Energy and Transport Development Strategy is centered on creating synergies between sectors: modernizing transport infrastructure (including the East-West and North-South corridors) requires a stable and diversified energy supply, while expansion of the transport sector stimulates demand and innovation in the energy sector. Key objectives include sustainable development, the adoption of renewable energy sources, environmental protection, and the introduction of digital technologies (Smart City/Mobility), all aimed at improving social well-being and fostering a competitive market environment [34 - 37].

The interconnection between strategies is not merely conceptual: transport activity depends directly on energy availability, and conversely, the energy system must adapt to the evolving patterns of mobility demand.

This mutual dependence creates both opportunities and systemic constraints, as gaps in infrastructure, regulatory coordination, or technological readiness can limit the effectiveness of strategy implementation. Fig. 3 illustrates the relationship between energy and transport sector strategies, highlighting how energy availability, sectoral integration, and emerging technological solutions interact to shape policy outcomes.

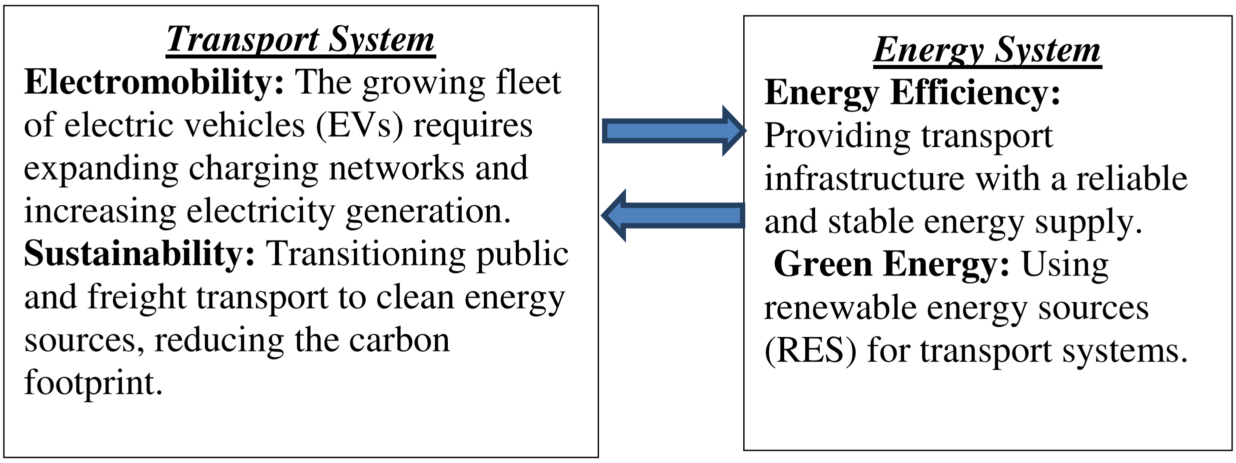

Fig. 3. **Interrelationship between energy and transport sector strategies**
Source: compiled by the authors

As Fig. 3 shows, decarbonization of the transport sector entails a systemic reduction in carbon footprint while simultaneously improving economic efficiency. Several priority strategic areas can be identified for Azerbaijan:

1. Energy diversification of transport – the gradual replacement of vehicles with internal combustion engines with electric, hybrid, and biofuel vehicles.

2. Integration of renewable energy sources into the transport energy supply – the use of solar, wind, and hydroelectric power sources to re-charge electric vehicles, which reduces the carbon footprint and increases energy independence.

3. Development of intelligent charging infrastructure – the implementation of Smart Charging and V2G systems, which optimize grid loads and ensure the efficient use of vehicle batteries.

4. Modernization of public transport – the electrification of buses, trams, and trolleybuses, as well as the development of «green routes» with priority given to the busiest city lines.

The implementation of these strategies lays the foundation for a sustainable transition to low-carbon mobility, while stimulating local technology production and the development of innovative infrastructure. However, the presence of strategic objectives does not automatically generate operational integration. The effectiveness of synergy depends on regulatory sequencing, infrastructural readiness, and digital coordination capacity.

Despite positive momentum, the development of green transport and the integration of renewable energy sources into the transport sector face a number of systemic constraints that require a comprehensive approach [16, 38]:

- Infrastructure limitations. The country's charging station network is still unevenly distributed: although a certain number of charging points are already operational in large cities such as Baku, their density and geographical coverage remain insufficient for the large-scale adoption of electric vehicles. New stations are being installed in the regions and liberated territories, but by the end of this year, for example, their number is only planned to reach 20, highlighting the need for accelerated infrastructure development to ensure equal access.

- Technical integration of electric charging stations into the power grid. The growing number of electric vehicles increases the load on distribution networks, creating voltage fluctuations and peak loads. This requires the implementation of intelligent grid management solutions, including adaptive power distribution and the integration of V2G systems for load balancing.

- Attitude and economic barriers among consumers. Electric vehicles have not yet become a mass choice due to the high acquisition cost, limited model range on the domestic market, and a lack of demand stimulation programs. Addressing these issues requires a comprehensive approach, including financial incentives, subsidies, educational and information campaigns, and the development of a secondary market for electric vehicles.

- Legal and institutional regulation. Despite the adoption of key government documents, the legislative and regulatory framework for renewable energy and green transport is still under development. To ensure a predictable and investment-attractive environment, further systematization of laws, standards, and rules for interaction between the energy and transport sectors is required. The above demonstrates that the current development of green transport in Azerbaijan is characterized by a combination of positive initiatives and structural constraints. This highlights the need for a comprehensive strategic approach combining infrastructure investments, institutional reforms, and economic incentives to create a sustainable and scalable green mobility system.

Potential for the use of renewable energy in the transport sector of Azerbaijan

In recent years, the development of the electric charging station (ECS) network in Azerbaijan has progressed from scattered installations by private operators to the formation of elements of a national charging infrastructure providing systemic support for electric mobility [21].

- Geographical structure. As of early 2026, more than 420 charging points were operating across the country, with the highest concentration in Baku and the Absheron economic region. A consistent network of fast and ultra-fast charging stations is being created along key transport corridors and highways, increasing interregional connectivity for electric vehicles and reducing user “range anxiety”. Specifically, a continuous chain of ultra-fast charging nodes with a capacity of 150-300 kW at intervals of 80-100 km has been formed on the M1 and M2 highways, enabling long-distance travel without the risk of energy constraints.

- Technological integration with renewable energy sources. One of the significant achievements of 2025 was the introduction of pilot autonomous charging hubs (off-grid) in Gobustan and Zangilan, which operate completely independently of the centralized power grid. These stations are equipped with solar panels and battery-storage systems (BESS), enabling a 100% green charging cycle and demonstrating the

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feasibility of combining renewable energy with local transport infrastructure.

Considering these indicators comprehensively, it can be concluded that Azerbaijan has created the infrastructure and energy foundation for the widespread adoption of green transport.

One of the priority areas for developing green transport in Azerbaijan is the phased electrification of public transport, including buses, trams, and trolleybuses. These modes of transport remain key elements of urban mobility, particularly in the capital, and their transition to electric traction powered by renewable energy sources can significantly reduce greenhouse gas emissions, improve air quality, and reduce noise pollution in urban areas.

Global experience demonstrates that combining solar and wind power with electric transport can reduce the load on power grids and optimize operating costs. This strategy is particularly relevant for Azerbaijan due to its high solar potential, which opens up opportunities for the creation of local solar power stations at terminal stations and depots, ensuring partial autonomy of transport.

Pilot projects, such as the purchase of the first electric buses in Baku, are showing positive results: reduced fuel consumption, reduced emissions, and improved passenger comfort. A key element of the strategy is the gradual replacement of diesel transport with electric vehicles, starting with the busiest routes and major transport hubs, ensuring a managed transition to environmentally sustainable urban mobility.

Azerbaijan's rail transport is already partially electrified, but the majority of its electricity is generated from traditional sources. Switching to renewable energy sources such as solar, hydroelectric, and wind power plants will significantly reduce the transport system's carbon footprint and enhance its environmental sustainability. International experience shows that such solutions improve economic efficiency and environmental sustainability, allowing for significant savings in operating costs. For example, in a number of European cities, solar panels on the roofs of depots and charging stations provide up to 30–40 % of the energy needed for electric vehicles, significantly reducing operating costs. Similar models could be adapted for Azerbaijan in both large cities and regional centers with high solar potential.

The interaction of renewable energy generation, electrified transport, and supporting infrastructure can be conceptualized as a coordinated system, as illustrated in Fig. 4.

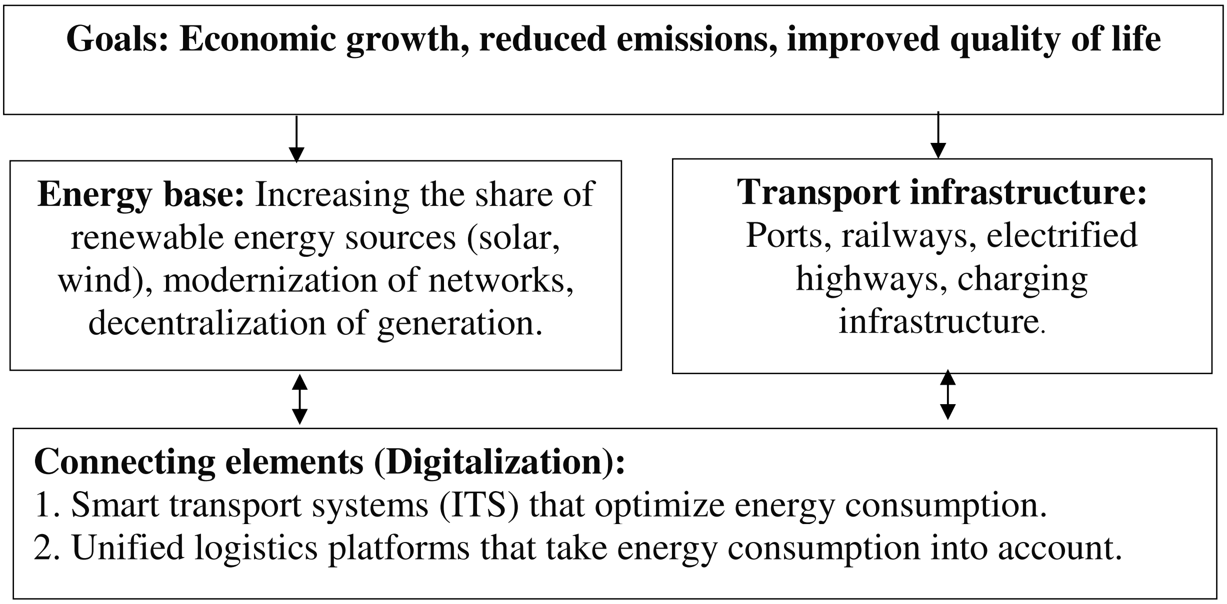

Fig. 4. **Interaction (integration) diagram**
Source: compiled by the authors

As shown in Fig. 4, the integration of energy supply, transport electrification, and digital management mechanisms forms the backbone of a sustainable, low-carbon mobility network in Azerbaijan. This diagram highlights the key interaction points where energy generation, renewable integration, and transport infrastructure converge, ensuring that each component contributes to an efficient and environmentally friendly transport system.

These integration mechanisms are being implemented within the framework of the «Azerbaijan 2030: National Priorities of Socioeconomic Development» concept, which places primary emphasis on the creation of green transport corridors and the digital transformation of infrastructure [21]. Within this strategic framework, the main mechanisms supporting systemic interaction between the energy and transport sectors include:

1. Creation of multimodal energy and transport corridors

– *Middle Corridor (MCTR):* Integration of transport routes with energy infrastructure to facilitate the transit of resources from Central Asia to Europe.

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- *Zangezur Corridor:* Functions as both a transport route and a corridor for exporting electricity, including renewable energy, to Turkey and Europe.
- *Caspian Corridor:* Combines high-voltage communication and power transmission lines along the Caspian Sea with new and existing logistics hubs.

2. Energy transition in the transport sector

Electrification and renewable energy: Implementation of Power Purchase Agreements (PPAs) enables the attraction of foreign investment, such as the 230 MW Garadagh solar power plant, to supply transport infrastructure with clean energy.

3. Digital and legal integration

Unified digital platforms: Development of data exchange systems between ports (e.g., Alaty, Aktau) and other logistics nodes to optimize supply chains and reduce energy consumption.

4. Investment incentives

Legislative and fiscal mechanisms designed to support projects that jointly address transport and energy objectives, with special focus on liberated territories like Karabakh, which have been designated as “clean energy zones”.

5. Greening port infrastructure

Green Port initiatives: As exemplified by the Baku International Sea Trade Port, this includes process automation and the deployment of renewable energy sources to power terminal operations.

Collectively, these mechanisms constitute a coordinated approach to energy–transport integration, providing a systemic foundation for Azerbaijan’s transition to low-carbon mobility while promoting digitalization, efficiency, and environmental sustainability.

Building on the identified strategic objectives and systemic constraints, it becomes evident that the successful transition toward low-carbon mobility requires more than isolated initiatives. To achieve coherent integration between the energy and transport sectors, a set of coordinated mechanisms is necessary, encompassing regulatory, infrastructural, digital, and economic dimensions. These mechanisms provide the operational foundation for aligning sectoral modernization with overarching strategic goals, which is examined in detail in the following section.

Mechanisms for Support and Effective Interaction Between the Energy and Transport Sectors in Azerbaijan

The empirical findings demonstrate that Azerbaijan's transition is characterized by partial sectoral modernization without full systemic synchronization. This condition justifies the need for an evolutionary coordination architecture capable of aligning infrastructure expansion, governance steering, and digital load management.

The conducted theoretical synthesis and contextual analysis allow the identification of a coordinated set of mechanisms ensuring systemic interaction between the energy and transport sectors in Azerbaijan.

Unlike linear electrification models, the proposed mechanism is structured across interconnected functional domains:

1. Regulatory and institutional mechanisms – alignment of energy and transport strategies, regulatory harmonization, incentive schemes, and tariff design supporting renewable-based electrification;
2. Infrastructure coordination mechanisms – synchronized development of renewable generation, grid modernization, charging infrastructure, and energy storage systems;
3. Digital integration mechanisms – implementation of smart grid technologies, demand-side management tools, and V2G solutions enabling bidirectional energy flows;
4. Investment and economic instruments – coordinated public–private financing models and long-term infrastructure investment planning to prevent sectoral asymmetry.

These mechanisms operate not independently but within an integrated coordination architecture, where institutional decisions influence infrastructure development, digital solutions regulate operational interaction, and economic incentives shape market behavior.

The systemic interaction of these mechanisms forms the foundation of the proposed Evolutionary Multi-Level Systemic Model of Energy–Transport Coupling in Azerbaijan, presented below.

The proposed framework conceptualizes energy–transport integration in Azerbaijan as an evolutionary, multi-level systemic coupling process grounded in sector coupling theory, systems integration logic, and multilevel governance approaches. Unlike static infrastructure-based representations, which treat electrification as a technological substitution process, the model interprets integration as a dynamic systemic transformation in which transport evolves from a passive energy consumer into an active balancing and storage component of the national power architecture.

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The framework is explanatory rather than purely descriptive: it identifies structural domains, coordination mechanisms, institutional drivers, and boundary conditions that jointly generate an emergent Energy–Transport Coupling System. Fig. 5 presents the architecture of the proposed model.

At the center of the framework lies the Energy–Transport Coupling System (Emergent Core), conceptualized as an emergent configuration generated by the structured interaction of material infrastructure, coordination mechanisms, governance instruments, transnational integration processes, and structural constraints. Converging arrows toward the core indicate systemic synthesis rather than hierarchical subordination, while bidirectional energy flows, distributed storage via electric vehicle batteries, smart charging, and real-time load balancing collectively create a dynamic coupling architecture. The circular flow surrounding the core reflects continuous adaptive recalibration based on system performance (Fig. 5).

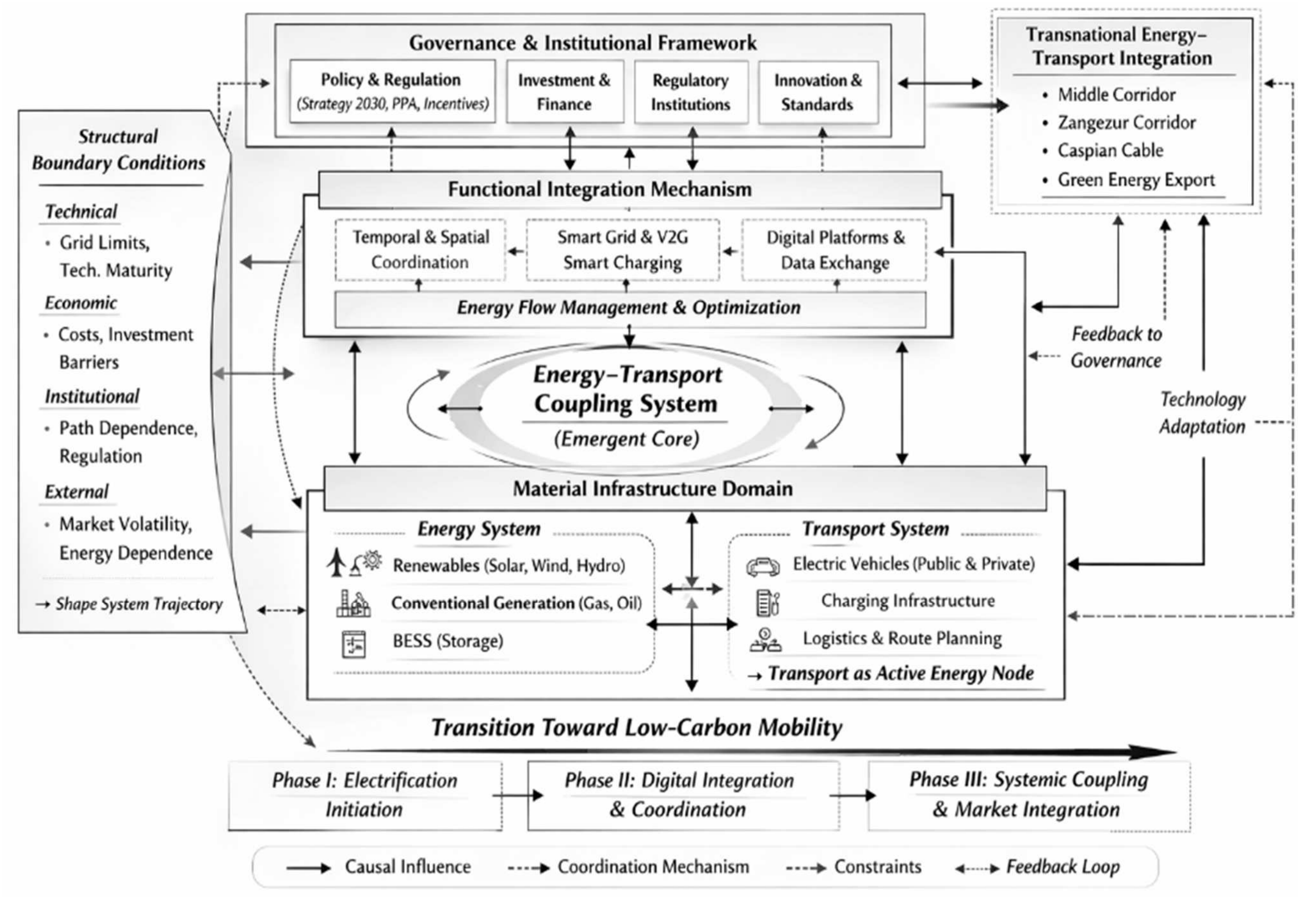

Fig. 5. **Evolutionary Multi-Level Systemic Model of Energy–Transport Coupling in Azerbaijan**

Source: compiled by the authors; visualization prepared using AI tools

The Material Infrastructure Domain forms the physical foundation of integration and consists of two interdependent subsystems: the Energy System (renewable generation, conventional capacity, battery energy storage) and the Transport System (electric vehicles, charging infrastructure, logistics optimization). Horizontal bidirectional arrows represent energy exchange, while vertical arrows toward the core demonstrate that infrastructure provides material capacity but does not itself generate systemic integration.

The Functional Integration Mechanism mediates between infrastructure and systemic emergence through three coordinated blocks:

1. Temporal and spatial coordination,
2. Smart grid, V2G, and smart charging technologies,
3. Digital platforms and data exchange systems.

Downward dashed arrows toward infrastructure reflect coordination-based regulation of energy flows, while the central element, "Energy Flow Management & Optimization", operationalizes integration by synchronizing renewable generation with mobility demand, redistributing charging loads, and managing bidirectional exchange.

At the governance level, the Governance & Institutional Framework exerts hierarchical steering over the system. Solid arrows indicate that policy instruments define strategic direction, investment priorities, regulatory alignment, and innovation standards. Transnational integration expands the system scale and channels technological adaptation, including grid solutions, battery innovations, and harmonized standards, directly influencing material infrastructure and enabling regional market participation.

Structural boundary conditions, including technical limits, economic barriers, institutional rigidities, and market volatility, shape the feasible trajectories and pacing of transformation. Dotted arrows represent these constraints, which influence the shift from initial electrification to digital integration and systemic coupling, and determine the duration and viability of each phase along the Transition Toward Low-Carbon Mobility axis.

The framework identifies four analytically distinct types of relationships:

- Causal links (solid arrows) – hierarchical steering by governance;

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- Coordination links (dashed arrows) – operational synchronization through integration mechanisms;
- Constraint links (dotted arrows) – structural conditioning;
- Feedback links (double arrows) – adaptive recalibration based on performance.

In summary, the model conceptualizes integration as a multi-level, co-evolutionary process where governance, digital coordination, material infrastructure, technological adaptation, and structural constraints interact recursively. Transport is not merely an energy consumer but becomes an active system component, contributing to grid balancing, distributed storage, and dynamic load management.

The proposed mechanisms for effective support and interaction between energy and transport sectors in Azerbaijan are:

1. Hierarchical regulatory steering – investment priorities, technological standards, and institutional alignment;
2. Operational coordination mechanisms – smart charging, V2G systems, and digital energy flow management;
3. Technological adaptation and transnational integration – transfer of standards, grid solutions, and innovative storage technologies;
4. Structural conditioning – economic, technical, and institutional constraints shaping transition feasibility.

Strategic application of these mechanisms prioritizes public transport and logistics corridors, phased electrification of bus fleets, modernization of depots with renewable energy, and deployment of distributed storage. Multimodal green corridors, such as the Middle Corridor and Zangezur initiatives, provide opportunities for Azerbaijan to emerge as a regional center for green energy integration.

By integrating renewable expansion, transport electrification, digital grid intelligence, institutional governance, and structural feedback, the framework ensures the formation of a resilient, low-carbon, and technologically advanced mobility system, supporting national energy security, economic competitiveness, and regional leadership in sustainable transport and energy solutions.

Conclusions. The conducted research confirms that the effective interaction between the energy and transport sectors in Azerbaijan should be understood not as a sectoral modernization process, but as a systemic transformation based on multi-level integration, technological adaptation, and coordinated governance. The study develops and substantiates an Evolutionary Multi-Level Systemic Model of Energy–Transport Coupling, in which infrastructure, digital coordination mechanisms, institutionnal regulation, and transnational integration operate as interdependent components of a unified architecture. Empirical analysis demonstrates gradual diversification of the generation structure, expansion of renewable energy capacity, and an accelerating phase of electric vehicle adoption and charging infrastructure development. The findings indicate that quantitative growth alone is insufficient for systemic sustainability: coordinated load management, smart charging, Vehicle-to-Grid integration, and alignment with renewable generation are essential to prevent operational imbalances and ensure efficient system functioning.

By combining regulatory, infrastructural, technological, and investment mechanisms within a multi-level framework, the proposed model provides a conceptual and practical foundation for advancing low-carbon mobility, enhancing energy security, improving economic efficiency, and promoting environmental sustainability in a hydrocarbon-dependent transition economy.

Conflict of Interest: The authors declare that they have no conflicts of interest.

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МЕХАНІЗМИ ПІДТРИМКИ ТА ЕФЕКТИВНОЇ ВЗАЄМОДІЇ ЕНЕРГЕТИЧНОГО І ТРАНСПОРТНОГО СЕКТОРІВ В АЗЕРБАЙДЖАНІ

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Анотація. *У статті досліджено концепцію «зеленого» транспорту на основі трьох взаємопов'язаних теоретичних підходів: декарбонізації та енергетичного переходу; сталої мобільності; енергетичної синергії та системної інтеграції. Проаналізовано ключові напрями інтеграції енергетичного і транспортного секторів, зокрема електрифікацію транспорту, розвиток зарядної інфраструктури, інтегрованої з електроенергетичною мережею, управління споживанням енергії транспортом відповідно до графіків генерації з відновлюваних джерел енергії, а також використання акумуляторних систем транспортних засобів як розподілених накопичувачів енергії. Підкреслено особливу актуальність інтеграції енергетичного та транспортного секторів для Азербайджану, що забезпечує перехід від нафтозалежної енергетичної моделі до моделі узгодженого управління розподілом і зберіганням відновлюваної енергії, перетворюючи транспорт на інструмент реалізації національної енергетичної стратегії. У дослідженні узагальнено міжнародний досвід з метою виявлення критичних чинників успішної секторальної трансформації та формування рекомендацій, релевантних для країн із різною економічною структурою та енергетичною інфраструктурою. Обґрунтовано, що зростання кількості електромобілів без інтегрованого управління навантаженням може створювати додатковий тиск на існуючу електромережеву інфраструктуру, спричиняючи пікові навантаження та знижуючи стабільність системи. У статті розроблено та теоретично обґрунтовано еволюційну багаторівневу системну модель енергетично-транспортного поєднання, яка інтегрує розширення відновлюваної генерації, електрифікацію транспорту, цифрові механізми координації, інституційне регулювання та транснаціональну інтеграцію в єдину архітектуру. Модель демонструє, що кількісне зростання електричної мобільності саме по собі є недостатнім для забезпечення системної сталості; необхідними є скоординоване управління навантаженням, впровадження технології інтелектуального заряджання (Smart Charging), інтеграція за концепцією «транспортний засіб – електромережа» (V2G) та узгодження споживання з режимами генерації відновлюваної енергії. Отримані результати мають як концептуальне, так і практичне значення для розвитку низьковуглецевої мобільності, підвищення енергетичної безпеки, зростання економічної ефективності та забезпечення екологічної стійкості в умовах гідрокарбон-залежної перехідної економіки.*

Ключові слова: *відновлювана енергія, зелений транспорт, енергетична система, транспортна система, інтеграція, декарбонізація, електромобільність.*

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