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Sustainable Mobility in Rural Environments: The Role of Hydrogen in Rural Transportation Evolution

L. Rodríguez-Urrego[1], B. González-Díaz[1], N. Martín-Dorta[2] and E. González-Díaz[2].

[1] Departamento de Ingeniería Industrial, Escuela Superior de Ingeniería y Tecnología,
Universidad de La Laguna (ULL), 38200, La Laguna, Tenerife, Spain.
Phone: +0034 922 316502 EXT 6252

[2] Departamento de Técnicas y Proyectos en Ingeniería y Arquitectura, Escuela Politécnica Superior de Ingeniería,
Universidad de La Laguna (ULL), 38200, La Laguna, Tenerife, Spain.

Abstract.

This paper examines the critical role of hydrogen in advancing sustainable mobility within rural landscapes, addressing the urgent global need for cleaner transportation solutions. Despite the focus on urban centers, rural areas present unique challenges and opportunities for implementing sustainable mobility solutions, particularly in developing countries and regions undergoing economic transition. Through an analysis of current trends, challenges, and future directions, we explore the integration of hydrogen technologies in rural transportation systems. This includes evaluating the environmental and social impacts of transitioning to hydrogen-based mobility, the potential for hydrogen to serve as a low-emission transportation vector, and the necessity of governmental and institutional frameworks to support such a transition. Our findings underscore the importance of innovative models and good practices in technology applications, including demand-sensitive transport and shared mobility, to facilitate social inclusion and environmental sustainability in rural mobility. The paper aims to contribute to the discourse on sustainable rural transportation by highlighting the need for comprehensive research, policy development, and the adoption of hydrogen technologies to address the unique mobility needs of rural communities.

Key words. Sustainable Mobility, Rural Transportation, Hydrogen Energy, Environmental Impact, Policy Frameworks.

1. Introduction

The development of sustainable rural mobility is one of the last links of the governments due to the need for a transition towards sustainable mobility in urban centers by congestion on their roads and environmental pollution. However, since mobility is a key dynamic for people, facilitating access to destinations, activities, services, and goods, it is important to consider rural areas as a key study center in the urbanization of the future and the conservation of biodiversity from isolated areas. Environmentally sustainable transport will help these regions to reduce environmental pollution, protect typical conservation areas in these countries, strengthen the social fabric and cohesion, and promote sustainable rural development practices. On the other hand, global sustainable mobility models seek, among others, the use of transport with low or zero emissions, and the world's research focuses on the search for biofuels, the use and storage of hydrogen, and new technologies in electrical storage.

With the global momentum in hydrogen projects growing by 35% from May 2022 to January 2023, bringing total large-scale projects to over 1,000, the role of hydrogen in sustainable mobility is more prominent than ever. This increase reflects a surge in direct investment to $320 billion by 2030, marking significant progress in hydrogen infrastructure development for mobility, including over 1,000 refueling stations now operational worldwide. North America is charging ahead, driven by new incentives under the Inflation Reduction Act, accounting for 70% of committed clean hydrogen production [1]. Fig 1 illustrates the distribution of hydrogen investment in different projects.

These advancements underscore the critical role that hydrogen plays in reducing emissions in transportation, especially in rural settings where mobility options are traditionally limited. The Hydrogen Council's report also emphasizes the need for swift action to scale up final investment decisions (FIDs) and accelerate project construction and operations. With hydrogen's potential to deliver on 2050 net zero carbon emissions targets, investment proposals must triple to $700 billion by 2030. The report also notes that the 2030 hydrogen investment figure is equivalent to less than 15% of investment committed to upstream oil and gas over the past decade, highlighting the importance of prioritizing hydrogen in sustainable development strategies.

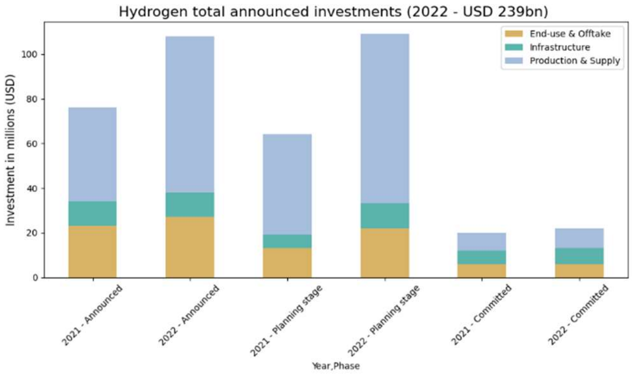

Fig. 1. The distribution of hydrogen investment across different project phases. Announced, Planning, and Committed—for the years 2021 and 2022. Data obtained from [1].

Considering these developments, this paper seeks to answer a fundamental question: What is the current context of hydrogen-based rural mobility projects in terms of technological development, regulatory frameworks, and environmental and social impacts, and what advantages might these initiatives offer for sustainable development in rural territories?

2. Sustainable Mobility from Urban Innovation to Rural Application

Since sustainable development in transportation systems is an urgent issue for nations and the world, countries are urgently concerned about changing the mobility matrices of the main cities [2]. The environmental impact, the socioeconomic effects associated with the interrelation with other sectors, and the quality of life make regulations, norms, and laws a priority that allows the development of cities in search of this transition. Likewise, an incentive policy is urgently needed to support the costs associated with changing technologies and new products in transportation [3].

Although most of the environmental impacts and effects on a global scale are concentrated in cities, the income generation to each country's GDP comes from these main cities due to their level of development. Mobility in rural areas frames an even greater problem due to the need to protect the biodiversity and ecosystems of the regions, economic development, and social equality due to the marked aging of the population in the isolated areas [4].

A. Models, Practices, and Challenges

In the rural mobility case, the role that governments play is essential in the institutional, organizational, regulatory, and financial frameworks to support rural transport services., it is also very important to know innovative models and examples of technology good practices applied to transport to communications technologies, intermodal services, shared mobility, demand-sensitive transport (DRT), and others. Some of these innovative good practices can be seen in reference 3, where most examples are from analysis cases in Europe. For example, in reference 3, a strong analysis of the DRT is carried out in search of offering sustainable local public transport to the communities, obtaining interesting results in social needs, but facing some challenges such as the issue of costs [5]. On the other hand, in reference 6, a rigorous study is carried out on the mobility of the elderly, who are one of the most disadvantaged social groups in both urban and rural areas [6]. The paper highlights emergencies such as COVID-19 and its impact on mobility issues regarding independence and social inclusion. The rigorous study analyses the three elements of the EU Active Aging Index: health, independence, and social connectivity.

When cases of transition towards sustainable rural mobility are analyzed, some interesting works are found. For example, in reference 6, there is an important analysis of car dependence in rural areas of rural Ireland, the private car prevalence, and the social and cultural impact that this has on society, resulting in the concept of forced car ownership (FCO), which are those people forced to acquire a vehicle as a means of economic subsistence [7]. Another example with the previously mentioned DRT transport, this time in the German rurality applied case can be seen in reference 7, where analysis of this transport type is carried out through the concept of shared trips [8]. However, the analysis is conclusive in that to lower costs, it should be applied to populations with demands for population growth and not purely rural environments. Another interesting model is presented in three Norwegian cities analyzed in reference 9, where the use of the land is considered essential as a planner for mobility systems and the non-use of a one-dimensional strategy of densification of rural areas based on the environment constructed [9].

Undoubtedly, the analysis presented in [7] offers insightful tools that are highly applicable to the Latin American context in addressing transport disadvantages and car dependency in rural areas. Both the methodology and the Venn diagram presented reflect similarities to many rural areas in Latin America, where a similar situation could be expected. Figure 2 adapts the Venn diagram from [7] to a comparable Latin American context, highlighting the pressing issue of Forced Car Ownership (FCO), a challenge that is particularly pervasive and critical in these regions due to limited public transportation and high rates of socioeconomic deprivation.

Fig 2. Venn Diagram of Factors Contributing to Forced Car Ownership in Rural Latin America. Adapted from [7].

3. Rural Mobility Evolution: Social and Environmental Perspectives in Latin America

The previous analyses, projects, and innovations open an interesting panorama of what mobility should be like in rural areas of the world. However, it is known that the technology transfer and the impact of new developments in indigenous, rural, or isolated communities from urban centers must be studied independently of the technology due to the impact it can have on society and its ecosystems. It is very important in rural areas to carry out a social inclusion analysis rather than a technical one when addressing the problems of sustainable transport; social research must be a focal point in the mobility progress and transport in the regions, thinking of new mobility policies governing [10].

When sustainable rural transport is analyzed in Latin American countries or countries with similar economic development levels, an informal transport type is analyzed in almost 100% of cases. In most of the isolated regions of Latin American urban centers, the only transportation systems are bicycles and informal rural transportation such as three-wheelers. There is not much research on this mobility type, and some do not analyze safety, sustainability, demand, or care for the environment; they only analyze the perception of user satisfaction [11]. An interesting conclusion from this previous analysis in Brazil is that informal transport represents a predominance as available transport for urban-rural connectivity in many regions of the world. In reference 11, a critical review is made of the concern for social inclusion and equity of mobility in Latin American countries, as well as the practices of territorial planning for new developments in rural transport systems [12]. The focus research is focus on the accessibility of means of transport as a rural and urban policy.

When sustainable rural mobility programs are reviewed in the literature, most papers conclude on the need for pilots, programs, and case studies through applied research where the impact of these transport systems on rural society can be measured. For example, in reference 1, an analysis is made of a pilot project applied to four communities in the Black Forest in Germany [13]. The compiled data is analyzed to calculate energy consumption, carbon footprint, and implementation costs compared to fossil fuels. Surveys and interviews were conducted to verify community acceptance and it is concluded that electric vehicles are promising from the social and environmental perspective on sustainable rural mobility issues.

While numerous studies have examined rural transport, there remains a notable gap in research focusing on developing countries or those with economies in transition. The pursuit of sustainable mobility in these regions must prioritize observational studies that adhere to environmental standards without jeopardizing local biodiversity. Emphasizing the significance of sustainable transition strategies tailored to the unique needs of each rural area is crucial. Furthermore, the exploration of hydrogen as a clean energy vector offers a promising avenue for assessing environmental impacts and social acceptance, fostering an opportunity to integrate innovative, low-emission transportation solutions in rural settings. This approach aligns with global efforts to decarbonize transport and supports the broader objectives of sustainable development and energy diversification.

The examination of sustainable mobility transition is critical beyond European contexts, especially within biodiverse regions like Latin America. Here, urban models are often adopted without considering policies for sustainable territorial development that could mitigate impacts on biodiversity and regional social customs. Countries like Brazil, Colombia, and Ecuador are among the most biodiverse globally, yet many rural territories within these nations remain disconnected from urban areas. Rural mobility often relies on private vehicles, with a significant percentage utilizing three-wheelers for public transport. Notably, Ecuador, Mexico, and Guatemala have high usage rates of three-wheelers for public transportation, but rigorous studies examining the implications of this mode of transport are lacking in Latin America [14].

4. Hydrogen-Based Mobility Case Studies in Rural Areas

Given the fundamental nature of the hydrogen value chain, before considering a direct application towards sustainable mobility. The practices and framework guide developed in [15] showcase the main advantages of its incorporation in rural territories:

- *Energy Self-sufficiency:* Utilizing local renewable resources for hydrogen production, minimizing dependency on energy imports.
- *Sustainability:* Hydrogen generated from renewable sources offers a completely fossil-free alternative, aligned with sustainability objectives and CO2 emission reduction goals.
- *Resilience:* Establishing a hydrogen supply chain contributes to a more resilient energy system in rural areas, where infrastructure options may be limited.
- *Available Space Potential:* Rural areas provide abundant space for the installation of renewable energy generation infrastructures necessary for hydrogen production.
- *Sustainable Mobility:* Hydrogen supports the transition towards sustainable rural mobility, reducing the carbon footprint of transportation.

This guideline for setting up a hydrogen ecosystem for rural areas, considers key differences between urban and rural environments, such as lower population density, greater transport distances, and limited infrastructure, highlighting the importance of a customized approach. Community participation and collaboration with local stakeholders are crucial for ensuring the acceptance and sustainability of hydrogen technologies in rural areas. It is important to emphasize step 1 of Table 1 in [15] because rural areas in Latin America are mostly rich in biodiversity. Aware that 6 countries in Latin America have approximately 60% of the world's biodiversity, and 95% of this figure is in their rural areas [16].

4.1. Case studies and pilots

Analyzing some successful cases of rural pilots, three of them particularly stand out in the scientific literature.

The first explores the development of an energy system based on local production and utilization of hydrogen in a small remote village in Valle d'Aosta, Italy [17]. Hydrogen is produced through electrolysis from electric energy generated by renewable sources and is used to power a hydrogen vehicle and for thermal purposes, i.e., heating three buildings, thus allowing a real field test (Village-Laboratory). Regarding mobility issues, the pilot verifies characteristics such as the type of vehicle whether it is a fuel cell or adapted from an internal combustion engine, the refueling station, the plant distribution, and its site plot: position of production, storage, and refueling devices. Finally, it performs a simulation of the performance and energy flow of the plant. One of the major advantages of this pilot is the ability to generate hydrogen locally, leveraging the specific renewable resources of the rural area, which is crucial for increasing resilience and energy autonomy. By developing a local hydrogen production infrastructure, dependency on fossil fuels and centralized energy networks is minimized, allowing the rural community to have greater control over its resources and foster local economic development. Additionally, the project's replicability and scalability in other rural communities are highlighted.

The second pilot is very interesting as it analyzes the unconnected island of Anafi, Greece [18]. The study implements a hybrid wind and photovoltaic energy system using the excess production of renewable energy for both heating buildings through heat pumps and generating hydrogen for mobility. Regarding mobility issues, the produced hydrogen is primarily used to cover the energy needs of the island's mobility sector, focusing on public transport vehicles (buses) and, secondarily, on private vehicles. It was modeled that the generated hydrogen could cover all the bus routes on the island and approximately 200 vehicles for moderate use, demonstrating the potential of hydrogen as a sustainable solution for mobility on islands. The main highlight in this second case of analysis lies in the focus on public mobility through hydrogen generated in an insular environment, and a detailed financial viability analysis, assessing the economic feasibility of the hydrogen infrastructure and renewable energy systems, a crucial step to ensure the long-term sustainability of the transition towards hydrogen-based mobility in purely rural insular environments.

Finally, the third pilot is very interesting because it is in a developing country like Latin American countries. This study stands out for its innovative approach to combining rural electrification and sustainable mobility through the production and use of hydrogen in a hybrid renewable energy configuration in Ouenskra, a rural community in Morocco [19]. The comprehensive approach not only addresses the energy needs of the community but also provides practical and tangible solutions for sustainable mobility, aligning with Morocco's sustainable development goals and offering a replicable model for other rural communities. In terms of sustainable mobility, the system can meet a hydrogen load of 0.2 kg/h for 70 daily charging sessions to power fuel cell bicycles, thus addressing the community's mobility needs with a sustainable solution. The adoption of hydrogen-powered fuel cell bicycles transforms a traditionally manual mode of transportation, primarily used for short to medium distances with minimal loads, into an advanced, motor-assisted vehicle capable of efficiently covering longer distances and handling higher load capacities. This breakthrough significantly enhances the utility of bicycles in rural areas, where the need for sustainable and accessible transportation solutions is crucial. Table 1 below provides a comparison of the advantages of each practical application or pilot study.

Table I. - Comparative Advantages of Rural Hydrogen Mobility Pilot Studies

Authors	H_2 Production:	Mobility Use	Key Benefits	Replicability & Scalability
Degiorgis et al. [17] Valle d'Aosta, Italy	Electrolysis is powered by locally generated renewable electric power to produce green hydrogen.	Hydrogen is utilized in a demonstration vehicle and as an alternative fuel for heating systems, promoting a 'Village Lab' for sustainability.	Pioneers the use of green hydrogen in a rural, mountainous setting, serving as a versatile energy source for both mobility and heating. Demonstrates an effective loop of energy sustainability by integrating local renewable energy sources, minimizing external energy reliance. Showcases a real-world application of hydrogen in a 'Village Lab', reinforcing the village's autonomy and ecological footprint. Offers a blueprint for rural communities to transition towards self-sustained energy ecosystems. High potential for adaptation and scaling in similar rural environments with an abundance of renewable resources.	High potential to be replicated in other mountainous or rural communities with similar characteristics, scalable based on the availability of renewable sources and energy needs.
Dimou et al. [18] Anafi, Grecia	Integration of wind and photovoltaic systems to produce hydrogen, utilizing excess renewable energy generation.	Hydrogen is primarily used to power public transportation buses, with potential extension to private vehicles.	Addresses energy and mobility challenges of a non-interconnected island with an innovative wind and solar power synergy. Utilizes renewable overproduction for hydrogen generation, ensuring a consistent and clean energy supply for public transportation. Enhances the island's sustainability profile and reduces dependency on external fuel imports. Conducts a comprehensive economic feasibility study, paving the way for financial sustainability in renewable energy projects.	Moderate potential for replication in other isolated or island environments, contingent on local renewable energy profiles and transport needs.

			Demonstrates moderate scalability potential, with particular suitability for similar island communities seeking energy independence.	
Allouhi et al. [19] Ouenskra, Morocco	Utilizes a hybrid system consisting of solar photovoltaic (PV) and wind turbine with battery storage to assist a micro-hydropower plant for hydrogen production	The hydrogen produced is employed to power fuel cell bikes, promoting green transportation for the local young population.	Promotes sustainable development and energy access in the region. Enhances energy autonomy by utilizing local renewable resources. Contributes to the resilience of the energy system, important for areas with limited infrastructure options. Demonstrates the cost-effectiveness of rural electrification with a Net Present Cost (NPC) of 473.6 k$ and a Cost of Electricity (COE) of 0.147 $/kWh.	High, given the integration of different renewable sources, it can be adapted to various rural contexts with similar renewable potentials.

Upon analyzing the aforementioned pilot projects, it becomes apparent that societal and ethical considerations are pivotal when integrating hydrogen solutions into rural mobility. These case studies not only demonstrate technological viability but also underline the importance of aligning such innovations with a framework that supports equitable and socially inclusive development. Therefore, it is crucial to analyze the intersection between mobility and broader ethical and social issues and to define a possible framework of actions where hydrogen transcends its role as an energy vector to become a catalyst for social development.

A particularly relevant analytical framework is developed in [12], which synthesizes various studies in South America and proposes an approach for socially oriented accessibility assessments. This framework unfolds a holistic vision that spans from underlying ethical issues to practical accessibility components and culminates in implications for planning and public policy, thus offering a robust guide to understanding and improving social inclusion through sustainable mobility. Figure 3 illustrates the evolution of the conceptual model from [12], highlighting the proposed modifications in blue.

To further enrich our analytical framework with contemporary concerns, we integrate the concept of an equitable energy transition as a core component of accessibility assessments. Recognizing the transformative potential of clean energy sources, such as hydrogen, our revised approach examines how energy transition policies can promote or hinder social equity in the realm of transportation. This consideration aligns with the ethical stance that underpins our framework, where accessibility is not merely about physical reach but also about ensuring that the benefits of sustainable energy advancements are shared equitably, thereby contributing to a more inclusive and just society.

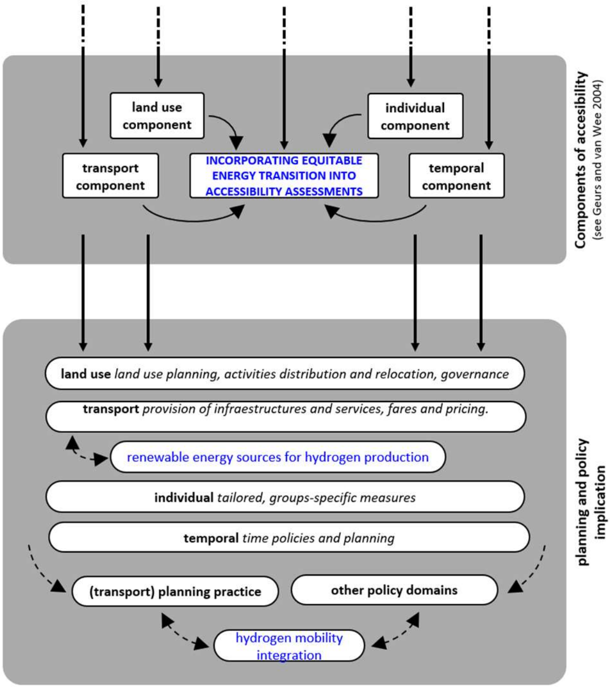

Fig. 3. An adapted framework approach for assessing accessibility with a focus on equitable energy transition [20].

5. Conclusions and future research

In conclusion, our study underscores the transformative role of hydrogen technology in revolutionizing rural mobility. By analyzing diverse pilot projects, we've showcased hydrogen's capability to provide sustainable transportation solutions that not only meet environmental standards but also advance social equity. These initiatives illuminate the path towards a more self-sufficient and resilient rural community by leveraging local renewable energy sources for hydrogen production.

In future research, we will endeavor to develop a verification model to assess the environmental impacts of hydrogen mobility solutions, focusing on pollution levels and ecosystem impacts across South America. This comprehensive model aims to compile and analyze environmental statistics to provide a clearer understanding of the regional implications of adopting hydrogen technologies. Additionally, we will delve into financial viability analyses for a pilot project, aiming to unravel the economic aspects and ensure the sustainability of hydrogen solutions in rural settings. These investigations will contribute to a holistic view of hydrogen's role in sustainable mobility, considering both ecological and economic dimensions.

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