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DETERMINANTS OF ELECTROMOBILITY DEVELOPMENT FROM THE PERSPECTIVE OF A ZERO EMISSION, INNOVATIVE AND RESILIENT ECONOMY

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ABSTRACT: The aim of this article is to identify the critical factors and assess the specific actions conditioning the development of electromobility from the perspective of a zero-carbon, innovative and resilient economy. These issues have a particular dimension in relation to individual mobility. The study used a combination of primary and secondary data, using various research methods and techniques, such as descriptive analysis, desk research, diagnostic survey, cause-and-effect analysis and statistical analysis. Additionally, in-depth interviews were conducted with experts in managerial positions. The literature review and the results of our own research confirmed the importance of the identified factors in the uptake of electric cars. At the same time, the study highlighted the high complexity of problems regarding investment decisions determining the development of electromobility. Taking active steps to increase the level of sustainability and resilience of the electromobility system should first focus on further development of charging infrastructure, uptake of electric vehicles, development of renewable energy sources and creation of an electric vehicle battery value chain. The main expectations for the development of electromobility are to reduce CO_2 emissions, reduce dependence on fossil fuel supplies, increase the competitiveness and innovation of the economy and reduce external costs generated by transport. Attempts were made to achieve the originality of the research carried out through its measurable nature. The proposed electromobility development model may contribute to the improvement of decision-making tools regarding the allocation of public funds and other sources for investments so that they contribute to the sustainable development of mobility systems.

KEYWORDS: zero-emission economy, sustainable transport, zero-emission mobility, electromobility, electric vehicles

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Introduction

Active engagement in supporting the global fight against climate change is a political priority for the European Union (EU), aimed at developing an innovative, zero-carbon and resilient economy. In theoretical terms, it is defined as an economy that pursues long-term development based on endogenous factors while seeking to minimise negative impacts on the natural environment through, among other things, reduced emissions and efficient use of resources (Baker et al., 2021). It aims to reduce anthropogenic climate change, manage resources rationally, improve society's quality of life, increase competitiveness and ensure sustainable economic growth.

In the strategy of an innovative and zero-carbon economy, the key factors in determining the EU's growth and development are the continued investment in human capital and technological progress associated with decarbonising and resource-intensive economies to achieve net zero greenhouse gas (GHG) emissions by 2050 (European Commission, 2019). Demand for new technologies, as well as capital and consumer goods that contribute to energy efficiency and decarbonisation of the economy, remains a function of many variables. Of key importance are regulations that tighten environmental standards and force innovation, as well as setting sanctions for businesses and individuals that do not meet set environmental criteria. At the same time, harnessing technological potential as a driver of economic growth requires ensuring an adequate level of diffusion of innovative solutions (Liao et al., 2017). This entails taking measures to increase social acceptance of new solutions and create effective investment and consumption demand. In addition, it requires state support for measures to stimulate the supply of modern low- and zero-carbon technologies and resource-efficient goods and services that are initially not profitable but are essential for the public good (Champagne & Dubé, 2023).

The development of zero-carbon mobility is an essential part of the transition towards an increasingly zero-carbon and innovative economy, which is important for Europe to maintain its competitiveness and be able to adapt to the changing needs of passenger and freight mobility. Passenger and freight transport accounts for ¼ of EU CO_2 emissions and is a significant source of urban air pollution. At the same time, given that among global economic sectors, transport is responsible for the largest increase in CO_2 emissions (IEA, 2023), implementing low- and zero-carbon mobility systems is a prerequisite for achieving the Paris Agreement targets (Du et al., 2018).

The process of transition to climate-neutral mobility has already begun, but its pace needs to accelerate. Mobility in EU Member States, heavily influenced by global development trends, shows a strong preference for individual motorisation. These trends determine the increase in demand for petroleum-based fuels, resulting in increasingly high CO_2 emissions from passenger cars. The current lack of a viable substitute for these fuels does not encourage the development of zero-emission mobility. A factor supporting this possibility, especially in the medium term, could be the use of electricity in car transport, including mainly from renewable energy sources (RES) (ETC/CME, 2020; Shaukat et al., 2018). Successful electrification of automotive transport requires a systemic approach to the development of zero-emission mobility (Gallo & Marinelli, 2020; Jagiełło, 2021). At the heart of the transformation is investment in new technologies, digital solutions, and mobility patterns that will foster new business models. However, the development and diffusion of innovations often encounter market, organisational and institutional failures, pointing to the need to identify and evaluate planned actions (Weber & Rohracher, 2012; Liao et al., 2017).

The aim of the study, the results of which are presented in this article, is to identify the critical factors and assess the specific actions conditioning the development of electromobility from the perspective of a zero-carbon, innovative and resilient economy. For the research objective thus defined, the research questions formulated are:

- How can we shape zero-carbon electromobility models while maintaining operational efficiency and cost-effectiveness, thinking about climate change and increasingly difficult access to resources?
- In an environment of permanent change, what actions should organisations take to add value to the electromobility system?

The focus of research on finding connections between the development of electromobility and the formation of a zero-emission and resilient economy determined the research hypothesis: the assumptions of EU policy influence the development of electromobility while ensuring the implementation of the objectives of the strategy for shaping an innovative, zero-emission and resilient

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economy. The effects of activities undertaken to develop electromobility may constitute the basis for constructing a dependency model for making decisions on the allocation of financial resources for transport investments.

The structure of this article is organised as follows. After the Introduction section, an overview of existing, selected research results is presented (Literature review section) and the methodological approach (Materials and methods section) in relation to the essence of the electromobility system and the main conditions of its development from the perspective of a zero-emission, innovative and resilient economy. The Results of the research section contain the conceptual assumptions of the model for the sustainable development of electromobility in individual road transport from the perspective of the system value chain. Moreover, it presents the results of empirical research, allowing for the determination of actions to support this development. The Discussion section presents the conclusions from the analysis and the contribution of the study to the literature on the subject. The Conclusions section contains recommendations and proposals for potential directions for further research, as well as the most important limitations in relation to the research being carried out.

Literature review

Transport sustainability is one of the most discussed topics in the context of local, national and international economic, environmental and climate policies (Ren et al., 2020). Linking global economies and societies, transport directly and indirectly influences the achievement of all the Sustainable Development Goals (Magalhães & Santos, 2022; Silvestri et al., 2021). Responsible for the movement of people and cargo, it is an essential link in supply chains in the modern world. At the same time, the implementation of transport processes is driven by economic, social and environmental factors (Zhao et al., 2020; Rajak et al., 2016).

Transport is now an important sector of the economy, making a major contribution to its growth, employment and the mobility of society. As the second largest area of expenditure by European households, it accounted for 5.8% of European GDP in 2022. At the same time, it provided jobs for 10 million people, accounting for 5.4% of total employment (EU Transport, 2023). Projections show that transport activity will continue to grow. In 2020, passenger and freight volumes fell as a result of the COVID-19 pandemic in the post-2020 period. The EU Reference 2020 (European Commission, 2021) scenario forecasts a rebound in passenger and freight volumes until 2025 and further growth thereafter. Compared to 2015, the number of passenger-kilometres (pkm) travelled by road is forecast to be approximately 13% higher in 2030 and 27% higher in 2050. For inland freight transport, the scenario forecasts an increase in transport work, expressed in tonne-kilometres (tkm), of 31% by 2030 and 55% by 2050 compared to 2015.

The dynamic growth of transport in recent decades is, at the same time, a significant source of nuisances and problems (de Souza et al., 2019; Leach et al., 2020). The adverse effects of transport growth are a consequence of among other things, the increasing popularity of car transport, which is the least environmentally friendly and the least friendly to human health and life. The direct and indirect external costs of transport services are increasingly analysed through the prism of not only local and national but also global risks (Mnusso & Rothengatter, 2013; Petruccelli, 2015; Sovacool et al., 2021). From the point of view of the development of sustainable, innovative and resilient mobility, as envisaged by the European Green Deal (European Commission, 2019), they are mainly related to the use of fossil fuels, mainly oil, and the generation of CO_2 emissions.

Record global oil prices following the outbreak of war in Ukraine and escalating geopolitical conflicts, combined with unsustainable transport energy consumption, environmental degradation and climate change, confirm the need to implement decisive measures for greater use of sustainable modes of transport and the development of alternative fuels. A promising direction for decarbonising mobility in the medium to long term is EV technology (Li et al., 2016; van Soest et al., 2021). Over the last decade, the electrification of road transport has been the subject of particular interest in the context of developing a zero-emission and innovative economy, both in EU transport policy and research work[1].

[1] The phrase “electrification of road transport” appeared in 7,919 publications indexed in Science Direct in the period 2013-2023, while the issue of “innovative, sustainable electrification of road transport” was analyzed in 2,245 scientific studies.

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Electric car technology is now recognised as a future-proof alternative to internal combustion engines (Weber, 2022; Chinoracky et al., 2022). The potential benefits of this propulsion system have contributed to efforts to electrify EU car transport. The electromobility development strategies and programmes adopted by the EU and national governments were intended to accelerate the process of shaping sustainable mobility. Its development should support the implementation of sustainable development principles, assuming that all activities are carried out so as to reduce CO_2 emissions (Helmers et al., 2020; Nour et al., 2020). This objective has now become even more relevant, and one important tool for achieving it is to accelerate the development of emissions-neutral and intelligent mobility 4.0 (European Commission, 2020).

By analysing the development of mobility systems in the 20th and 21st centuries and the subsequent challenges they face, it can be concluded that a dynamic transformation of the current 3.0 mobility model to a 4.0 mobility model is underway (Mantouka et al., 2022; Zhao et al., 2020). According to the available technological and digital solutions, the concept of electromobility 4.0 is a networked model cooperating with the electricity system powered by RES (Table 1). Its realisation will be facilitated by system innovations such as Smart Grid, V2G and Smart Charging (Das et al., 2020; Rehman et al., 2023). At the same time, it should be emphasised that this concept is in its infancy, and its understanding in the next decades may differ significantly from the contemporary approach. This is primarily due to dynamic technological advances, including the development and diffusion of solutions in the area of smart, digital and networked technologies (Sanguesa et al., 2021; Yu et al., 2022).

Table 1. Evolution of the zero-emission electromobility development concept

Aspect	Current model Electromobility 3.0	Target model Electromobility 4.0
Technological	Research, pilot and implementation projects in energy storage and electric drive technology Technological development of batteries First projects using used batteries as stationary energy storage Industry 3.0	Electric vehicles with energy storage capability Fully electric propulsion technology Electric autonomous vehicles Batteries with extended life Industry 4.0
Organisational	Development of network infrastructure: transport, electricity and ICT Smart meters Unidirectional vehicle-to-network communication systems (V1G) Non-contained charging of vehicles Night-time charging Integration of renewable energy sources Smart City 3.0	Integrated network infrastructure: transport, electricity, ICT Intelligent energy systems Intelligent vehicle charging systems Two-way communication systems: vehicle-to-network, vehicle-to-home, vehicle-to-vehicle Domination of RES Smart City 4.0
Social	Building a new mobility culture Increased awareness of efficient vehicle charging Development of shared electromobility	A new culture of mobility Conscious charging of vehicles (guided charging) Dominance of shared electromobility
Business	Reconfiguration of business models in electromobility Linear electromobility model	Mobility as a service New business models for battery lifecycle management Closed-loopel ectromobility
Governance	Centralised electricity systems Dominance of fossil fuels as an energy source Oil and energy companies	Self-sufficient local authorities in terms of energy and fuel Distributed local electricity systems Local energy communities

Source: authors' work based on Chinoracky et al. (2022), Zuo et al. (2021), Mantouka et al. (2022), Shafiei and Ghasemi-Marzbali (2022), Lia et al. (2023).

Innovative and zero-emission solutions in mobility systems are related to the latest technological solutions and socio-economic trends, referred to as intelligent. Due to the particular importance of two mutually interacting megatrends, i.e. urbanisation and digitalisation, the vision of the development of "Smart electromobility" is most often referred to as the Smart City concept. Electric mobility

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4.0 is identified with a city of smart and green energy, i.e. highly energy- and resource-efficient, increasingly powered by renewable energy sources (European Commission, 2020; Dróżdż et al., 2019).

The introduction of electricity to the motor vehicle fuel market significantly changes the organisation of transport processes and causes the dependencies governing the functioning of road transport and the reactions between this functioning and the environment to become more diverse and complex. In their research, Chinoracky et al. (2022) drew attention to the multidimensionality of the development of the intelligent and sustainable electromobility system, treating this system as a "complex construct" whose meaning is interpreted by researchers in many ways. Kolz and Schwarz (2017), in their research, indicated key areas influencing the development of electromobility, both globally and locally. They identified a total of 55 impact factors, including 29 with a global dimension and 26 with a local impact. They emphasised that due to the small scale and relatively short period of use of electric drives in cars, it is difficult to clearly assess the directions and amounts of their impact on the development of a sustainable and innovative mobility system. However, they can be identified, described and analysed.

In response to the rapidly changing demand for electric vehicles, Suhail et al. (2021) pointed out, among others, attention to the need to develop charging infrastructure. They showed that the demand for publicly available chargers is important not only due to the increase in the number of EVs but also due to range concerns. The strategic deployment of public charging infrastructure helps build trust among electric vehicle users, especially in densely populated urban areas, improves user convenience and accelerates the adoption of electric vehicles (Gupta et al., 2021). According to Tian and Talebizadehsardari (2021), the development of intelligent and emission-free electromobility requires the development of a Smart Grid and Smart Charging. The Smart Charging concept is presented as one of the intelligent system solutions, the implementation of which may contribute to the emergence of a zero-emission mobility system (V2G) integrated with the power grid in the future, based on renewable energy (Mirzaei et al., 2019). It has great potential in the field of intelligent energy management.

Materials and methods

The research process for the development of electromobility, in accordance with the assumptions of an innovative, zero-emission and resilient economy, is presented in Figure 1. In pursuit of the aim of the study and verification of the main hypothesis, primary and secondary data were used. Data were obtained using selected research methods and techniques. The desk research method was useful for systematising the existing scientific output and state of knowledge on the essence and motives for the development of zero-emission mobility and electromobility in the context of individual motorisation. The literature review of the subject was carried out according to the classical approach, i.e., selection of sources, keyword search, review and selection of articles, and in-depth analysis of selected publications in relation to the subject of the study. The time range covered by the search covers the period 2015-2023. The number of publications found by combining keywords is 7,390. At the same time, it was assumed that the last five years sufficiently presented the latest scientific achievements on the basis of which it was possible to formulate the development of innovative, zero-emission electromobility in road transport. According to this criterion, the number of identified articles was narrowed to 177. After analysing the titles of publications and abstracts, taking into account the criteria of place and type of publication, number of citations and preferring the latest research results, the final number of publications used in the research process is 70.

The analysed scientific articles are indexed in databases: Scopus, Science Direct and Google Scholar. The compact scientific publications, expert scientific reports and statistical data used in the study were published by recognised publishing houses and foreign and domestic institutions. The literature review identified a general knowledge gap on an integrated approach to decision support objectives for the development of innovative, zero-carbon and residual electromobility.

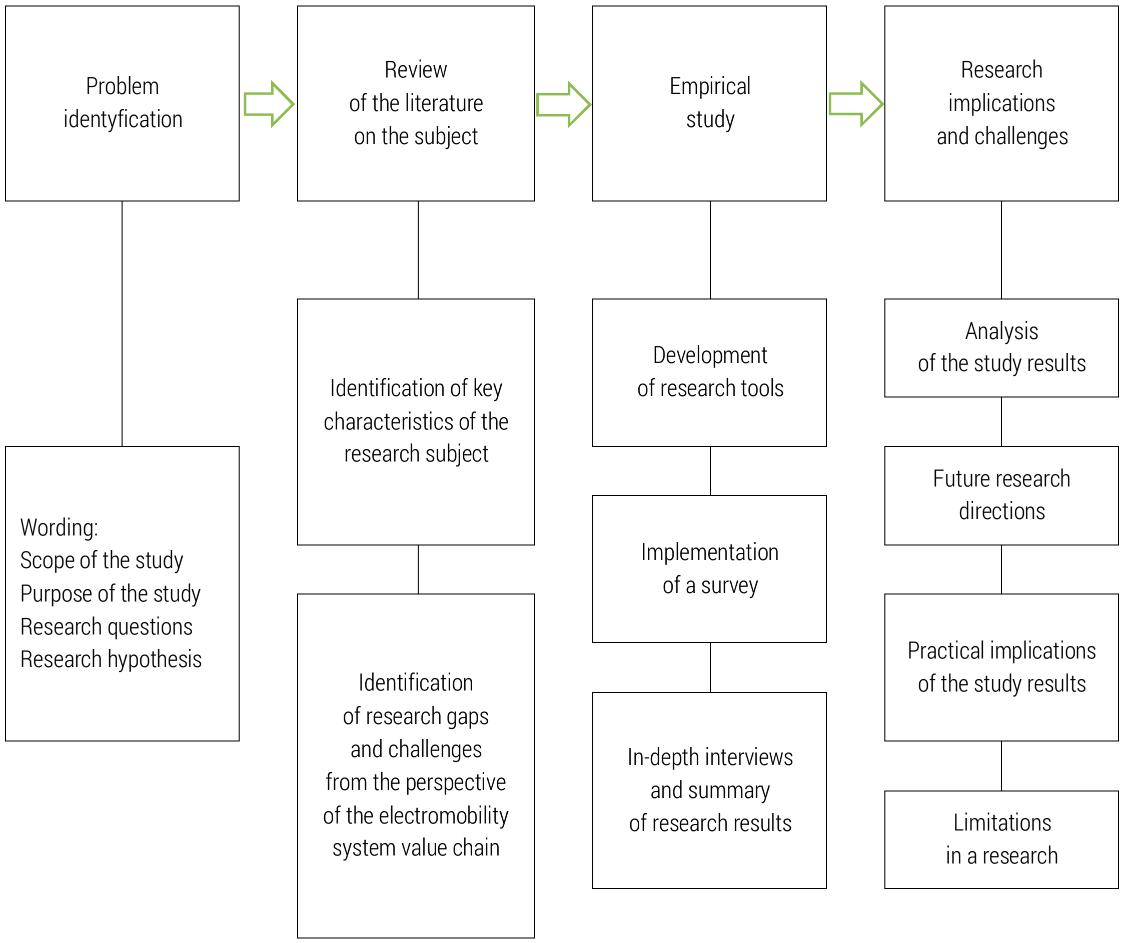

Figure 1. The research process for the development of electromobility, in accordance with the assumptions of an innovative, zero-emission and resilient economy

The research procedure (Figure 1) consisted of two stages (theoretical and empirical approach). Stage one consisted of identifying key characteristics describing the functioning of the current electromobility 3.0 system and the target 4.0 model. Using logical analysis and construction, as well as qualitative analysis, a conceptual framework for a model of sustainable electromobility development in individual car transport was developed from the perspective of the system value chain.

Assuming that the developed model of an integrated electromobility system network can contribute to the improvement of decision support tools for the development of zero-emission mobility, an empirical study was conducted. The study used methods and techniques including diagnostic survey, cause-effect analysis and qualitative analysis. The second stage of the study involved participating in an asynchronous response to the questions posed in a face-to-face, in-depth interview. Experts gave their answers on a forced-choice scale by giving weights to each characteristic – from 1 (not very important) to 5 (crucial). Omitting the neutral point from the responses allowed for more relevant ratings by eliminating central tendency errors (Sroka, 2022).

The survey was carried out within the framework of statutory tasks in the period 2022-2023. The selection of the research sample was purposive. The invitation was addressed to managers of companies operating in Poland who are responsible for car fleet management. A total of 123 experts with many years of professional experience in managerial positions took part in the survey. The survey had a pilot character. However, it allowed an estimation of the importance of the essential factors/ specific measures from the perspective of innovative, zero-emission and resilient mobility. The results of this assessment were used to detail the directions for further research.

Results of the research

In thinking about the development of a zero-emission electromobility system, a systems approach, the implementation of technological innovations and an increase in corporate responsibility and public awareness are required (Coban et al., 2022; Xia et al., 2022). Such an approach will foster the main objectives of developing innovative, zero-carbon and resilient electromobility, as seen in the context of the sustainability paradigm (Figure 2). It represents a new system of shared value creation resulting from the interactions taking place between the transport sector, the automotive industry, the electricity sector, the petrochemical industry and the chemical industry (Gómez Vilchez et al., 2022). The result of this collaboration is to pursue:

- improving the energy efficiency of EVs and the possibility of using them as energy storage,
- building a sustainable battery value chain, i.e. supporting projects for the safe and sustainable production of batteries as a key driver of EU competitiveness,
- resource-efficient use of raw materials and materials, with a focus on critical minerals,
- creating value from waste, in line with a closed-loop economy,
- the use of RES and the development of Smart Grids,
- developing electro-mobility as a service,
- developing the right relationship between consumption and production, e.g. by extending the life-cycle of EV batteries, developing Vehicle to Grid (V2G) technologies,
- developing solutions to increase economies of scale.

The development of the EV market under conditions of intensifying environmental change, geopolitical considerations and disruptions in global supply chains requires effective preventive and adaptive measures in the value chain of the electromobility system (Table 2). The key areas of impact that influence the development of a zero-emission, innovative and resilient electromobility system, identified using the PESTEL analysis, take into account political, economic, social, technological, environmental and legal aspects. In-depth literature research allowed for the identification of each area of influence and the selection of potential impact factors (Table 2). These factors influence decision-making processes in the development of electromobility to varying degrees (Chinoracky et al., 2022; Karmaker et al., 2023). However, they are important for all stakeholders involved in investment processes (Hasan, 2021; Haidar & Aguilar Rojas, 2022).

Table 2. A set of variables to assess the importance of the key enablers for the development of a zero-emission and resilient electromobility system

Factor	Essential factors / Specific actions
F_1	Economic and political support
F_2	Promotion of electromobility
F_3	Development of charging infrastructure
F_4	Regulatory framework
F_5	Technological developments in the battery field
F_6	Development of renewable energy technologies
F_7	Development of smart grid
F_8	Development of V2G technology
F_9	Development of new information and material technologies
F_{10}	Increased awareness of supply chain disruptions and environmental change
F_{11}	Development of recycling and the circular economy
F_{12}	Behavioural changes and new mobility patterns

Source: authors' work based on literature analysis.

The implementation of low- and zero-carbon solutions in electromobility systems involves a number of investment projects that will not be economically viable in the short term. Among other things, they are characterised by a high degree of capital intensity and complexity of implementation, while the effectiveness of their implementation is associated with certain risks and uncertainties in the context of interoperability and consistency of charging infrastructure, the expected level of public acceptance crucial for increasing the uptake of EVs. As a rule, the measures accompanying investment

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projects for the development of the EV market and charging infrastructure are treated as those whose costs are as real and measurable as possible at a given point in time, while the benefits are often quite postponed.

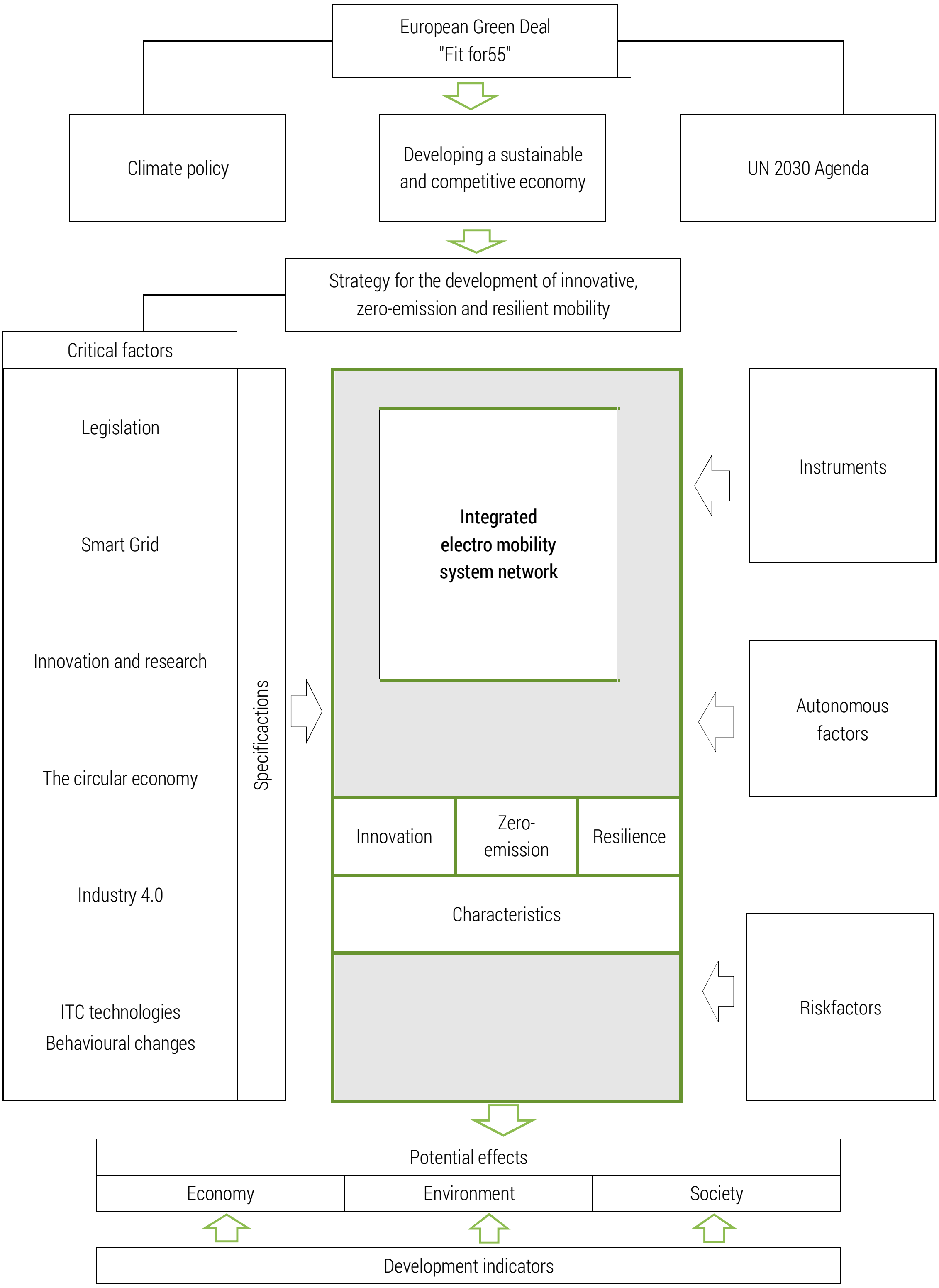

Figure 2. Model for the development of an electromobility system for road transport in line with an innovative, zero-emission and resilient economy

The analysis of investment project feasibility studies confirms that the highest levels of complexity and risk are shown by projects for the development of infrastructure and low-carbon propulsion technologies as well as solutions to foster greater cross-border interoperability and data exchange opportunities (Wappelhorst, 2021; Fescioglu-Unver & Yıldız, 2023). At the same time, these projects can be credited with a high degree of efficiency in the deployment of EVs. Information and promotion activities are characterised by a low level of complexity while showing a high potential for efficiency and effectiveness in the development of electromobility. They are aimed primarily at raising awareness and creating pro-environmental transport behaviour. Achieving these benefits is important for the gradual uptake of low-carbon mobility systems, which will result in, among other things, an increase in the economic viability of their implementation and an improvement in the climate (Gevaers et al., 2014). The study by Hall et al. (2021) highlights that legislative support is also key.

Developed design standards, as well as the expansion of an appropriate EV charging infrastructure, may not be sufficient in the context of the challenges to strengthen resilience and sustainability. Successful implementation of these challenges is not possible without achieving an appropriate level of awareness of the nature of the critical factors and the need for specific measures in the value chain of the electromobility system (Table 3).

Table 3. Characteristics of response variability

Factor	Measurement of consentintensity [%]					Measures		
	5	4	3	2	1	Mean	Variation	Standard deviation
F_1	55.2	39.1	4.1	1.2	0.4	4.48	0.45	0.67
F_2	35.1	44.2	14.5	6.1	0.1	4.08	0.74	0.86
F_3	80.2	11.9	1.4	0.3	6.2	4.61	1.03	1.02
F_4	49.8	44.1	2.8	3.1	0.2	4.40	0.51	0.71
F_5	69.2	22.7	5.8	2.1	0.2	4.59	0.52	0.72
F_6	33.1	28.2	35.8	2.1	0.8	3.91	0.84	0.91
F_7	48.5	36.8	7.9	3.9	2.9	4.24	0.92	0.96
F_8	15.6	24.7	48.5	11.2	0.0	3.45	0.78	0.88
F_9	18.6	32.0	37.3	11.8	0.3	3.57	0.87	0.93
F_{10}	28.1	35.8	26.2	9.8	0.1	3.82	0.91	0.95
F_{11}	22.3	39.1	27.2	7.2	4.2	3.68	1.06	1.03
F_{12}	22.8	47.2	17.3	12.3	0.4	4.48	0.45	0.67

Source: authors' work based on research results.

The results of the survey, shown in Table 3, indicate an overall high awareness among managers responsible for fleet management of the importance of critical factors in the development of sustainable and resilient electromobility systems. All measures were considered important. Variables perceived by respondents as very important were the development of charging infrastructure (F3), technological advances in batteries (F5) and economic and political support (F1). The adoption of appropriate regulations (mean 4.40 and standard deviation 0.71), the development of a smart grid (mean 4.24 and standard deviation 0.96) and changes in transportation behaviour and the development of new mobility patterns (mean 4.48 and standard deviation 0.68) were also highly rated. There were two variables in the study that were considered important but had a lower degree of significance. These are F9 (development of new information and material technologies) and F8 (development of V2G technologies). According to respondents, adaptation measures based on so-called "engineering resilience" and behavioural changes toward "homo sustained" are of the greatest importance.

Discussion

The concept of electromobility is becoming increasingly popular in academic research and is a frequent part of discussions among government policymakers. Research confirms the growing importance of electrification of automobile transportation and its management, and provides guidance on the direction this process should take (Kumar & Alok, 2020). This article provides some findings that contribute to the development of research in shaping electromobility of passenger cars, taking into account the assumptions of sustainable development.

The development of an innovative, zero-emission and resilient electromobility system is a complex process. The roadmap for low- and zero-emission energy for automotive transportation focuses on the development of renewable energy sources, new propulsion technologies and infrastructure. Chinoracky et al. (2022) emphasise that if electromobility is to contribute to reducing CO_2 emissions in line with sustainable development, the policy implications must be long-term. Studies by Liao et al. (2017) and Du et al. (2018) reveal positive policy implications for socially acceptable electrification of passenger cars. The proposed qualitative model for the development of passenger car electromobility indicates the need for a systems approach in the context of the system value chain in accordance with the paradigm of sustainable development. The model identifies the basic interactions occurring between EV passenger cars, the economy, the environment and society (theoretical dimension). Quantitative characteristics can support investment decisions in the development of electromobility, which is in line with the goals of an innovative, sustainable, and resilient economy (practical dimension). In addition to the need to reduce CO_2 emissions (Woo et al., 2017; Yu et al., 2018) in pursuit of the goals of the Paris Agreement and European climate and transport policy objectives, there are economic (Milakis et al., 2017) and social (Moreno et al., 2018) arguments for increasing the use of electricity to power passenger cars. At the same time, a review of the literature has provided research findings indicating that there are a number of challenges to the production and use of EVs and batteries.

Given the guiding objective of electrification of individual motorisation, priority should be given to changing the structure of electricity generation towards increasing the share of less carbon-intensive raw materials, with a focus on RES (Sadeghian et al., 2022). Thompson and Perez (2020), in their research, argue that the development of electromobility based on renewable energy sources is complex. Therefore, measures to improve the quality of electricity grids, their capacity and the development of Smart Grid are important. Research by Shi et al. (2020) further shows that these grids would enable the use of EVs as electricity storage, generating economic and environmental benefits and contributing to balancing and grid stability.

Findings on environmental aspects of EV electromobility development also point to issues related to battery cells, as confirmed by proposals for new EU battery regulations (Regulation, 2023). An ecologically critical factor is the need for scarce mineral resources (Romare & Dahllöf, 2017). EVs most often use lithium-ion battery cells, which use lithium, nickel, cobalt, manganese and graphite. The process of refining and processing almost all of these raw materials to the standard required for batteries is currently carried out 85% in Asia, mainly in China, making this country the dominant player in the battery supply chain. A similar relationship also applies to the value chains of other key materials used in electric vehicles, in particular rare earth metals for the production of high energy density permanent magnets, which are now crucial to the production of the highest power density electric motors. In some cases, the availability of raw materials can be compromised by political instability, which can lead to disruption of raw material supplies or involve other constraints due to widespread unethical and unsustainable mining practices (Arias et al., 2020). The production and development of batteries for electric cars has, therefore, become a strategic goal for Europe to prevent serious technological dependence. It is a key element in the competitiveness of the automotive sector. Important milestones in the context of the added value of the electromobility system are the standardisation of components, designing to extend the life of products and facilitating the segregation, separation or reuse of used products and materials.

The development of electromobility also involves economic and social aspects. Based on the findings and conclusions of the Barrett and Bivens (2021) study, several impacts of the development of EV electrification can be observed from the perspective of costs and benefits in economic and social terms. Research and development expenditures, changes in EV supply chain architecture, or uncertainty in public acceptance do not change the overall perception of electromobility as an innovation. It has great potential to add value for all chain participants, which is ultimately expected to lead to reduced CO_2 emissions and increased innovation in the EU economy.

At the same time, it should be borne in mind that due to the innovativeness of the proposed low- and zero-emission solutions for EVs, significant effects may take a longer period of time to emerge. At the same time, obtaining them will require the implementation of specific measures within the framework of national and local policies aimed not only at implementing new EV technologies but also at raising public awareness for new propulsion technologies. The implementation of the electromobility concept is an important element in the development of a zero-emission, innovative and resilient EU economy.

Conclusions

Based on the review of the literature on the subject and the results of the study, it can be concluded that the actions taken by the EU, inspired by climate protection and the pursuit of the development of an innovative and sustainable economy, will require decisive solutions in the field of popularisation of EVs, development of charging infrastructure and changes in the context of the value chain. Due to the complexity of the concept of sustainable development of transport infrastructure in the EU, it can be concluded that its implementation will be a gradual and long-term process, requiring an integrated approach. Significant effects of the implemented activities may appear in the longer term. Obtaining them will also require the implementation of specific action strategies under national and local policies aimed not only at the development of sustainable transport infrastructure but also at increasing public awareness of new solutions. The development and modernisation of transport infrastructure are important elements that determine the development of an emission-free, innovative, and disruption-resistant EU economy.

Scientific research has seen a systematic increase in interest in measuring the effects of electromobility development in the context of its value for the economy, society and the environment. One of the key challenges for future research directions is the development of algorithmic approaches that allow the use of the proposed qualitative model in investment decision-making processes in the development of electromobility. The dependencies presented in the model may be helpful for assessing the impact of individual EU policy instruments dedicated to electromobility in terms of reducing CO_2 emissions from transport, developing renewable energy sources, increasing energy security and the competitiveness of the broadly understood electromobility industry.

Regardless of the challenges facing the global economy, it seems that the development of electromobility will increase every year. The factor determining the direction of the evolution of the current mobility model is the development of smart technologies, including technologies integrating telecommunications and ICT solutions with innovative solutions in the automotive industry. Innovative system solutions, intelligently integrating the activities of all system participants, change the principles of operation of electromobility and the electricity market as a result of the emergence of new services and business models, as well as changes in the roles of existing system participants. The concept of electromobility 4.0 is one of the breakthrough system innovations with great development potential, which creates a number of benefits as well as many challenges for various entities and stakeholders.

The article does not assess the importance of the fundamental factors determining the development of an innovative, emission-free and resilient electromobility system, taking into account the benefits for individual stakeholders. A prerequisite for successfully completing such a task is the availability of a comprehensive dataset. The results of the present analyses indicate that this may pose another challenge for future research.

The contribution of the authors

Conceptualization, U.M. and A.B.-P.; literature review, U.M. and A.B.-P.; methodology, U.M.; formal analysis, U.M. and A.B.-P.; writing, U.M. and A.B.-P.; conclusions and discussion, U.M. and A.B.-P.

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DETERMINANTY ROZWOJU ELEKTROMOBILNOŚCI Z PERSPEKTYWY ZEROEMISYJNEJ, INNOWACYJNEJ I ODPORNEJ GOSPODARKI

STRESZCZENIE: Celem artykułu jest identyfikacja czynników krytycznych i ocena działań szczegółowych warunkujących rozwój elektromobilności z perspektywy zeroemisyjnej, innowacyjnej i rezylientnej gospodarki. Zagadnienia te mają szczególny wymiar w odniesieniu do mobilności indywidualnej. W badaniu wykorzystano kombinację danych pierwotnych i wtórnych, stosując różne metody i techniki badawcze, takie jak: analiza opisowa, analiza deskresearch, ankieta diagnostyczna, analiza przyczynowo-skutkowa i analiza statystyczna. Dodatkowo przeprowadzono wywiady pogłębione z ekspertami na stanowiskach menedżerskich. Przegląd literatury przedmiotu oraz wyniki badań własnych potwierdziły znaczenie zidentyfikowanych czynników w procesie absorpcji samochodów elektrycznych. Badanie uwidoczniło jednocześnie dużą złożoność problemów w zakresie decyzji inwestycyjnych warunkujących rozwój elektromobilności. Podjęcie aktywnych działań w zakresie zwiększenia poziomu zrównoważenia i odporności systemu elektromobilności należy w pierwszej kolejności skoncentrować na dalszym rozwoju infrastruktury ładowania, upowszechnianiu pojazdów elektrycznych, rozwoju odnawialnych źródeł energii oraz kreowaniu łańcucha wartości baterii do pojazdów elektrycznych. Główne oczekiwania w zakresie rozwoju elektromobilności dotyczą redukcji emisji CO_2, ograniczenia zależności od dostaw paliw kopalnych, wzrostu konkurencyjności i innowacyjności gospodarki oraz ograniczenia kosztów zewnętrznych generowanych przez transport. Oryginalność zrealizowanego badania, starano się uzyskać poprzez wymierny jego charakter. Zaproponowany model rozwoju elektromobilności może przyczynić się do doskonalenia narzędzi decyzyjnych w zakresie alokacji środków publicznych i z innych źródeł na inwestycje, by przyczyniły się one do zrównoważonego rozwoju systemów mobilności.

SŁOWA KLUCZOWE: gospodarka zeroemisyjna, transport zrównoważony, mobilność zeroemisyjna, elektromobilność, pojazdy elektryczne

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