

Article

Hydrogen Mobility in Bulgaria—Analysis of the Challenges, Prospects and Opportunities for Integration of Transport Systems (Case Study from the City of Ruse)

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Abstract

This study investigates the prospects for implementing hydrogen mobility in Bulgaria within the broader context of transport decarbonization. Using a three-dimensional framework—policy, technology, and geography—it combines analysis of European and national strategic documents, technological feasibility assessment, and a pilot case study in the city of Ruse. The pilot scenario includes a regional hydrogen ecosystem with a photovoltaic-powered electrolyzer, two refueling stations, deployment of 20 hydrogen buses, and retrofitting of a river vessel with fuel cell propulsion. Results indicate that hydrogen technologies can significantly reduce transport-related emissions, particularly where battery-electric solutions face operational constraints. Total Cost of Ownership (TCO) analysis shows that hydrogen buses remain more expensive than diesel or battery-electric alternatives under current conditions, even with locally produced green hydrogen. Sensitivity analysis demonstrates that cost competitiveness may be achieved after 2030 with large-scale investments, policy support, and reduced hydrogen prices. The study highlights the importance of coherent national strategies, public–private partnerships, and targeted financial instruments to enable sustainable integration of hydrogen in urban and river transport systems.

Keywords: hydrogen mobility; decarbonization; transport policy; total cost of ownership; pilot projects; green hydrogen production; transport integration; fuel cell propulsion; EU strategy



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1. Introduction

The transport sector is one of the main sources of greenhouse gas emissions in the European Union, accounting for approximately 25% of total emissions [1]. In light of growing climate issues and the urgent need for deep decarbonization, the European Union has implemented several strategic frameworks to shift towards sustainable, intelligent, and low-carbon mobility. The European Green Deal (2019) and the Fit for 55 packages aim to cut greenhouse gas emissions by at least 55% by 2030 and by 90% by 2050 compared to 1990 levels, moving towards achieving climate-neutral transport.

Table 1 summarizes the dynamics of greenhouse gas emission reduction targets in the EU transport sector.

Table 1. Reduction in greenhouse gas emissions from the transport sector in the EU (1990–2025).

Year	Emission Reductions, %	Comment
1990	0	Base year
2030	–55	Reduction in accordance with Regulation (EU) 2021/1119 establishing the framework for achieving climate neutrality ('European Climate Law').
2050	–90	A goal to achieve climate neutrality, which implies reducing emissions to almost zero.

Achieving these objectives requires a fundamental transformation of energy sources used in transport and the development of new infrastructure for alternative fuels. Among various technological solutions is hydrogen, and in particular “green hydrogen”—produced by electrolysis of water [2] using renewable energy—is emerging as a key energy carrier in the decarbonization process [3,4]. Its advantages include zero emissions during use, high energy density, and storage and transport capabilities, making it suitable for both passenger and commercial vehicles, including in hard-to-decarbonize sectors such as heavy-duty and waterborne transport.

Hydrogen mobility is also recognized in EU strategy documents, including [5], which emphasizes developing an integrated European hydrogen infrastructure and establishing regional “hydrogen valleys”. These initiatives support research, demonstration projects, and cross-sector cooperation among energy, transport, and industry. The strategy aims for 10 million tons of renewable hydrogen by 2030. It states that this requires “a supporting framework mechanism, functioning markets, clear legislation, as well as a dedicated infrastructure and logistics network”.

In Bulgaria, interest in hydrogen technologies is gradually growing, with the first pilot projects being introduced in public transport, industry, and energy. However, deployment remains constrained due to a lack of infrastructure, high initial costs, and regulatory difficulties [6,7].

In this context, the city of Ruse plays a strategic role in the national transport network due to its geographical position along the Danube River and its function as a key logistics hub between Bulgaria and Romania. The combination of urban passenger transport and river navigation offers favorable conditions for demonstrating integrated solutions for hydrogen mobility, including the production, storage, and use of hydrogen in real operational settings. This makes the city of Ruse an appropriate example of a pilot model for a regional hydrogen ecosystem that involves public, industrial, and academic partners.

To address the gaps in current research, this study adopts a three-dimensional framework of policy–technology–geography. This framework identifies key theoretical and empirical gaps: the lack of models for hydrogen energy integration in Eastern European countries, Bulgaria’s reliance on EU-level policy incentives, and localization challenges, such as infrastructure constraints and regional resource availability. By explicitly considering these factors, this study contributes to the understanding and design of multimodal hydrogen systems in transitional economies, offering both empirical evidence and strategic insights for policy and technology deployment.

The manuscript is organized as follows: Section 2 presents a review of strategic documents and the literature; Section 3 outlines the research methodology; Section 4 describes the case study and presents results; and finally, Section 5 provides conclusions and recommendations.

2. Review of Strategy Documents and Literature

Hydrogen occupies a central place in a number of strategic documents of the European Union:

- Ref. [5] outlines a roadmap for the production and use of green hydrogen by 2030. The document presents a three-stage plan by 2050, with a target of 40 GW of electrolyzers by 2030;
- Ref. [8] envisages the integration of alternative fuels into urban transport by 2030;
- Ref. [9] introduces requirements for H₂ stations along the main corridors of the Trans-European Transport Network (TEN-T);
- Ref. [10] 2023/2413 (RED III) establishes requirements for the share of renewable hydrogen in transport—5.5% by 2030.

Some authors [11,12] describe the role of hydrogen in the decarbonization of heavy-duty, rail, and maritime transport, whereas electrification is more appropriate for light vehicles.

In Bulgaria, the development of hydrogen energy is set in the following:

- National Recovery and Resilience Plan (2021)—includes the construction of pilot hydrogen stations and laboratories;
- Integrated Energy and Climate Plan of the Republic of Bulgaria 2021–2030 (NECP, 2023) [13]—sets an indicative target for the integration of hydrogen in transport by 2030;
- The National Roadmap for Hydrogen Technologies (2023–2026) outlines Bulgaria's strategic vision to promote the development and adoption of hydrogen technologies. It aims to achieve climate targets, reduce greenhouse gas emissions, facilitate the transition to sustainable and efficient renewable energy sources, and support a circular economy.

Recent studies [14] highlight Bulgaria's potential to produce green hydrogen through electrolysis, leveraging existing photovoltaic and wind capacities. However, systematic policy measures and financial support for its deployment in the transport sector remain limited.

Hydrogen is considered a crucial energy carrier for decarbonizing transport, especially in applications where battery electrification is constrained by vehicle volume, weight, or operational range.

Table 2 summarizes the applications, advantages, and challenges of hydrogen across different transport sectors, illustrating both its potential benefits and the barriers to large-scale adoption.

Table 2. The role of hydrogen in transport sectors.

Type of Transport	Application	Advancements	Challenges
Bus transport	Bus and intercity buses	-No local emissions (CO ₂ , NO _x , particulate matter); -Fast charging (approximately 10–20 min); -Suitable for high-mileage lines where batteries would be heavy.	Infrastructure for hydrogen stations and a higher cost compared to diesel or electric buses.
Heavy Goods Transport (Long-Distance Trucks)	Long-distance transportation of goods.	-High energy density of hydrogen, which allows a long range without large batteries; -Reducing CO ₂ emissions in the transport sector.	Development of a logistics network for refueling and the high cost of hydrogen.

Table 2. *Cont.*

Type of Transport	Application	Advancements	Challenges
Rail	Regional and intercity trains	-Suitable for lines without electrification; -Reduces dependence on diesel locomotives; -Germany already has hydrogen trains on some regional lines.	The purchase of hydrogen trains and the construction of the necessary infrastructure (charging stations, hydrogen depots) is a significant capital barrier.
Sea and river transport	Ferries, short and medium sea and river routes	-Reducing emissions in maritime transport, which traditionally relies on heavy fuels. -Hydrogen and ammonia (as a derivative of hydrogen) are promising for longer routes.	Storage and safety on board, charging infrastructure in ports.

Table 2 provides an overview of the applications, advantages, and challenges of hydrogen across various transport sectors. To further contextualize these findings, a comparative discussion of key references is presented. Specifically, in Hydrogen Strategy for a Climate-Neutral Europe [5] outlines the roadmap for hydrogen deployment, highlighting national strategies and milestones, whereas in Sustainable & Smart Mobility [8] emphasizes the integration of alternative fuels in urban transport systems. Additionally, in Regulation Alternative Fuels Infrastructure Regulation (EU 2023/1804) [9] specifies technical requirements for H₂ refueling stations along TEN-T corridors, while in Renewable Energy Directive (RED III) [10] sets targets for renewable hydrogen adoption in the transport sector. This comparison illustrates the interplay between policy frameworks, infrastructure planning, and practical implementation considerations for hydrogen mobility.

The fuel cell-based electric vehicles come with an additional burden of safety hazards; therefore, the manufacturers have to undergo increased scrutiny from government permitting agencies regarding electrical safety and hazards from stored hydrogen. Although the mileages and zero tailpipe emissions are strong selling points, hydrogen-based fuel cell EVs have failed to gain market in the automobile industry [15].

Research has demonstrated that using hydrogen as a fuel for buses can cut CO₂ emissions by more than 80% when integrated into urban transport, depending on the hydrogen source [16]. Ref. [17] examines the economic viability of H₂ infrastructure in Central Europe and emphasizes the importance of public–private partnerships. In [18], it is noted that combining hydrogen and electric mobility enhances the flexibility of energy systems.

Table 3 presents the total cost of ownership (TCO) comparison between diesel, battery-electric, and hydrogen fuel cell buses. The high initial cost of fuel cell systems remains the main bottleneck for economic viability, despite lower operational costs and zero tailpipe emissions. To improve the accuracy of long-term cost projections, we incorporate the effects of electrochemical degradation in PEM fuel cells, specifically reversible voltage loss, following the life prediction model proposed by [19]. This model quantifies the impact of voltage recovery on system longevity, thereby strengthening the durability assumption used in the TCO analysis. By including these effects, the projections that hydrogen bus costs may converge with diesel vehicles after 2030 are supported with a more robust, microscopic electrochemical basis.

Table 3. The Essential Elements of TCO in Hydrogen Buses.

TCO Components	For Fuel Cell Buses	Variable	Baseline Assumption	Optimized Assumption (ML/Transformer)	Impact on TCO
The initial purchase price of the asset (e.g., bus)	Higher than diesel buses, due to fuel cell, high-pressure tanks and system integration.	Fuel Cell Stack Life	15,000–20,000 h	22,500 h (via Predictive Maintenance)	−8.5%
Installation, infrastructure and preparation costs	Costs for the construction of hydrogen stations and related maintenance.	Replacement Frequency	Fixed (every 8 years)	Condition-based (Optimized)	−4.2%
Operating costs such as fuel/electricity, depreciation, repair and maintenance	Maintenance of the fuel cell and hydrogen system; Hydrogen is more expensive than diesel, but higher efficiency partially offsets the costs.				
Training, safety and operation costs	Specific training of personnel for safe work with hydrogen systems.				
Insurance costs, taxes, licenses, fees	It depends on government incentives and regulations; in the long run, the costs can be compensated and become comparable or lower than diesel.				
End-of-life costs—e.g., disposal, recycling or disposal	Complex dismantling of tanks and fuel cells; the need for certified operators; limited capacity for recycling fuel cells and membranes; the secondary market is still limited.				

While traditional durability assumptions rely on static electrochemical degradation models, recent advancements in deep learning have introduced more robust predictive capabilities. Specifically, the use of Transformer models (as discussed in [20]) allows for capturing long-term temporal dependencies in fuel cell operational data. This leads to a more accurate prediction of the State of Health (SoH) and enables optimized maintenance scheduling, which directly impacts the long-term TCO by extending the stack replacement interval.

By 31 December 2030, EU Member States must ensure that publicly accessible hydrogen recharging stations with a total capacity of at least 1 ton per day are located at least every 200 km along the core trans-European transport network. At least one charging station must be situated in each urban hub [9].

Much of the research on hydrogen concentrates on the role of public transport. According to [21], hydrogen can easily power passenger vehicles in urban areas. The study includes an assessment of the environmental, economic, and social benefits of deploying hydrogen technologies in city transport. One of the essential conditions for hydrogen transformation processes is energy from renewable and affordable sources. Combining these elements enhances the feasibility of using hydrogen as an alternative fuel. Additionally, restructuring mobility economies requires a shared decision-making process among con-

sumers, politicians, and companies promoting such technologies [22]. Although it is still in its early stages concerning electric mobility, discussion about the use of hydrogen vehicles is also beginning. Among the positive aspects noted by consumers, alongside reduced pollutant emissions, are the lower weight compared to electric cars [23], as well as safety, stability, and rapid recharge times, estimated at 10 to 20 min, similar to conventional vehicles.

3. Research Methodology

3.1. Methodological Framework for Assessing Hydrogen Mobility in the Transport Sector of Bulgaria

The study employs an integrated three-stage analytical approach. This method aims to provide a comprehensive assessment of the challenges, prospects, and opportunities for deploying hydrogen technologies in the transport sector. With objectives outlined in Figure 1, the study is based on three analytical techniques: documentary review, technological analysis, and case studies. The methodology is designed to cover the entire life cycle of hydrogen infrastructure—from production and storage to actual operation in urban and river transport.

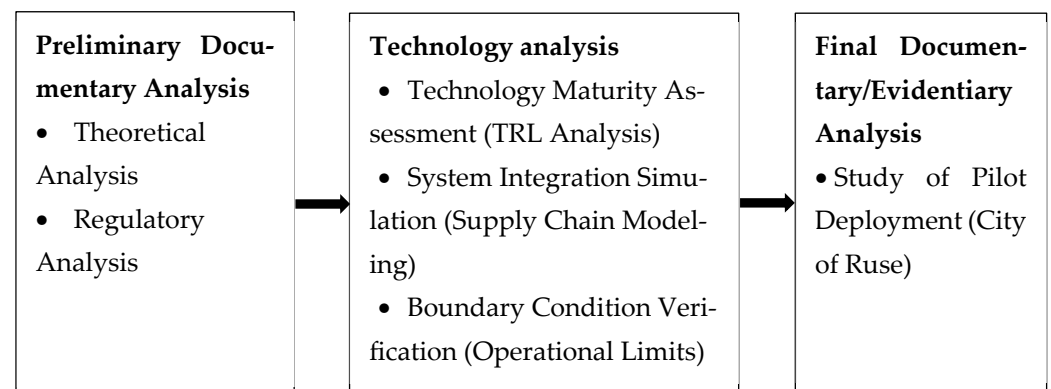


Figure 1. Analytical stages of the study on hydrogen mobility in Bulgaria.

The documentary analysis stage involves a systematic review and critical examination of existing strategic documents and regulatory frameworks of the European Union and Bulgaria, along with the relevant scientific literature on energy, transport, and sustainable development. This analysis provides the theoretical and regulatory foundation for assessing hydrogen technologies and highlights the legal and strategic frameworks that affect their deployment.

The case study phase features the city of Ruse as a potential pilot center for hydrogen mobility. The city was selected because of its strategic geographical location and available transport infrastructure, the experience of the sole urban operator “Municipal Transport Ruse” EAD with innovations in public transport, the prospects for river transport, and the strong cooperation among the local administration, businesses, and scientific institutions. At this stage, the analysis involves a quantitative and qualitative assessment of the potential for deploying hydrogen technologies, identifying barriers and incentives for development, and scenario modeling of environmental impacts, costs, and transport efficiency.

The technological analysis explores the potential role of hydrogen in decarbonization and its applicability across various transport modes in Bulgaria. By examining current technological capabilities, infrastructure requirements, and energy system integration, the study identifies the most efficient and sustainable solutions for incorporating hydrogen into the national transport system. Furthermore, by synthesizing the three analytical approaches outlined in the methodology, practical recommendations are derived for effectively implementing hydrogen mobility in Bulgaria. These recommendations are grounded

in real-world data, existing regulatory frameworks, and the technological feasibility of hydrogen-based transport solutions, ensuring both environmental benefits and economic viability [23,24].

The study combines technical analysis, policy review, and case study methods to evaluate hydrogen integration in urban transport. To ensure methodological rigor, key data sources, collection cycles, and verification methods are documented in Appendix A—Data Collection Protocol. Electrolyzer efficiency measurements follow IEC 62282-3-100 [25] ship conversion costs are itemized, and a triangulation approach combining policy documents, technical reports, and operator interviews is applied. The evaluation of micro-fuel cell power systems and portable modules follows the guidelines of IEC 62282-6-100 [26] to ensure standardized performance metrics. These measures enhance the transparency, credibility, and reproducibility of the study.

The introduced three-dimensional model (policy–technology–geography) not only complements existing methods, such as LCA (Life Cycle Assessment) or TEA (Techno-Economic Analysis), but integrates them into the context of economies in transition. Traditional TEA models often ignore the logistical and geographical specifics of Eastern Europe, accepting the presence of a developed infrastructure. In this case, it is not so. In order to eliminate the need for long pipelines or expensive transport of hydrogen in the initial phase, hydrogen production (electrolyzer), its storage, and charging station are in close proximity to consumers, as they are located in the bus depot.

Table 4 compares the proposed 3D framework (policy–technology–geography) with traditional methods.

Table 4. Comparison between the 3D framework (politics-technology-geography) and traditional methods.

Characteristics	Traditional TEA/LCA	Proposed 3D Framework (Policy–Technology–Geography)
Scope	Mainly economic/environmental	Integrated: regulatory, technical and local
Geographical focus	General/national	Node-specific (e.g., Ruse as a TEN-T node)
Infrastructure	It is often assumed to be available	Analyzes barriers and distances in real time
Optimization	Cost-oriented	Oriented towards synergy between sectors (urban/river)

The 3D framework (policy–technology–geography) provides more complete information about the characteristics under consideration, taking into account the specifics of the region.

3.2. Methodological Major Barriers and Challenges Hindering the Deployment of Hydrogen-Powered Buses

In the Ruse case study, battery-electric buses face several operational constraints, including limited range on high-mileage lines (>300 km/day), long charging downtime incompatible with continuous service, increased vehicle mass reducing passenger capacity, and sensitivity to winter operating conditions. These factors motivated the consideration of hydrogen buses for specific operational niches rather than as a universal replacement.

Barriers are classified into four main categories: economic barriers (Table 5), technological and infrastructural barriers (Table 6), regulatory and institutional barriers (Table 7), social and organizational barriers (Table 8), and political and financial barriers (Table 9).

Table 5. Economic barriers.

Factor	Description	Influence
High initial investment	The cost of a hydrogen bus is 2–3 times higher than that of a diesel bus; the construction of a charging station costs 1–2 million euro.	Withholds the decisions of municipalities and operators
High operating costs	Hydrogen is still expensive (€8–12/kg) and infrastructure is underdeveloped.	Increases TCO and requires subsidies
Lack of access to capital and subsidies	Small operators do not have access to green funds and innovative financial instruments.	Reduces investment opportunities
Dependence on public funding	Without state or European support, projects are not economically viable.	Creates a risk when programs are suspended

Table 6. Technological and Infrastructure Barriers.

Factor	Description	Influence
Lack of charging infrastructure	There is no national network of H ₂ stations	Restricts deployments outside pilot areas
Insufficient integration of production and storage	There is no link between production (electrolyzer), transport and use	Increases logistics costs
Logistics challenges for H ₂ ships and transport	High safety requirements and specialized systems	Delays implementation in port cities (Ruse, Burgas)
Technological uncertainty	Lack of long-term operational data in Bulgarian climate and road conditions	Reduces operators' trust

Table 7. Regulatory and institutional barriers.

Subfactor	Description	Influence
Lack of a national strategy for hydrogen mobility	No legal framework has been adopted yet	Uncertainty for investors and municipalities
Lack of standards and certification procedures	Especially in safety, logistics and maintenance	Delays approvals and permits
Institutional fragmentation	Inconsistencies between ministries, agencies and municipalities	Leads to duplication or lack of initiatives
Complex administrative procedures	Delayed public procurement, permits, licenses	Reduces execution speed

The economic barrier is a function of capital expenditure C_{capex} , operating costs C_{opex} and public funding F_{public} .

$$B_{barrierecon} = f(C_{capex}, C_{opex}, F_{public}). \quad (1)$$

$$Barrier_{tech} = f(Infrastructure, Integration, Safety), \quad (2)$$

where *Infrastructure* are all physical and technological facilities necessary for the use of hydrogen vehicles;

Table 8. Social and organizational barriers.

Factor	Description	Influence
Limited experience of operators	Lack of experience in operating H ₂ systems	Increases the risk of errors and costs
Need for staff training	Technical teams and guides must undergo specialized training	Requires time and resources
Low public awareness	Citizens and the media often perceive hydrogen as “dangerous”	Slows down social acceptance
Resistance to change	Traditional operators and unions may be sceptical	Support for new technologies decreases

Table 9. Political-financial barriers.

Factor	Description	Influence
Insufficient coordination at national level	Different institutions act out of sync	Leads to loss of efficiency
Lack of long-term financial predictability	European programmes are cyclical	It is difficult to plan for 10–15 years of investments
Unclear sustainability criteria (ESG)	There is no uniform methodology for measuring benefits	Makes it difficult to report projects

Integration is the connectivity and optimization of the various components of the system;

Safety—Measures and standards for the safe operation of hydrogen vehicles and infrastructure.

$$Barrier_{reg} = f(Policy_{clarity}, Norms, Governance), \quad (3)$$

where *Policy_{clarity}* is clarity of policies;

Norms—norms, standards;

Governance—governance/institutional framework.

$$Barrier_{soc} = f(Experience, Awareness, Training), \quad (4)$$

where *Experience* is the practical experience of operators and staff with new technologies (hydrogen buses, ships);

Awareness—the extent to which employees, the community and consumers are informed about hydrogen mobility, the benefits and risks;

Training—training of workers.

The scaling-up of hydrogen mobility in Bulgaria is constrained by several regulatory gaps, including the absence of a dedicated legal framework for hydrogen transport applications, unclear certification procedures for hydrogen refueling infrastructure and vessels, and the lack of operational support schemes linked to decarbonization performance. These gaps create uncertainty for municipalities and investors and limit the transition from pilot projects to commercial deployment.

$$Barrier_{sys} = f(Coord, F_{long}, ESG_{clarity}, Policy_{stability}), \quad (5)$$

where *Coord* is the coordination between the institutions (0–1, 0 = Full coordination, 1 = lack of coordination);

F_{long} —Long-term financial predictability (0–1, 0 = Stable funding, 1 = Lack of predictability);

$ESG_{clarity}$ —Clarity of the sustainability of the criteria (0–1, 1 = Lack of methodology);

$Policy_{stability}$ —Political stability/support (0–1, 1 = Strong instability).

3.3. Model of Total Cost of Owning a Hydrogen Bus

The TCO model includes

$$TCO = C_p + C_i + C_{op} + C_{tr} + C_{adm} + C_{end}, \text{ €}, \quad (6)$$

where C_p is the initial price for the purchase of the bus, €;

C_i are the costs of infrastructure and preparation, €;

C_{op} —operative expenses, €;

C_{tr} —training, safety and operating costs, €;

C_{adm} —administrative costs (insurance, taxes, licenses, fees), €;

C_{end} —end-of-life costs (decommissioning, recycling), €.

Initial purchase price

$$C_p = N_{bus} P_{bus}, \text{ €}, \quad (7)$$

where N_{bus} is the number of hydrogen-powered buses purchased;

P_{bus} —single price, €.

Infrastructure and preparation

$$C_i = C_{station} + C_{storage} + C_{permit} + C_{site}, \text{ €}, \quad (8)$$

where $C_{station}$ is the construction of a hydrogen charging station, €;

$C_{storage}$ are the costs of tanks and compressors, €;

C_{permit} —Licenses, Projects, Safety, €;

C_{site} —construction and logistics activities, €.

Operating expenses

$$C_{op} = (C_{fuel} + C_{maint} + C_{rep} + C_{amort})Y, \text{ €}, \quad (9)$$

where $C_{fuel} = d_{avg} p_{H2} e_{cons}$ is the annual energy consumption, €;

d_{avg} —Annual mileage (km);

p_{H2} —Price per kg H_2 (€/kg). This price includes a combined value formed by energy from a solar plant and energy from the national grid. The trend is determined on an annual basis, averaged over the entire period;

e_{cons} —Consumption H_2 (kg/km);

C_{maint} —Maintenance and technical inspections, €;

C_{rep} —Repairs, €;

C_{amort} —Asset depreciation, €;

Y —Number of years of operation.

Training and safety

$$C_{tr} = N_{staff} (C_{train} + C_{safety}), \text{ €}, \quad (10)$$

where N_{staff} is the number of employees (drivers, mechanics, operators);

C_{train} —Tuition fee, €;

C_{safety} —Certification and safety measures, €.

Administrative costs

$$C_{adm} = (C_{ins} + C_{tax} + C_{lic} + C_{fee})Y, \text{ €}, \quad (11)$$

where C_{ins} is asset insurance, €;

C_{tax} —Road and environmental taxes, €;

C_{lic} —Licenses, €;

C_{fee} —Other administrative fees, €.

End of life cycle

$$C_{end} = C_{disposal} - V_{res}, \text{ €}, \quad (12)$$

where $C_{disposal}$ is dismantling, transporting, waste treatment, €;

V_{res} —residual value from the sale/recycling of components (e.g., batteries, tanks, catalysts), €.

The model facilitates a quantitative comparison of hydrogen, diesel, and electric buses and functions as a tool to evaluate the project's economic viability.

4. Case Study and Results

This section presents the results of the pilot project for the implementation of hydrogen mobility in the City of Ruse, structured in accordance with the methodological framework outlined in Figure 1. Each analytical sub-stage corresponds directly to a specific methodological step and integrates regulatory, technical, economic, and operational evidence. This structured approach ensures internal consistency between the applied methods and the resulting case-specific findings.

Preliminary Documentary Analysis

Theoretical Analysis. Based on the existing literature and international best practices, hydrogen mobility offers significant environmental benefits by reducing CO₂ emissions. Modeling the bus routes in Ruse indicates that hydrogen vehicles can cover the required daily distances without intermediate refueling.

Regulatory Analysis. The regulatory review confirms that Bulgarian legislation aligns with EU directives on hydrogen station safety and licensing. Key requirements include pressures of 350 and 700 bar, safety measures, and personnel certification. The project design strictly adheres to ISO 19880-1 [27] for hydrogen refueling stations and ISO 15399 [28] for gaseous hydrogen fuel station components. The available locations in Ruse allow safe deployment of stations within the urban infrastructure.

Technology Analysis

Table 10 presents technical parameters for hydrogen necessary for the implementation of the project.

Table 10. Summary table of technical parameters for hydrogen.

Technical Parameter	Target Value/Threshold	Reference Standard
Electrolyzer efficiency	≥70%	IEC 62282-3-100
Storage density (H ₂)	≥40 kg/m ³ (at 350 bar)	ISO 19880-1
Loading Pressure (Bus)	350 bar (±5% tolerance)	SAE J2601 [29]
Purity of Hydrogen	≥99.97% (Grade D)	ISO 14687:2025 [30]

Technology Maturity Assessment (TRL Analysis). This is the first and fundamental level that determines whether a technology is sufficiently developed for the purposes of the project. It uses the Technology Readiness Level (TRL) scale. For the purposes of hydrogen mobility in Ruse, the focus is on technologies with TRL 7–9, which includes a

demonstration in a real environment and full operational deployment. The task is related to the transition from initial laboratory tests with a minimum TRL4 to the implementation of proven engineering applicability with TRL9. In this way, it is ensured that the selected components (electrolyzer, fuel cells and charging station) are not only theoretical prototypes, but commercially available solutions capable of withstanding the load of public transport.

System Integration Simulation (Supply Chain Modeling). Once the maturity of the technologies is confirmed, they move on to modeling how they interact within a closed ecosystem. This includes modeling the value chain ‘production-storage-distribution’. They simulate energy balances: how much solar energy from the photovoltaic park is needed to produce a unit of hydrogen, and how this amount corresponds to the daily mileage of the 20 buses in the city of Ruse. The simulation identifies critical points, such as the required buffer volume of hydrogen storage, to ensure the continuity of the transport process. As a result, an integrated energy transport system is obtained, which includes the individual technological units.

Boundary Condition Verification (Operational Limits). The last level checks the stability of the system in real, often extreme operating conditions, and strict technical indicators and operational limits are defined here. Quantitative thresholds for electrolyzer efficiency $\geq 70\%$, storage pressures of 350–700 bar are applied, and compliance with standards such as IEC 62282-6-100 and ISO 19880-1 is verified. In this way, the limits of safety and efficiency are established, which are related to the influence of temperature amplitudes in the region of Ruse on the loading speed and pressure in the hydrogen tanks. This is the final step in the implementation, which turns the simulation model into a concrete technical project for implementation.

When implementing the project, the following must be taken into account:

- Possibility of storing hydrogen in tanks. The analysis of hydrogen storage indicates that composite tanks provide the necessary capacity for the Ruse bus fleet while ensuring safety and efficiency in daily operations.
- Possibility of refueling from stationary stations. Currently, Bulgaria does not have a national network of hydrogen refueling stations [31]. The pilot station, established jointly by the Bulgarian Academy of Sciences and Hitmobil in 2024, accommodates both light and heavy-duty vehicles, with capacities and pressures of 350 and 700 bar [32]. The main barriers to expansion are high investment costs, lack of incentives, and limited sector expertise.
- Possibility of transporting hydrogen to mobile machines. Hydrogen buses can cover the standard routes in Ruse without changes to the schedule. According to [33], the Total Cost of Ownership (TCO) of hydrogen buses will match that of diesel buses after 2030, provided large-scale investments are made. This confirms the economic feasibility of hydrogen mobility in an urban context. While these findings confirm the technical and schedule feasibility of hydrogen buses at the route level, their practical validation requires assessment within an integrated pilot deployment encompassing infrastructure, operations, and institutional conditions.

The main challenges that hydrogen vehicles need to solve are related to [34]:

Integration challenges in hybrid systems. A major factor is the complexity of energy management in hybrid configurations involving a fuel cell and a battery in ships and buses. The most critical is optimizing the efficiency and extending the life cycle of components related to the distribution of power between the fuel cell and the battery package, due to the low performance and high cost of the fuel cell, which points to the search for more sustainable and low-cost solutions through new research.

Cold Start Problems. The challenges of starting hydrogen fuel cell systems (PEMFC) at low temperatures are particularly relevant to the climatic conditions in Bulgaria and

the Ruse region. This requires policies in the country to support research in the field of adaptive management strategies to mitigate these effects.

Technical barriers to ship retrofit. In the retrofit of the Voyager ship, the challenges are related to the volumetric energy density of hydrogen compared to marine fuel. The need for vessels with larger volumes for storing hydrogen and the necessary safety zones on board the ship are major engineering limitations that require specific regulatory standards made of non-porous composite material and raise public awareness.

Policy framework for technological development. National policies are needed that focus not only on financial subsidies but also on the creation of specialized certification procedures for hybrid systems and support for innovation in vehicle energy management, as well as policies for recycling end-of-life systems.

Final Documentary/Evidentiary Analysis

Study of Pilot Deployment (City of Ruse). The pilot scenario includes the following:

- Deployment of two hydrogen stations covering the main routes;
- Training of personnel for safe operation;
- Monitoring of vehicle and infrastructure performance.

The results show that the project is technically and economically feasible and complies with regulatory requirements. The expected CO₂ emission reduction is approximately 25% within the first year of pilot operation.

4.1. Case Study: City of Ruse

The city of Ruse is a key transport center with significant potential for a pilot project on hydrogen mobility. Its main advantages include access to renewable energy sources, such as photovoltaic parks, which can provide green hydrogen through water electrolysis. The city also possesses an existing transport system suitable for a pilot project involving 20 hydrogen buses and a mobile electrolysis plant (Ruse Municipality, 2024). Furthermore, there are opportunities to combine hydrogen transport with river transport by upgrading a cargo ship with a hybrid battery system (Port of Ruse, 2024). According to [35], under the Union guidelines for the development of the TEN-T network, Ruse has been included in the list of urban nodes as of July 2024.

The project provides hydrogen production from electrolysis with a capacity of 700 kg H₂/day, supplied by a 2 MW photovoltaic park. Hydrogen is stored in compressed tanks and dispensed through a charging station at 350 bars. The pilot includes 20 hydrogen buses intended to replace the currently used diesel buses. In addition, the project involves retrofitting the Voyager pusher ship with electric motors and hydrogen fuel cells, marking the initial step towards decarbonizing marine applications in the Danube region. The vessel, owned by Bulgarian River Navigation AD, is designed to push two barges of 1000 tons each or one barge of 2000 tons (Figures 2 and 3).



Figure 2. General view of the Voyager ship.

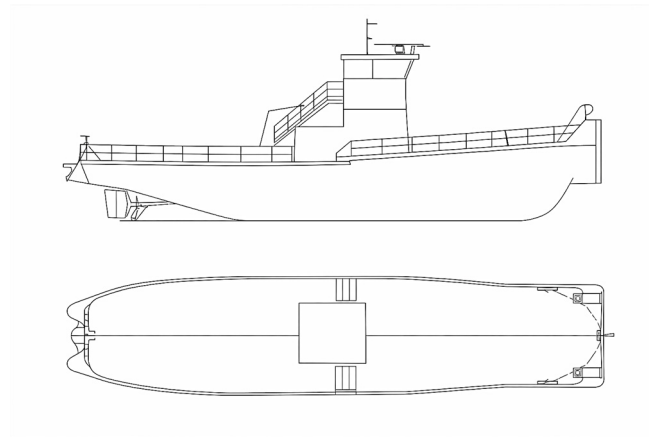


Figure 3. Diagram of the Voyager ship.

Buses are charged directly at the hydrogen station, while the ship is refueled using mobile hydrogen containers transported by truck and semi-trailer. This integrated approach demonstrates a scalable model for hydrogen mobility in both urban and river transport systems.

Tables 11 and 12 present data on the selected ship, and the planned major changes in the modernization of the power transmission and propulsion system.

Table 11. Data about the Voyager ship.

Data	Quantity
Days of work per year	252 days
Usage: 126 days 5 h/day; 126 days 8 h/day	1638 h/year
Location	Port of Ruse East
Length	24.25 m
Width	6.2 m
Board height	2.80 m
Engine power	2 × 220 kW
Ship class	BR100A5 I (3) Z pusher
Sailing Region	Danube

Table 12. Key alterations in the modernization of the powertrain and drive system.

Voyager Ship	Before Retrofitting	After Retrofitting
Main engine	Diesel engine: 2 × 220 kW	Electric motor 2 × 220 kW
Loading	Daily	Daily
Type of fuel	Diesel	Hydrogen

The main changes on the ship are indicated in Table 5.

Beyond system integration and refueling logistics, vessel retrofitting introduces additional engineering constraints that are fundamentally different from those encountered in road transport. From an engineering perspective, the conversion of a river vessel to hydrogen fuel cell propulsion poses significant volumetric energy density challenges. Compressed hydrogen at 350 bar has a volumetric energy density approximately 4–6 times lower than marine diesel, requiring substantially larger storage volumes. This affects onboard layout, safety zoning, and payload capacity. Consequently, the Ruse vessel retrofit should be interpreted as a pilot-scale demonstration rather than a fully scalable solution for long-distance inland navigation. Nevertheless, inland navigation vessels with lower average speeds and predictable routes, such as Danube pushers, represent suitable candidates for early hydrogen demonstrations.

The total investment costs of the project amount to EUR 23,400,000 excluding VAT, distributed by individual components:

- Electrolyzer with photovoltaic park—8,000,000 €;
- Buses—11,070,000 €;
- Re-equipment of a ship—3,900,000 €;
- Other expenses—384,000 €.

To operationalize the concept of a regional hydrogen ecosystem, the electrolysis facility is conceived as a shared infrastructure element supplying both urban buses and river transport. The daily production capacity of 700 kg H₂ has been dimensioned to meet aggregated demand, assuming priority refueling of urban buses due to fixed public service schedules. Hydrogen supply for the river vessel is organized via mobile containers and scheduled during off-peak hours, allowing flexible operation without compromising public transport reliability.

The life cycle of green hydrogen, from its production to its utilization in transport systems, is illustrated in Figure 4.

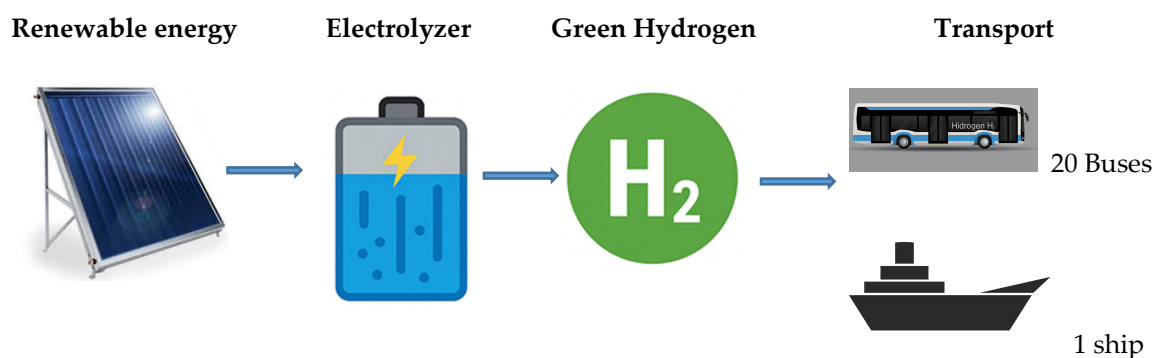


Figure 4. Schematic representation of the process of production and use of green hydrogen in the project.

The process of implementing hydrogen mobility in Ruse comprises four main stages, each crucial for ensuring a sustainable and efficient system.

The first stage, Renewable Energy, involves the generation of carbon-free electricity through sources such as solar panels. In the Ruse pilot project, photovoltaic parks supply electricity directly to the electrolyzer, ensuring that the hydrogen produced is derived entirely from renewable energy. This approach minimizes the carbon footprint of hydrogen production and supports the city's objectives for sustainable urban transport.

The second stage, Electrolyzer, entails the splitting of water (H₂O) into hydrogen (H₂) and oxygen (O₂) through the process of electrolysis. The hydrogen generated serves as a usable fuel for vehicles, while oxygen is released as a harmless by-product. The electrolyzer is the core technological component, determining the efficiency and volume of hydrogen production. In Ruse, the pilot uses an electrolyzer capable of producing 700 kg of hydrogen per day, matching the projected demand for the fleet of hydrogen buses.

The third stage, Green Hydrogen, focuses on the storage and management of the hydrogen produced. Hydrogen can be stored under high pressure in tanks or in liquefied form, depending on the operational requirements. Because the electricity used in the electrolyzer comes entirely from renewable sources, the hydrogen generated is classified as “green,” ensuring zero carbon emissions. When utilized in fuel cells, the only by-product released is water vapor, demonstrating the environmental benefits of this energy carrier.

The fourth stage, Transport, applies the hydrogen in buses and ships using fuel cells, which convert hydrogen back into electricity for propulsion. This stage allows for rapid

refueling—typically between 10 and 20 min—while providing high mileage and zero local emissions. In Ruse, 20 hydrogen buses are integrated into the urban fleet, and the Voyager pusher ship is retrofitted with a hybrid hydrogen-electric propulsion system. This dual application showcases the versatility of hydrogen mobility for both land and river transport and provides practical insights for scaling similar solutions in other regions.

The Ruse pilot project highlights a set of interrelated challenges that are representative of the broader Bulgarian context. These challenges extend beyond technical feasibility and reflect systemic constraints affecting hydrogen mobility deployment at the national level. They can be grouped as follows:

- Economic barriers linked to high initial investments and operational costs for hydrogen buses and ships; the need for funding from the public sector and European programmes.
- Technological and infrastructural challenges for the optimal placement of charging stations, the integration of hydrogen production and storage, and logistics for ships.
- Regulatory and institutional issues related to the absence of a national strategy and regulatory incentives for the development of hydrogen mobility; limited experience among operators.
- Social and organizational—the need for staff training and preparing society for the adoption of new technologies and vehicles.

Based on the analysis, the following recommendations can be formulated:

1. Development of a National Strategy for Hydrogen Mobility with clear quantitative targets for stations and vehicles;
2. Support for pilot cities (Ruse, Varna, Plovdiv, Burgas) with the construction of hydrogen infrastructure and the deployment of fuel cell vehicles;
3. Creation of public–private partnerships for the production of green hydrogen, construction of stations;
4. Integrating hydrogen mobility into the National Transport Strategy 2030 and regional plans;
5. Promoting research, innovation and training programmes, including training for drivers and operators of hydrogen vehicles.

The project for the town of Ruse shows that successfully introducing hydrogen mobility requires a systematic approach to integrating transport infrastructure, hydrogen production, and logistics, as well as cooperation between academic institutions, municipal authorities, and industry. The pilot project demonstrates that, with proper planning and funding, hydrogen can cut emissions, create new jobs, and serve as a model for other cities in Bulgaria.

The project draws on the experience and expertise gained by the team at the University of Ruse under the National Scientific Programme “Low-Carbon Mobility for Transport and Household” (2018–2023), funded by the Ministry of Education and Science. The established scientific competence and strong partnerships with the Municipality of Ruse and the Association of Danube Municipalities “Danube” served as a foundation for developing a project idea for infrastructure for hydrogen refueling, the purchase of electric vehicles powered by fuel cells, and the re-equipment of a river vessel with a hybrid drive.

Impact of Seasonal Temperature Variations on PEM Fuel Cell Performance

In addition to infrastructural and operational constraints, regional climatic conditions introduce a further layer of technical uncertainty affecting fuel cell durability and performance. Temperature fluctuations affect electrochemical reaction rates, membrane hydration, and degradation mechanisms, leading to variations in fuel cell state-of-health (SoH). Recent studies have demonstrated that PEMFC degradation exhibits strong temper-

ature sensitivity and that adaptive control strategies can effectively mitigate performance losses under variable thermal conditions [36].

In the context of the Ruse case, these findings are directly applicable to both ship propulsion systems operating on the Danube and urban bus fleets exposed to seasonal extremes. The integration of thermal management systems and adaptive operating strategies is therefore a key prerequisite for ensuring reliable long-term operation of hydrogen-powered vehicles under regional climatic conditions.

4.2. Environmental Life Cycle Assessment (LCA)

While the pilot results demonstrate technical and economic feasibility under specific conditions, a comprehensive evaluation of hydrogen mobility requires assessment of its environmental performance across the full life cycle. The assessment adopts a screening LCA approach and considers multiple environmental indicators, including CO₂ emissions, water consumption, and local air pollutants.

Hydrogen production via water electrolysis requires approximately 9 L of water per kilogram of hydrogen, which is explicitly accounted for in the analysis. While this represents an additional resource demand compared to conventional fuels, the localized nature of water use allows for context-specific mitigation measures, particularly in regions with sufficient water availability.

In addition, hydrogen fuel cell systems eliminate tailpipe emissions of nitrogen oxides (NO_x) and particulate matter, offering significant benefits for urban air quality compared to diesel-powered buses. These reductions are particularly relevant in densely populated areas, such as the case study region.

The multi-pollutant LCA highlights that the environmental advantages of hydrogen extend beyond CO₂ mitigation, while also revealing important trade-offs related to resource use, thereby providing a more comprehensive basis for sustainability-oriented transport planning.

4.3. Comparison of the Cost of Ownership of Different Bus Technologies in Ruse

Numerically justified TCO calculations and tables for comparison between diesel, battery-electric and hydrogen (FCEV) city bus, consistent with the typical operational parameters of the transport company “Municipal Transport Ruse” EAD (MTR), are obtained taking into account the initial parameters (Table 13).

Table 13. Model output parameters.

General Parameters	
Parameter	Value
Bus mileage per year	60,000 km (typical value for a city line)
Life cycle	12 years (data from MTR)
Total mileage for 12 years	720,000 km
Fuel/energy consumption	
Diesel bus	35 L/100 km
Electric Bus	130 kWh/100 km
Hydrogen bus ((FCEV)	8.5 * kg H ₂ /100 km
Fuel prices	
Diesel fuel	1.35 €/L

Table 13. Cont.

General Parameters	
Parameter	Value
Electricity	0.15 €/kWh
Green hydrogen	10 €/kg (market), 6 €/kg (in local electrolysis—both options are used)
TCO calculations (12 years, 720,000 km)	
Fuel costs	
Diesel bus	340,200 € ($35 \text{ L} \times 1.35 \text{ €} \times 720,000 \text{ km} / 100 \text{ km}$)
Electric Bus	140,400 € ($1.3 \text{ kWh/km} \times 0.15 \text{ €} \times 720,000 \text{ km}$)
FCEV, Option A, market price 10 €/kg	612,000 € ($8.5 \text{ kg H}_2 \times 10 \text{ €} \times 720,000 \text{ km} / 100 \text{ km}$)
FCEV, Option B, local electrolysis 6 €/kg	367,200 € ($8.5 \text{ kg H}_2 \times 6 \text{ €} \times 720,000 \text{ km} / 100 \text{ km}$)
Initial investment	
Diesel bus	250,000 €
Electric Bus	600,000 € (520,000 € (Electric bus) + 140,000 € (new stack batteries) + 40,000 € (Depot + charging station **))
FCEV	960,000 € (650,000 € (hydrogen bus) + 200,000 € (new stack fuel cells) + 110,000 € (station, compression, safety ***)
Maintenance costs ****	
Diesel bus	158,400 € ($0.22 \text{ €/km} \times 720,000 \text{ km}$)
Electric Bus	108,000 € ($0.15 \text{ €/km} \times 720,000 \text{ km}$)
FCEV Bus	240,000 € ($0.33 \text{ €/km} \times 720,000 \text{ km}$)

* The calculations can include the annual degradation rate of the fuel cell system, which accounts for a 1.5–2% drop in efficiency per year. This also leads to an increase in hydrogen consumption per kilometer driven as the vehicle ages. In order not to complicate the model, an average drop of 1.75% is assumed, which is reflected in the average fuel consumption of the bus. ** When scaling up a large charging system for 20 buses, this figure includes AC/DC chargers, depot adaptations, and cable lines. In the calculations, the costs of changing the battery stack were not taken into account, because in the literature, the main calculations were made without changing the stack. *** For 20 hydrogen buses, the infrastructure is scaled. One station costs approximately €2.2 million, i.e., around €110,000 per bus, evenly distributed. The calculations did not take into account the cost of changing the fuel cell stack because in the literature, the main calculations were made without changing the stack. **** The maintenance costs of hydrogen buses are determined using standardized TCO models, which are based on current data from European projects JIVE 2 and H2Bus Europe [37]. Real market conditions and empirical data from European operators are utilized for validation. Maintenance costs of diesel and electric buses are estimated based on their operation under conditions similar to those at Ruse Airport.

For easier summaries for TCO, initial investment, fuel/energy, and maintenance are reported (Table 14).

The TCO calculations show a clear difference between the three technological options. Over 12 years and a distance of 720,000 km, the total cost of ownership for a diesel bus is €748,600, whereas for an electric bus it amounts to €808,400. The hydrogen bus remains the most capital-consuming choice with a TCO of €1,367,200 (assuming a green hydrogen price of €6/kg).

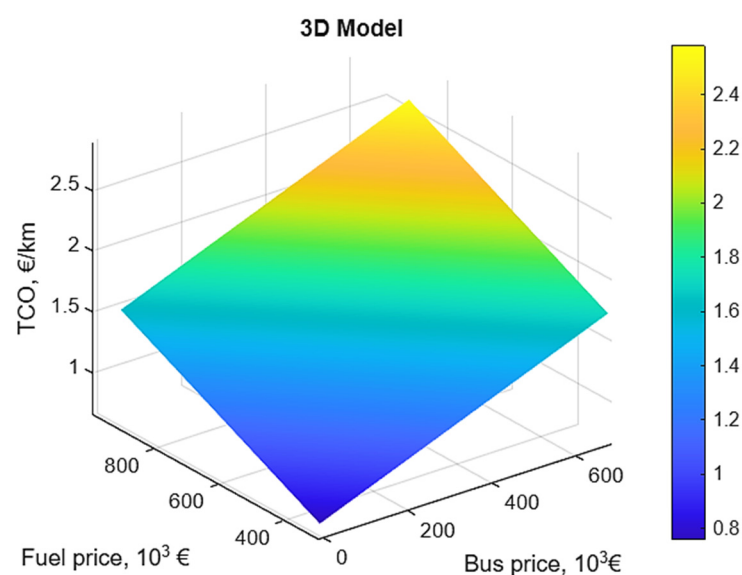
Table 14. Summarized TCO scores (12 years).

Using Local Green Hydrogen—6 €/kg			
Cost (12 Years)	Diesel Bus	Electric Bus	FCEV
Initial investment, €	250,000	560,000	760,000
Fuel/Energy, €	340,200	140,400	367,200
Support, €	158,400	108,000	240,000
TCO (Total—12 years), €	748,600	808,400	1,367,200
Consumption, €/km	1.04	1.12	1.90

Operating costs for diesel and electric buses are the lowest and highest for hydrogen buses. The main cost factors are the price of hydrogen and the expenses involved in building a compression and charging station. When hydrogen is produced locally via an electrolyzer, hydrogen buses are nearing electric buses in total cost of ownership, but still fall behind.

The results confirm that hydrogen mobility can become cost-competitive after 2030, subject to substantial investments, subsidies, and a reduction in green hydrogen prices below €5/kg.

Figure 5 presents the change in TCO in euro/km with hydrogen costs changing from 5 to 15 euro/kg and a vehicle subsidy from zero to 100%. This allows a decision to be made on what costs to anticipate and what form of financing to implement the project proposal.

**Figure 5.** Dependence of TCO on hydrogen costs and vehicle subsidy.

The forecasts highlight several factors expected to drive reductions in the overall cost of FCEVs. With increasing production volumes, the initial investment required for these vehicles is anticipated to decline. Simultaneously, the cost of green hydrogen is projected to decrease as mass production and infrastructure development advance. Maintenance expenses are also expected to be lower due to the enhanced reliability of components, the simplification of mechanical systems, and the adoption of standardized procedures. Furthermore, European and national green bus programmes, through mechanisms such as investment grants or tax incentives, provide direct support that positively influences the total cost of ownership. Lastly, improvements in energy efficiency, optimization of fuel cells and batteries, and integration with fleet energy management systems are expected to further reduce operating costs per kilometer.

4.3.1. Sensitivity Analysis and Scale Effects

To further enhance the economic assessment, Monte Carlo simulations were performed to evaluate the sensitivity of the TCO to variations in carbon pricing, ranging from €50 to €100 per ton of CO₂. Each simulation sampled 10,000 scenarios, incorporating uncertainties in fuel costs, operational expenses, and carbon charges, providing a probabilistic distribution of TCO outcomes.

In addition, a learning curve analysis was applied to estimate the effect of fleet scale on hydrogen costs, capturing potential reductions in unit prices as the number of hydrogen buses increases. These analyses demonstrate how policy interventions and scale effects may influence the total cost of ownership, highlighting the conditions under which hydrogen buses could achieve greater cost-competitiveness.

These sensitivity results also form the basis for assessing the regional transferability of the Ruse case study.

4.3.2. Transferability and Regional Applicability of the Ruse Case Study

The Ruse pilot project is based on favorable geographical and infrastructural conditions, including proximity to the Danube River, access to photovoltaic generation, and the possibility of local hydrogen production. To assess the broader applicability of the proposed hydrogen mobility model, its transferability to inland and mountainous regions of Bulgaria was evaluated.

In mountainous regions (example: the city of Smolyan), where local hydrogen production and river transport are not available, hydrogen supply would rely on road transport using compressed hydrogen trailers. Incorporating additional logistics costs into the TCO framework indicates an increase in hydrogen fuel costs of approximately 15–30%, depending on transport distance and delivery frequency.

Topographical constraints, lower renewable energy potential, and limited infrastructure density further affect economic feasibility in mountainous areas. As a result, large-scale deployment of hydrogen buses in such regions is more sensitive to fleet size, hydrogen price volatility, and policy support mechanisms.

Therefore, the Ruse pilot model is considered transferable primarily to regions with access to hydrogen production facilities or economically viable hydrogen logistics chains, while deployment in remote inland regions should be limited to niche or fleet-specific applications unless additional infrastructure investments are undertaken.

4.3.3. Logistics Cost

Logistics cost analysis shows the following three advantages:

- Location optimization. Through the geographical analysis of the city of Ruse and the choice of a production location close to end users, the construction of a distribution network is avoided;
- Investment savings. The use of mobile hydrogen containers for refueling ships (instead of fixed shore infrastructure) can reduce the initial costs of specific port infrastructure compared to standard stationary solutions for river terminals. The distance from the production base to the port is 13.6 km and runs through the entire city. The use of a trailer with a capacity of 560–900 kg of hydrogen gas reduces the risk and saves time for the construction and commissioning of a hydrogen pipeline to the port;
- Regional applicability. A new transferability analysis is included, showing that in mountainous and hilly regions (excluding local production), the cost of fuel rises by 10%, sometimes even more, due to logistical distances, proving the key role of the geographical module in reducing TCO.

4.4. Evaluation of European and National Strategic Documents

This sub-section evaluates the alignment of the Ruse hydrogen mobility pilot project with relevant European and Bulgarian strategic documents. The analysis considers both policy objectives and implementation targets for sustainable urban transport.

European Level: The project aligns with the EU Hydrogen Strategy (2020), which promotes the deployment of hydrogen for transport and the creation of hydrogen infrastructure networks across member states [5]. The EU Green Deal also emphasizes zero-emission public transport, supporting the transition to hydrogen buses in urban areas.

National Level: According to Bulgaria's National Energy and Climate Plan (NECP) 2021–2030 [26,38] and the Sustainable Urban Mobility (2020), hydrogen technologies are explicitly mentioned as key solutions for decarbonizing public transport fleets [39]. The Ruse pilot project contributes to these targets by introducing hydrogen buses and a pilot refueling station, serving as a model for broader national deployment.

Analysis: By integrating hydrogen buses into the Ruse fleet and establishing a refueling station, the project supports the achievement of both European and national sustainability goals. The feasibility study confirms that the pilot implementation is compliant with regulatory and strategic requirements, providing practical insights for future scale-up.

4.5. Future Research Directions: Predictive Monitoring of Fuel Cell Performance

The limitations identified in the pilot-scale implementation, particularly regarding durability and long-term system behavior, naturally point towards the need for advanced predictive monitoring approaches. Transformer-based predictive models can be applied to operational data from hydrogen buses and retrofitted river vessels to forecast degradation trends. Such predictive monitoring would inform maintenance scheduling, life-cycle optimization, and validation of the pilot results under real operational conditions, providing a robust framework for scaling hydrogen mobility in transitional economies.

4.6. Technology Roadmap and TRL Evolution

At this stage, hydrogen buses still have a high price, and this is proven both by the obtained TCO values and by the hydrogen buses implemented in operation in Germany, Great Britain, Japan and other countries. All these projects are financed by projects and supported by state policies. For Bulgaria, financing is provided for in the National Recovery and Resilience Plan. At this stage, there are still no programs in the country under which to apply for financing. At the same time, the company "Municipal Transport Ruse" relies entirely on financing under this plan and from the state. Regarding the ship "Voyager" of the private Bulgarian company, the re-equipment is expected to be fully financed with project funds. For the company, this is an expensive innovation, and it agrees to participate in the project by providing the ship for re-equipment and then bearing the operating costs.

The IPCEI Hy2Tech model for public–private partnership shows that it is possible to use state aid for innovative projects that exceed the usual market levels of risk and attract private investment in charging infrastructure [33]. This is an issue that is currently being considered and has not yet been resolved. Steps were taken to partner with the company "Bulgaria Glass", Targovishte, but they purchased electrolyzers and produce the necessary hydrogen for the glass production process themselves. Therefore, this issue remains open for a further period.

In Bulgaria, it is still difficult to outline the stages for the transition from a pilot project to national implementation. However, taking into account the provisions of the National Recovery and Resilience Plan, the following can be outlined, which will provide a clearer vision of the practical steps in the implementation of the hydrogen strategy in Bulgaria:

- Short-term plan (until 2027): Construction of infrastructure under the NRW and adoption of safety and certification standards;
- Medium-term plan (until 2030): Construction of charging stations along the TEN-T corridors (every 200 km) in accordance with Regulation (EU) 2023/1804 [40];
- Long-term plan (after 2030): Achieving economic viability (TCO parity) and scaling up hydrogen mobility in river and heavy goods transport.

To address the phased deployment of the proposed regional hydrogen ecosystem, a structured technology roadmap aligned with Technology Readiness Level (TRL) evolution is introduced for the period 2025–2035. The roadmap defines sequential development stages for hydrogen production, infrastructure, and transport applications, ensuring technical feasibility under regional constraints.

In the short-term phase (2025–2026), the system operates at TRL 4–5, focusing on pilot-scale deployment of hydrogen buses and river vessels, limited refueling infrastructure, and small-scale electrolyzers primarily coupled with photovoltaic generation. This phase emphasizes operational validation, safety assessment, and data acquisition (Figure 6).

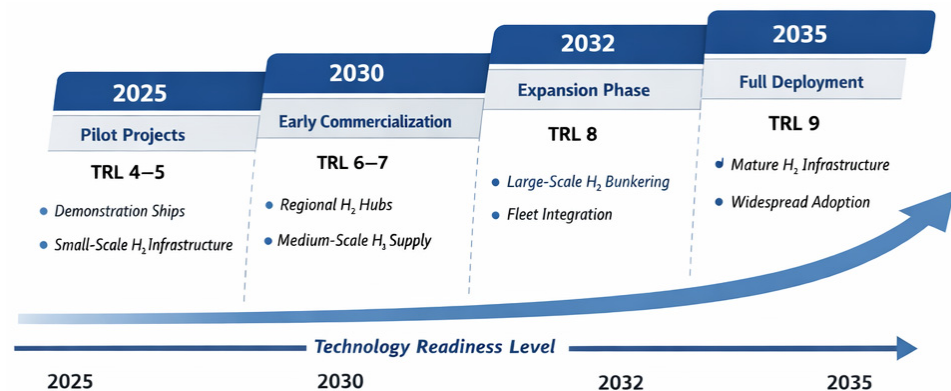


Figure 6. Hydrogen technology readiness roadmap.

The mid-term phase (2027–2030) targets TRL 6–7 and involves infrastructure expansion, increased electrolyzer capacity, and partial fleet scaling. During this stage, hydrogen production is progressively coupled with both photovoltaic and wind energy sources. Grid interaction effects, including renewable intermittency and power fluctuations, are explicitly considered as constraints influencing electrolyzer utilization and hydrogen output stability.

In the long-term phase (2030–2032), the ecosystem advances towards TRL 8 and (2032–2035) TRL 9, enabling near-commercial operation. This phase includes full integration of hydrogen refueling stations into regional transport networks and optimization of hydrogen production scheduling in response to grid variability.

The coupling between renewable energy resources and hydrogen production facilities is analyzed using the REMAP framework, allowing assessment of system resilience under fluctuating power supply conditions. This approach supports adaptive infrastructure planning and enhances the robustness of the proposed regional hydrogen ecosystem.

By combining phased TRL evolution with system-level modeling of renewable coupling and grid interaction, the proposed roadmap provides a structured pathway from experimental deployment towards scalable hydrogen mobility solutions.

5. Conclusions

The pilot study in Ruse demonstrates that hydrogen mobility is technically feasible and can substantially reduce CO₂ and local air pollutant emissions in urban and river transport. Hydrogen buses can operate on existing routes without schedule modifications,

and river vessel retrofitting is viable for demonstration purposes, although larger-scale maritime deployment requires further technological adaptation.

Economic analysis shows that hydrogen buses currently have the highest Total Cost of Ownership (TCO), driven by vehicle purchase prices and infrastructure investments. Local hydrogen production reduces operational costs but does not yet achieve parity with battery-electric or diesel options. Cost competitiveness is projected to improve after 2030, contingent on large-scale deployment, declining green hydrogen prices, and supportive financial schemes.

The 3D framework (policy–technology–geography) provides more complete information on the considered characteristics related to hydrogen mobility. It takes into account the specifics of the region, where the city of Ruse is the largest and most developed city in Bulgaria along the Danube River and is part of the TEN-T. It also allows for the development and provision of hydrogen in road and water transport.

The innovative solution for the use of mobile hydrogen containers for refueling ships with a trailer with a capacity of 560–900 kg of hydrogen gas allows for fast deliveries to the port, reduces the risk of building a hydrogen pipeline to the port, and the dissatisfaction of citizens with construction activities through the city.

The main barriers to hydrogen mobility in Bulgaria include the following:

- Economic: high CAPEX and OPEX, dependence on public and EU funding;
- Technological and infrastructural: limited refueling networks, integration of production, storage, and transport, and logistics for river vessels;
- Regulatory and institutional: absence of a national hydrogen strategy, unclear standards and certification procedures, fragmented governance;
- Social and organizational: need for staff training, limited public awareness, and resistance to change.

To overcome these barriers, the study recommends:

1. Development of a National Strategy for Hydrogen Mobility with clear quantitative targets for stations and vehicles;
2. Support for pilot cities with the construction of hydrogen infrastructure and deployment of fuel cell vehicles;
3. Establishment of public–private partnerships for green hydrogen production and station construction;
4. Integration of hydrogen mobility into national and regional transport planning;
5. Promotion of research, innovation, and training programs for operators and technical personnel.

In conclusion, hydrogen mobility in Bulgaria is currently most suitable for pilot and demonstration projects. Its broader adoption requires a coordinated approach combining technical feasibility, economic incentives, regulatory stability, and institutional capacity, serving as a model for sustainable low-carbon transport in transitional economies.

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Data Availability Statement: The data presented in this study are available on request from the corresponding author due to privacy reasons.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. Data Collection Protocol

Table A1. Main data source.

Data Source/Measurement	Details
Electrolyzer Efficiency	Measured according to IEC 62282-3-100; calibration procedures, testing intervals, and environmental conditions documented.
Ship Conversion Costs	Itemized breakdown, including fuel cell system, installation, auxiliary components, and labor.
Data Collection Cycle	Monthly data collection over pilot project duration; raw data cross-checked with operator logs.
Triangulation Approach	Cross-validation of data from policy documents, technical reports, and operator interviews to ensure reliability and reduce bias.

Note: All data sources, measurement protocols, and verification methods are fully documented to allow replication and support the credibility of the methodology.

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