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SUSTAINABLE ELECTRIFICATION OF ROAD TRANSPORT IN RURAL AREAS: CHALLENGES, OPPORTUNITIES, AND CLIMATE CHANGE IMPACT

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Abstract

The electrification of road transport is one of the key mechanisms for reducing emissions and mitigating climate change. However, the transition to electric vehicles in rural areas faces specific challenges, such as the large distances between settlements, underdeveloped electrical and road infrastructure, and limited economic opportunities for the local population. This paper examines the potentials and obstacles of electrification in rural environments, with an emphasis on the impact of climate change on the planning and maintenance of necessary infrastructure. Extreme temperatures, intense precipitation, and increasingly frequent extreme weather events further increase the vulnerability of rural roads to erosion, floods, and damage, making the infrastructure for electric vehicles more challenging to maintain. While electrification can contribute to reducing climate risks, it requires a systemic approach that encompasses technical solutions, resilient infrastructure, and adequate planning. Special attention is devoted to raising awareness and informing the population as a key element for a successful and sustainable transition to electric transport in rural areas.

Keywords: electric vehicles, climate change, rural areas, infrastructure resilience, sustainable transition

1 Introduction

Road transport is one of the largest sources of greenhouse gas emissions, with a significant share in total energy consumption and a negative impact on climate change [1]. For this reason, the electrification of road transport has been recognized as one of the key elements for decarbonizing the transport sector and achieving climate neutrality goals. Accordingly, transport electrification is increasingly emphasized as a central measure in international strategies aimed at reducing greenhouse gas emissions and the gradual phasing out of fossil fuel sources [2]. The adoption of electric vehicles has so far made significant progress primarily in urban areas, while the electrification of road transport in rural areas is proceeding considerably more slowly. This discrepancy results from the specific characteristics of rural areas, which have been insufficiently addressed in existing literature. Rural areas are characterized by low population density, longer travel distances, limited availability of public transport, and a pronounced dependence on individual motorized transport. These characteristics lead to relatively higher per capita emissions, but also to increased complexity in implementing sustainable transport solutions. Additional challenges for the adoption of electric vehicles in rural areas relate to underdeveloped charging infrastructure, limited capacity of the electricity distribution grid, and weaker investment potential. For this reason, the models and policies for transport electrification developed for urban areas cannot be directly applied to rural areas without appropriate adaptations [3].

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Nevertheless, despite these limitations, rural areas possess significant potential for sustainable transport electrification. The availability of space for renewable energy production, such as solar and wind power, enables the integration of electric vehicles with decentralized energy systems, microgrids, and local energy communities. Such an approach can contribute to increased energy security, reduced operating costs, stimulation of local economic development, and simultaneous reduction of negative environmental impacts. Consequently, the aim of this paper is to analyze the specific challenges and opportunities for the sustainable electrification of road transport in rural areas, and to assess their overall impact on mitigating climate change.

2 Challenges of sustainable electrification in rural areas

The process of rural electrification faces a series of complex challenges spanning economic, spatial, and social aspects. A lack of financial resources, unfavorable geographical conditions, and low population density significantly hinder the implementation of infrastructure projects and increase costs per user. Simultaneously, socio-cultural factors, institutional capacities, and the internal dynamics of local communities play a significant role in the level of acceptance of new energy solutions and their long-term sustainability [4]. Understanding the interdependence of these factors is essential for shaping effective strategies that meet the specific needs of diverse rural environments [5]. To overcome these challenges, numerous countries and international organizations have developed various policy and institutional frameworks to enhance the electrification of rural areas [6]. At the international level, initiatives such as the World Bank's DARES platform are focused on supporting the development of mini-grids and off-grid solar systems, aiming to accelerate access to electricity in rural areas [7]. At the national level, countries like India and Rwanda are implementing specific rural electrification programs that encompass grid extension as well as the development of decentralized energy systems, often with support from international funds and institutional development [8]. Clear financial incentives are essential to address financial barriers and attract private capital. Public institutions employ various forms of support, including subsidies, grants, and fiscal incentives, to enhance the economic viability of projects and reduce investment risk [9]. Properly designed and targeted incentives can significantly contribute to overcoming financial barriers and accelerating the implementation of infrastructure initiatives [5].

In addition to financial incentives, establishing transparent and enabling frameworks is a prerequisite for the successful implementation of rural electrification projects. Such systems should facilitate the easier integration of renewable energy sources, streamline planning and permitting procedures, and provide stable conditions that encourage private investor participation [10]. Well-designed regulation contributes to the long-term sustainability of energy systems and increases the likelihood of project success. Electrifying the transport sector is of particular importance, as it represents one of the largest sources of greenhouse gas emissions. Globally, transport contributes approximately 24% of total carbon dioxide emissions, with about 75% coming from road transport [11]. The dominant use of internal combustion engine vehicles, reliant on fossil fuels, makes road transport a key focus of climate policies. Besides greenhouse gas emissions, these vehicles also contribute to air pollution through emissions of nitrogen oxides and particulate matter, which have serious negative consequences for public health [2].

However, a key obstacle to electrification is the deep spatial inequality in infrastructure. While urban centers are well covered, the availability of chargers in rural areas lags dramatically behind. This inequality is clearly visible in the data. For instance, in the U.S., a fast chargers exist in only 45% of rural counties [12], while in the United Kingdom, as much as 92% of public chargers are concentrated in urban areas, with a mere 8% in rural ones [13].

This pattern of uneven infrastructure distribution is also characteristic of Europe as a whole [14]. Due to the long-term dependence of the transport sector on fossil fuels, reducing greenhouse gas emissions in this sector presents a greater challenge compared to other economic sectors [15, 16]. Transport electrification, particularly through the broader adoption of electric vehicles, is recognized as one of the key directions for mitigating the negative environmental impacts of transport. This process contributes to the reduction of fossil fuel consumption, the improvement of air quality, and the achievement of international climate goals, including commitments stemming from the Paris Agreement [17]. Simultaneously, transport electrification also has significant economic and energy security implications, as it enables reduced exposure to oil price volatility and increased reliance on more stable, domestic, and renewable energy sources [2].

3 Opportunities and enabling factors

The electrification of road transport plays a crucial role in decarbonizing the transport sector and reducing its negative environmental impacts, particularly in the context of climate change. The heterogeneous group of electric vehicles (EVs), which includes battery electric vehicles (BEVs), plug-in hybrid vehicles (PHEVs), and extended-range electric vehicles (EREVs), offers significant potential for reducing air pollution and achieving climate goals. However, this potential is fully realized only if the electricity for their operation is supplied from renewable energy sources [18]. The development of appropriate charging infrastructure is a prerequisite for wider adoption. Although some progress has been made in urban areas, the public charging network, especially in rural areas, remains insufficient [19]. At the same time, rural areas possess significant spatial and organizational advantages, such as land availability, fewer land-use conflicts, and more flexible local planning frameworks. This enables the development of decentralized and adaptable charging solutions aligned with local needs and mobility patterns. Increased EV adoption imposes new demands on the power system but simultaneously opens avenues for its modernization. The integration of smart grids, load management systems, and flexible consumption represents an important step toward a more resilient and efficient system. In rural areas, the combination of local renewable energy generation, energy storage systems, and smart grids can further enhance supply reliability and resilience to climate and market disruptions.
A particular opportunity lies in the linkage between transport and energy. Integrating EVs with local renewable energy sources, such as solar and wind power, enables the decarbonization of the entire vehicle lifecycle and contributes to increasing the energy autonomy of local communities. The development of microgrids and energy communities, where EVs also function as mobile energy storage units, further strengthens this synergistic potential and positions rural areas as important actors in the sustainable energy transition. Support at the global and national levels is a major driver of transport electrification, as reflected in ambitious strategies by the European Union, Japan, China, and certain U.S. federal states aimed at achieving a zero-emission vehicle fleet by mid-century. However, the gap between strategic goals and their consistent implementation remains pronounced, especially in rural areas with limited institutional and financial capacities. Therefore, it is essential to ensure coherent regulatory frameworks, appropriate financial mechanisms, and integrated planning tailored to the specificities of the rural context [20]. Successful transport electrification in rural settings requires coordinated action across technological innovation, infrastructure development, and supportive policies. The synergy between EVs, renewable energy sources, and smart energy systems presents a key opportunity not only for reducing emissions but also for strengthening energy security and fostering sustainable local development.

4 Climate change impact and resilience aspects

In rural areas, the transition to low-emission road transport is taking place amid increasingly pronounced climate change, which has multiple and interconnected impacts. On one hand, climate change may adversely affect the infrastructure necessary for electric vehicles to function, while on the other hand, the electrification of transport itself represents a key element of adaptation strategies and enhancing the resilience of rural communities.

4.1 Direct impacts of climate change on EV infrastructure

Electric vehicle infrastructure in rural areas faces heightened climate risks, stemming from the spatial dispersion of the system, geographic exposure, and limited options for rapid intervention during extreme weather events. Heatwaves can lead to the overheating of EV charging equipment, resulting in reduced efficiency and a shortened operational lifespan [21]. Elevated temperatures also negatively impact the performance of lithium-ion batteries, accelerating their degradation and causing a reduction in vehicle range [22]. These effects are particularly problematic in rural areas, where distances between destinations are greater and the charging network is limited. Conversely, extremely low temperatures lead to reduced battery capacity and significant slowing of the charging process, further impacting the reliability of electric vehicles in cold climates [23].

Intense rainfall and flooding can incapacitate charging stations due to short circuits, corrosion of electrical equipment, and sediment deposition, while road network damage caused by erosion and landslides disrupts traffic and increases maintenance costs. This undermines the reliability of the entire transportation system, especially as extreme weather events increasingly cause power outages that hinder the operation of charging stations and electrical facilities [24, 25]. Storm surges can damage or topple power lines and distribution grid elements, causing widespread power outages across large areas. In arid rural regions, increasingly frequent forest and agricultural fires pose an additional threat to infrastructure, while smoke and high temperatures can interfere with the operation of sensors and communication systems essential for the functioning of smart power grids.

4.2 The resilience concept in EV infrastructure

The resilience of electric vehicle infrastructure refers to the system's ability to withstand climate disruptions, adapt to changed conditions, and quickly restore basic functions. In rural areas, strengthening EV infrastructure resilience requires simultaneously enhancing the system's physical and energy dimensions [24]. Physical resilience encompasses design and construction solutions that proactively account for climate risks. This includes siting charging stations in areas less prone to flooding, utilizing raised platforms, and protecting critical electrical and electronic equipment within weather-resistant and hermetically sealed enclosures [24]. Energy resilience is a key aspect of EV infrastructure sustainability, as relying solely on the centralized grid makes the charging system vulnerable to outages caused by extreme weather events [26]. Decentralization and the integration of renewable energy sources, such as solar panels installed on or near charging facilities, combined with stationary battery storage, enable the formation of autonomous microgrids. Such systems can ensure a continuous supply of electricity during multi-day main grid outages. This directly links the spatial advantages of rural areas with strategies for strengthening climate resilience and supporting the sustainable electrification of the transport sector [10].

4.3 Electrification as a tool for mitigating and adapting to climate change

In the context of climate change mitigation, the broader adoption of electric vehicles, coupled with electricity supply from renewable sources, directly contributes to the long-term goal of decarbonizing the transport sector and reducing its contribution to global warming. From the perspective of climate change adaptation, electric vehicles equipped with vehicle-to-grid (V2G) and vehicle-to-home (V2H) technologies can play an additional role as mobile units for storing and distributing electrical energy. During prolonged power outages caused by extreme weather events, an electric vehicle parked at a household, healthcare facility, or agricultural property can, with appropriate equipment, supply energy for essential needs. In this way, electric vehicles can become active elements in the system of energy security and resilience for rural communities.

4.4 Public education and raising awareness

Increasing the adoption of electric vehicles requires targeted public information and awareness campaigns aimed at debunking the most common myths regarding their range, reliability, and practicality of use, while simultaneously highlighting their environmental and economic benefits, as well as available financial incentives [27]. A 2022 study [28] conducted in the United States shows that 29% of drivers in rural areas would consider purchasing or leasing an electric vehicle, but also that there is a pronounced lack of familiarity with this technology, as even 90% of respondents have never had direct experience with electric vehicles. Although the survey was conducted in a specific national context, the identified deficiencies in the level of information and direct experience with electric vehicles represent challenges characteristic of rural areas worldwide, particularly in less developed countries and developing nations. Therefore, effective policies in rural areas must include education and community engagement, focusing on key obstacles identified in surveys, such as the availability of charging infrastructure, vehicle range, high upfront costs, maintenance, and performance in cold climate conditions. Automobile manufacturers and dealerships play an important role in the education process by training their staff and providing reliable information to potential users, as well as by developing skilled personnel for servicing electric vehicles. In addition to institutional activities, raising awareness should also encompass the wider community through local media, educational institutions, and digital platforms, while direct experience, achieved through test drives and demonstration events, represents one of the most effective ways to increase trust and acceptance of electric mobility in rural settings.

5 Conclusion

As demonstrated, rural areas should not be viewed solely as passive victims of climate change facing complex and costly challenges, but also as active participants and unique "laboratories" for implementing innovative solutions. Their spatial capacity and lower degree of urbanization enable the implementation of integrated systems that are often not technically or economically feasible in dense urban environments. These characteristics create favorable conditions for the synergistic integration of the energy and transport systems in the context of responding to climate change. Realizing this potential requires a fundamental shift in strategic approach-moving away from separate, sector-oriented policies (energy, transport, risk management) towards holistic and integrated development planning. Within such a framework, electric vehicle infrastructure, local renewable energy sources, and emergency management systems are not viewed as isolated projects, but as interconnected and mutually reinforcing elements of a single strategy for building a climate-resilient rural space.

This systemic approach, coupled with consistent implementation and raising local community awareness about the dual role of electric vehicles - both as a means of cleaner mobility and as an element of energy security - can fully realize the potential of sustainable electrification. In this way, the process of electrifying rural road transport becomes not only a mechanism for mitigating climate change but also a driver of climate-resilient, equitable, and sustainable rural development.

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