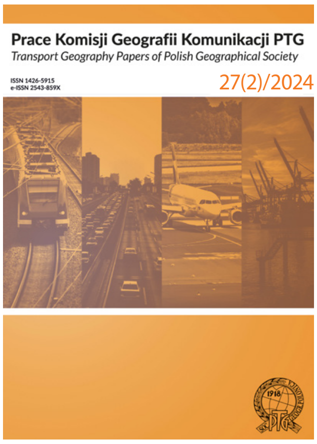

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SCENARIOS FOR THE DEVELOPMENT OF HYDROGEN TECHNOLOGY IN MOBILITY IN EUROPE

Scenariusze rozwoju technologii wodorowych w mobilności w Europie

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Abstract: This article aims to compare the time horizon of the EU hydrogen mobility policy with the potential commercialisation of this technology based on the law of market diffusion of innovation. There is growing discussion about using hydrogen as an alternative to fossil fuels in cars. This direction is further supported by EU policy and initiatives to ban the sale of new petrol and diesel cars from 2035. Alongside the development of electromobility, there is an intensification of research into technologies that will allow the widespread use of hydrogen-fuelled cars. The technology could become a future solution, primarily due to the zero-emission nature of the vehicles. However, the commercial potential of hydrogen-fuelled cars is a pertinent question. Can the interest in this technology grow sufficiently, and if so, when will it capture the early majority of the market? When can we expect hydrogen to gain a significant market share in the mobility sector? The Bass model, a reliable tool for forecasting, was used to answer these questions. The analysis of the diffusion of this innovation indicates that it is in its infancy, as its diffusion couldn't be predicted within the time horizon adopted by the EU.

Keywords: Bass Model, Hydrogen Policy, Management, Mobility, Sustainability

Introduction

For energy potential, hydrogen has recently become a vital link. This is due to the search for renewable energy alternatives to fossil fuels and the EU policies supporting these efforts to decarbonise member states' economies. Using renewable hydrogen in the economy can significantly reduce the effects of global warming. According to the European Commission's 2020 Communication, "Hydrogen Strategy for a Climate Neutral Europe", renewable energy sources could make up a significant portion of Europe's energy mix in 2050, of which hydrogen could account for up to 20 per cent, especially 20-50% of energy demand in transport and 5-20% in industry (A hydrogen strategy for a climate-neutral Europe…, 2020). Moreover, in July 2020, the European Commission presented a set of policy initiatives as part of the so-called European Green Deal. They set the direction of the energy transition for all EU member states.

The European Green Deal aims to reduce greenhouse gas emissions by at least 55% by 2030 (compared to 1990) and achieve climate neutrality (i.e., net-zero emissions) in the EU by 2050. With these goals in mind, hydrogen is gaining increasing interest in this context, particularly in one of the nine types mentioned (grey, blue, white, black, turquoise, yellow, brown, and purple), as well as green, also known as renewable. It could serve as a fuel for power generation to bridge the gap between renewable energy sources (RES) and fossil fuels. The hope lies in its potential for decarbonization. Interest in green hydrogen also stems from a forward-looking vision of achieving energy security and independence from fossil fuels and the atom. Green hydrogen is produced by electrolysis of water using renewable energy. It can also be produced through biogas reforming, a biochemical conversion process that utilises biomass. It is considered an integral part of the European Green Deal, an element designed to fill the gap left by the gradual decline of the market for oil, natural gas, and coal. Hydrogen has been successfully utilised for several years as a fuel in various technological and propulsion applications. It is among the lightest gases known. The density of hydrogen is less than that of air. This means it can lift a balloon filled with it upwards. The calorific value of hydrogen is very high. It amounts to 33.3 [kWh/kg]. By comparison, the heating values of gasoline or natural gas are 12.0 [kWh/kg] and 10.6-13.1 [kWh/kg], respectively. An additional advantage of hydrogen is that it is currently the cleanest propellant. Only water is produced when electricity is generated using hydrogen for propulsion ($2H_2 + O_2 = 2H_2O$). Hydrogen, also used in a fuel cell (hydrogen cell), is characterised by high combustion efficiency, lack of vibration and quiet operation. Current technology allows vehicles to be powered by hydrogen fuel. Thus, the drive is distinguished by:

- Hydrogen cells can produce electricity for electric drive units. Thus, the cell can be a stand-alone power source for an electric motor.
- Internal combustion hydrogen engine. This suitably prepared engine runs solely on hydrogen and ethylene (gasoline).

As early as the late 1990s, developments in the application of hydrogen engines were tested and developed, among others, by the German company MAN with its H 2866 UH design. Today, much of the related work has been discontinued, with a focus on developing hydrogen cells that complement electric motors. It is worth noting that the production of green hydrogen remains more expensive than its fossil counterpart, grey hydrogen. To bridge this gap, the European Commission has launched a support mechanism. This pilot action allows hydrogen producers to apply for a fixed bonus for each kilogram of hydrogen produced. The maximum rate of the said bonus has been set at 4.5 euros/kg H2 (Helbin, 2023).

The EU's hydrogen strategy, released in July 2020, assumed the installation of RES-powered electrolysis in the European Union by 2030. These could produce up to 10 million tons of renewable hydrogen. The May 2022 REPowerEU plan aims to produce renewable hydrogen within the EU. It also formulated an additional target to ensure that 10 million tons of renewable hydrogen are imported into the EU by 2030. On September 14, 2022, the President of the European Commission announced the establishment of the European Hydrogen Bank (EHB), the main objective of which is to support the production of renewable hydrogen in the EU as well as its import into the EU and thus contribute to the construction of the EU hydrogen economy and the achievement of the goals set out in the EU's climate policy. March 16, 2023. The Commission presented a detailed communication, "A Hydrogen Strategy for a Climate-Neutral Europe" (2020).

It was noted that the European hydrogen market has four main investment challenges. The first is to increase the production capacity of electrolysis. The next is related to improving the new hydrogen production capacity. The third challenge will be to open up new sectors of demand for renewable and low-carbon hydrogen. The fourth and final step is the development of a hydrogen infrastructure specifically designed for the technology. Additional needs include meeting the demand for renewable energy, characterised by intermittent operation, and reconciling variable hydrogen production with technological processes in industries where hydrogen is already being used. These include refineries or chemical plants with high-volume installations characterised by high inertia. Maintaining feedstock availability is therefore critical to their operating costs and long-term reliability.

Forecasting a future in hydrogen can also be seen in the new policies of countries with vast oil reserves and one of the world's leading energy industries, such as Saudi Arabia, which is moving towards a low-carbon economy. Over the past decade, the country has promoted low-carbon development through local, regional, and global initiatives. Under the Vision 2030 strategy, the government aims to generate 50% of the country's electricity from renewable energy sources by 2030. In 2020, the country launched a national hydrogen strategy, aiming to become a major exporter of this fuel (Ali et al., 2023; Müller et al., 2024).

1. Research gap and questions

Searching two primary databases, Web of Science and Scopus, one can also observe a substantial increase in interest in hydrogen in the literature. Especially in 2021, there has been an enormous increase in published articles on this topic. Narrowing the topic to the use of hydrogen in mobility, particularly in the context of hydrogen propulsion for passenger vehicles, the journal publications focus on the technological aspects of hydrogen production and storage. Therefore, the question was asked about the real potential of this technology's development in people's mobility. Some publications begin with the enthusiastic statement that "hydrogen technology is developing rapidly" (Alanne, Cao, 2017) and hydrogen has emerged as a possible transportation fuel for addressing long-term, sustainable energy supply, security, and environmental problems (Meyer, Winebrake, 2009). Nevertheless, most attention in the scientific literature is devoted to developing this technology in the fields of hydrogen production, storage, and transportation (Dubent, Mazard, 2019; Pimenta Alves et al., 2022; Saldan, 2016; Sinigaglia, 2017). The literature primarily highlights the challenges in establishing the infrastructure for hydrogen refuelling points.

Incidents of explosions at such stations are recalled, which also affect public perception and the interest of potential consumers in this technology. However, a vehicle infrastructure system must be developed to discuss the penetration of hydrogen vehicles into the transport market. Hydrogen vehicles and the infrastructure required to operate them, such as refuelling, are complementary goods that need to enter transport markets to discuss the success of technology deployment (Meyer, Winebrake, 2009). Scientific research focuses on identifying suitable materials for producing tanks and on developing devices that enable hydrogen refuelling on a commercial scale (Genovese, Fragiacomo, 2023). Unfortunately, due to the high pressure required (30-70 MPa) and low temperature (-253 °C), existing and developing methods for hydrogen storage are highly energy-intensive (Pawelczyk et al., 2022). Another critical limitation to the development of this technology is its production, which requires high energy and the consumption of fossil fuels, mainly natural gas. Using hydrogen to produce energy in transport vehicles is environmentally friendly, but obtaining hydrogen is not. Therefore, to develop this technology, ecological technologies on an enormous scale are being sought (Pedicini et al., 2023; Singh et al., 2015; Yang et al., 2023). All these aspects contribute to the worst result of hydrogen as a sustainable solution (Müller et al., 2024).

Considering the above EU strategic demands, the ecological potential of hydrogen as a fuel for transportation, and the simultaneous controversies surrounding issues with its production and storage, the commercial potential of hydrogen-fuelled cars remains a perpetual question. Can the interest in this technology grow sufficiently, and if so, when will it capture the early majority of the market? When can we expect hydrogen to gain a significant market share in the mobility sector? Hydrogen technology, as an innovation, is a potentially interesting case study for research in innovation diffusion. However, the literature lacks attempts to estimate the time required for hydrogen technology to reach the mass user level and to model its development. The topic is practically not discussed. Filling this gap in the discussion, this article proposes an analysis of the possibilities for the diffusion of hydrogen innovations in the passenger vehicle market in the EU. It compares it to the time horizon of the EU's hydrogen mobility policy.

2. Methodology

An analysis of the literature on forecasting models for the technology market revealed a scientific paper with a detailed review of deterministic models that describe the accumulation of adoption (Meade, Islam, 2006). The cited volume reviews 24 different S-shaped models: Bass, Gompertz, Logistic, Log-logistic, Log Reciprocal, Ali-Schaeffer, Bridges, Hill, Hossfeld, Janoschek, McDill Amateis, Morgan-Mercer-Flodin (M-M-F) I and II, Levakovic I, Levakovic III, Lundqvist-Korf, Richards, Schnute, Sloboda, Stannard, von Bertalanffy, Yoshida, Weibull, ZengWan, and Growth models. To predict the commercialisation of hydrogen technology, all the models were used, but the outcome was interpreted using the Bass model. Using the Bass diffusion model to forecast the development of new technologies is a prevalent approach. This is particularly true in areas related to new technological developments in the energy field. Frank Bass, an American economist, developed a quantitative diffusion model in 1969, based on Rogers' analysis, to forecast future sales of marketed products. The choice of the Bass model is due to its widespread recognition and citation, as confirmed by literature sources (Bass, 2004). It is often used in conjunction with so-called logistic and Gompertz forecasts. A characteristic feature of the Bass model is its universality, which is confirmed by many applications in forecasting sales volumes of new products regardless of variables such as advertising or price. The usual forecasts based on the Bass model are the most pessimistic (Bauckhage, Kersting, 2014), which provides an additional argument for its selection. Another important aspect is the duality of the model with the Rogers model. In his work, Rogers proposed specific names for each group of technology users (Rogers, 1962). The Bass model, along with Rogers' interpretation, plays a crucial role in evaluating the innovation process, which is why the authors of this publication employed it as an analytical tool to predict the size of the hydrogen car market. The cumulative Bass model can be written in the form:

$$F(t) = m\frac{1 - e^{-(p+q)t}}{1 + \frac{q}{p}e^{-(p+q)t}}$$

which represents the current total number of vehicles on the market, where *m* – the total final number of hydrogen car users, *p* – the innovation coefficient, and *q* – the imitation coefficient (Bass, 2004; Brdulak, Chaberek, Jagodziński, 2021).

The market growth forecast was made based on hydrogen vehicle volume data from the European Alternative Fuels Observatory (EAFO) (European Alternative Fuels Observatory, 2023). The EAFO databases are one of the most relevant sources of data on the development of the alternative vehicle market. According to the EAFO website (European Alternative Fuels Observatory, 2023), the organisation compiles data from, among others, Eurostat, the European Commission's Mobility and Transport Directorate, ELTIS - The Urban Mobility Observatory, the European Environment Agency, and several governmental and non-governmental organisations. The data undergoes a rigorous validation process, and monthly and quarterly data are made available approximately 45 days after the end of each month or quarter. The unit of measure for EAFO data includes the total number of alternatively fueled vehicles, calculated based on both all existing registrations and newly registered vehicles (EAFO Annexe III, 2023).

3. Estimation of the hydrogen vehicle market

A forecast was made for Europe, using 24 different S-shaped models[1]. It should be noted that the data used for forecasting represent very short time series. This makes it very challenging to obtain a relevant forecast. S-shaped models perform best when the data exceeds the inflexion point of innovation development. In the case analysed, the technology is at such an early stage that only some of the models yielded a sufficiently high coefficient of fit between the model and the data, as indicated by the R-squared value. In addition, some of them did not allow the parameters to be calculated at all. The nonlinear least squares method did not return correct results due to numerical errors. Therefore, out of nearly 24 models, as many as 15 were rejected.

The models for which the calculations were relevant are presented in Table 1 and Figure 1. For model comparison, the Akaike information criterion (AIC) was used. The relative likelihood of model i is defined as the quantity

$$exp\left((AICmin - AICi)/2\right)$$

The final value of the hydrogen vehicle market in Europe, based on the calculated models, is also shown, along with the year of stabilisation, the point at which the growth curve does not change by more than 100 vehicles per year.

Table 1 indicates that the first four models are the best in terms of the information loss criterion. This shows that the development of this technology has been effectively halted. This is because, in some countries, no new hydrogen vehicle was registered in 2023 (Denmark, Germany, Norway), and practically all countries recorded a decline in sales. The study results indicate that the technology has stalled among the group of innovators and has not yet been adopted by early adopters (compare Rogers' model). Table 1 shows that for the most significant models, technology is expected to plateau at around 6,000 and will not develop further. More optimistic models indicate target market values of around 30,000. The trends indicated by the models presented may naturally change if additional factors arise.

Figure 2 and Table 2 present the development of the hydrogen vehicle market for selected countries based on the Bass model, which has well-established theoretical parameters: the innovation coefficient p

[1] The details of the simulations performed and the methods chosen are beyond the scope of this article and would require a more detailed presentation.

Table 1 Comparison of selected parameters of estimated S-shaped models for the development of the hydrogen vehicle market

Model	AIC	Relative likelihood	Final market value	Standard Error	P-Value	Year of stabilisation
Richards	205.373	1.	5618.39	583.715	$5.403\ 10^{-7}$	2027
Logistic	207.356	0.37097	6363.12	502.151	$1.085\ 10^{-8}$	2029
Bass	207.362	0.369785	6369.02	507.378	$1.215\ 10^{-8}$	2029
Janoschek	209.862	0.105956	5610.41	448.957	$3.074\ 10^{-8}$	2027
Gompertz	214.139	0.0124876	11508.	3449.64	0.005363	2039
Log Reciprocal	214.854	0.0087334	136876.*	**	**	∞
Lundqvist-Korf	215.903	0.0051684	32710.5	31329.	0.315468	2082
Weibull	217.897	0.0019073	26623.2	**	**	2071
Ali-Schaeffer	223.432	0.0001198	∞***	**	**	∞***

* Limit value at infinity.

**In the model, the final market value is not a parameter, therefore there is no error estimation.

*** The model does not have a finite limit of market value.

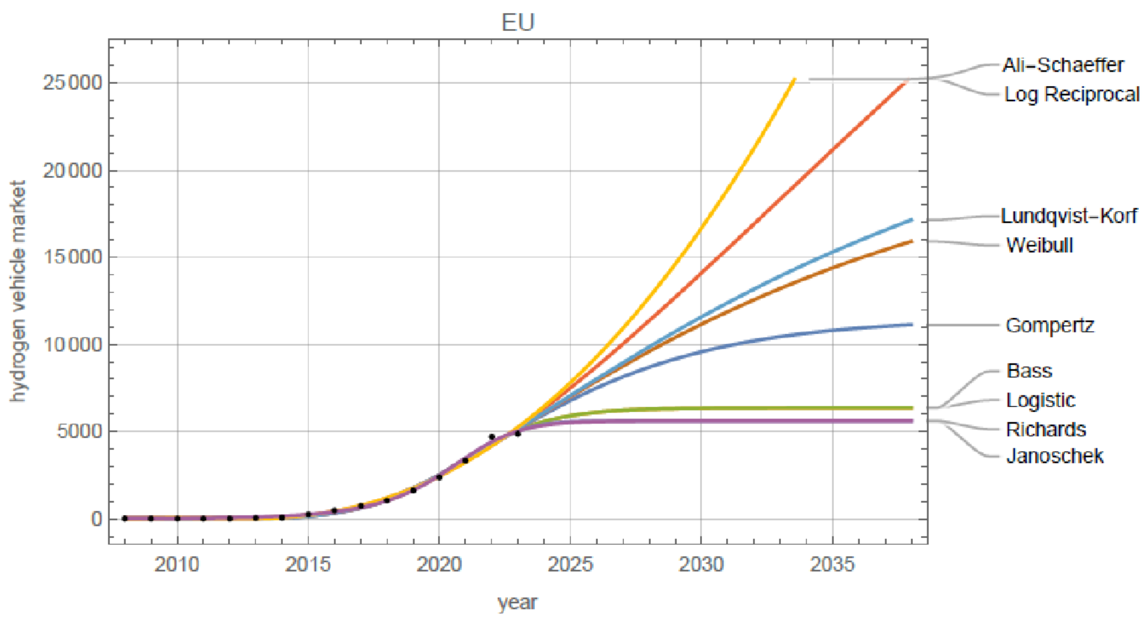

Figure 1. Selected unconstrained S-shaped models for the development of the hydrogen vehicle market.

and imitation coefficient q. In this case, Bass's model is in a way privileged over the other models. The p and q coefficients are evaluated from the perspective of similar previous technologies. Therefore, even in cases of poor estimates, the decision maker can apply these coefficients based on historical knowledge rather than the model's fit quality. Thus, the p coefficients are usually very small, while q is in the range of 0.4-0.8. Hence, in the authors' assessment, the data in Table 2 are appropriate due to the high R^2, low P-value, and additionally due to the meaningful context of knowledge about historical technologies. The values presented in Table 2, along with the final market value and adjusted R-squared coefficient, have been supplemented with P-values, facilitating model evaluation.

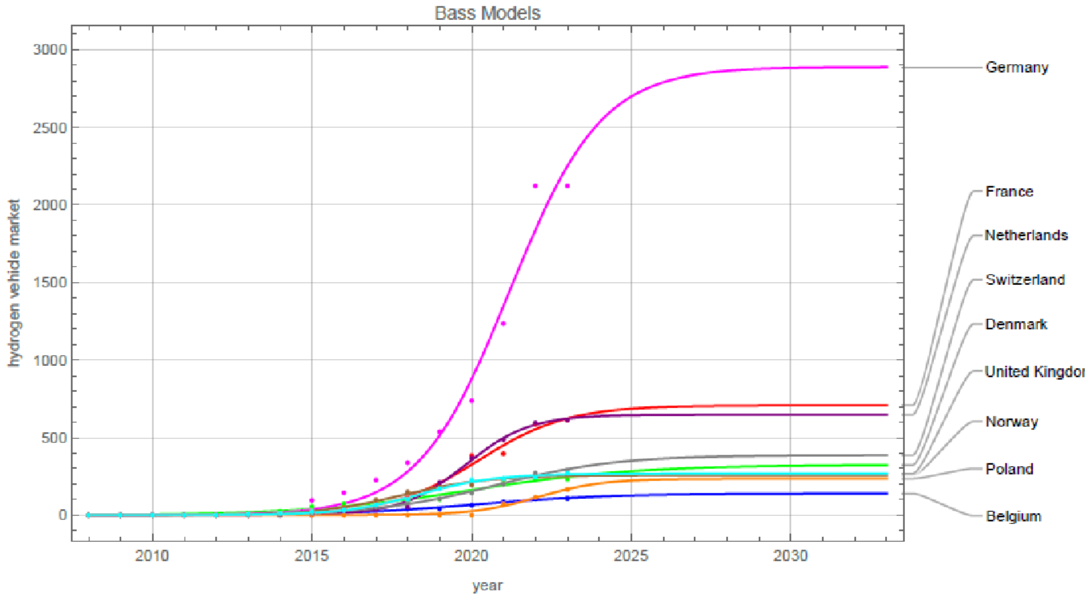

Figure 2. Bass model estimation for selected European countries (with more than 100 hydrogen vehicles).

Table 2. Bass model estimation for selected European countries (with more than 100 hydrogen vehicles)

Country	Adjusted R-squared	Innovation coeff. (p)	P-Value for p	Imitation coeff. (q)	P-Value for q	Market size (m)	P-Value for m
Europe	0.995661	0.0001649	0.05536	0.59654	4.49 10^{-8}	6369.02	1.22 10^{-8}
Belgium	0.991295	0.0008448	0.05172	0.480855	3.99 10^{-6}	139.44	1.14 10^{-6}
Denmark	0.98026	0.0026619	0.05620	0.379513	0.000735	325.32	0.000561
France	0.989251	5.242 10^{-5}	0.32739	0.720687	5.80 10^{-6}	708.62	3.08 10^{-8}
Germany	0.984484	3.520 10^{-5}	0.41006	0.69722	0.000050	2887.96	0.000024
Netherlands	0.997495	2.740 10^{-6}	0.19427	1.	1.27 10^{-9}	648.98	8.46 10^{-15}
Norway	0.995501	0.0002183	0.11786	0.752422	6.00 10^{-8}	257.12	6.75 10^{-14}
Poland	0.972493	2.790 10^{-7}	0.72938	1.	0.001084	235.08	0.002022
Switzerland	0.995487	0.0003531	0.02626	0.530708	7.34 10^{-8}	387.77	7.14 10^{-8}
United Kingdom	0.997359	5.767 10^{-5}	0.09547	0.844697	2.29 10^{-7}	267.47	1.78 10^{-15}

*Constrained Bass model $0 \leq q \leq 1$

Table 2 shows that Germany has experienced the most significant growth, accounting for one-third of European hydrogen vehicle development, according to current data. In terms of predictive value, however, Bass's model works best for the Netherlands and the United Kingdom.

5. Discussion

As mentioned, there is little discussion in the literature on estimating the mass commercialisation of hydrogen technology. Bogel et al. (2018) analysed the implications of previous attitudes for public communication campaigns on hydrogen technologies in Europe.

The results of a public opinion survey conducted in seven EU countries indicate a low level of strength and stability of attitudes towards hydrogen fuel cells in both stationary and mobile applications. They also highlight differences between countries. Communication campaigns can be a valuable tool at this early stage of hydrogen technology development, raising awareness among people with limited knowledge and positively influencing attitudes towards the technology. However, attention should be paid to the need to adapt these strategies to the greater dynamics of hydrogen technology deployment in the future.

According to Rogers, at the early stage of technology development, innovators are the first to purchase it, for whom the prestige of the technology, resulting from its novelty, is the most essential factor. They are wealthy and risk-takers. Only in the mass customer group are low costs and efficiency the most important factors. Meanwhile, the European Union's strategic communication already emphasises the low price and usefulness of this technology at this stage. Therefore, the public message is inappropriate for innovators, who are essential for attracting early adopters and the early majority. The Bogel team (2018) recommends regular monitoring at the individual country level, reflecting differences between countries in the degree of hydrogen technology deployment.

The discussion should also consider the market situation in Europe in 2023, as its impact is evident in the spread of the technology under analysis. An analysis of the market's stagnation points to a combination of technological, infrastructural, and political factors. These have slowed down the pace of diffusion of hydrogen innovations in transport.

In addition to economic stagnation in the European market, the high cost of fuel cells is a significant barrier to the widespread adoption of hydrogen technology. Despite advances in durability and efficiency, they remain several times more expensive than conventional combustion engines and competitive battery drives (Pedicini et al., 2023). The high price of hydrogen vehicles, primarily due to the cost of fuel cells and hydrogen storage systems, makes this technology only attractive to a small group of innovators. The lack of economies of scale results in a vicious circle. Limited production keeps prices high, and high prices limit demand (Bauckhage, Kersting, 2014).

Another barrier is the insufficiently developed network of hydrogen refuelling stations. This phenomenon is complementary in nature. The development of the vehicle market requires accessible infrastructure, and investments in infrastructure are only justified if there is a sufficient number of vehicles (Meyer, Winebrake, 2009). In 2023, no new hydrogen cars were registered in selected EU countries, including Germany, Denmark and Norway. Additionally, some stations have reduced their operations due to high operating costs and safety concerns (Genovese, Fragiacomo, 2023). Incidents such as leaks and explosions also have a negative impact on public perception of the technology (Bogel et al., 2018). Consumers who perceive hydrogen refuelling as risky and inaccessible are less likely to consider purchasing a vehicle.

Political and regulatory uncertainty can also be identified as a significant source of stagnation. Despite the ambitious goals of the EU hydrogen strategy and the establishment of the European Hydrogen Bank, real support instruments remain limited and scattered (Helbin, 2023). Subsidies granted to hydrogen producers and planned vehicle subsidy programmes vary from country to country. They often encounter bureaucratic barriers. There is also a lack of a coherent communication narrative. According to Bogel et al. (2018), the message focusing on the low cost and usefulness of the technology is premature. At this stage, it would be worthwhile to emphasise prestige and innovation – key elements from the perspective of market pioneers. As a result, potential innovators and early adopters are not receiving adequate motivation to purchase.

The year 2023 can therefore be seen as the moment when the potential of the technology collided with economic and institutional barriers. Bass's model suggests that diffusion halted at the innovator stage, without progressing to the adoption phase among early adopters (Rogers, 1962; Brdulak, Chaberek, Jagodziński, 2021). In practice, this may mean the risk of getting 'stuck in the valley of death' of technology, where further development requires not only technical progress but also systemic intervention. The lack of a quick response from public policy may postpone the moment of reaching critical mass adoption by years or even decades.

Comparing the results achieved in Europe with those in non-EU markets may provide a better context for understanding the reasons behind delays in implementing hydrogen technology. While 2023 saw stagnation in Europe, resulting in declining sales and a lack of new registrations (European Alternative Fuels Observatory, 2023), this technology developed at a more varied pace in leading non-EU markets such as Japan, South Korea and the United States.

Japan remains the leader in the implementation of hydrogen cars, as evidenced by the thousands of Toyota Mirai and Honda Clarity models sold. The country has been investing in a network of refuelling stations for years, creating coherent infrastructure corridors (Jiang et al., 2025; Sinigaglia et al., 2017). Thanks to consistent government policy and subsidies, the Japanese market has entered the early adopter phase. South Korea has adopted a similar strategy. The government plans to establish 2,000 hydrogen refuelling stations by 2050 (Choi, Bhakta, 2024). This initiative is part of a broader strategy to develop the hydrogen economy, involving significant investments from industrial companies such as Hyundai Motors Group (Stangarone, 2021). In the US, although development is more uneven and concentrated mainly in California, there has been steady growth in the number of vehicles, supported by local subsidy programmes and restrictive emission standards (Meyer, Winebrake, 2009).

Meanwhile, Europe is struggling with fragmentation. Despite the ambitious goals of the European Green Deal and plans to produce 10 million tonnes of green hydrogen by 2030, real progress is slower (A hydrogen strategy for a climate-neutral Europe…, 2020). The lack of a uniform support mechanism for consumers and the limited number of stations mean that the market is still in the innovator stage (Brdulak, Chaberek, Jagodziński, 2021). This situation is exacerbated by regulatory diversity. Different forms of support are being implemented in individual Member States, which makes it challenging to create a coherent market offering.

Saudi Arabia represents a slightly different context. As an exporter of fossil fuels, it sees hydrogen as a future source of export revenue. The country is implementing megaprojects, such as NEOM, where the production of green hydrogen on a global scale is planned (Ali et al., 2023; Boretti, 2024; Müller et al., 2024). A similar approach is being taken by Australia and the United Arab Emirates, which see hydrogen as a strategic raw material for economic diversification.

The available data, therefore, indicate that there are examples outside Europe of successful transitions to the subsequent stages of hydrogen technology diffusion. In the EU, despite greater determination in strategic terms, practical implementation is slower. The lack of widespread adoption of vehicles is currently due to both costs and insufficient synchronisation of transport and energy policies.

It could be argued that if Europe does not accelerate infrastructure development and coordinate support systems, there is a risk of a permanent lag behind non-EU leaders. On the other hand, the lack of equally intensive activities in some regions of the world (e.g. Latin America, Africa) confirms that the barriers to adoption are global in nature and result from similar technological and economic conditions.

6. Conclusion

The forecast based on Bass's methodology shows that despite advances in hydrogen technology in passenger cars, valuable (realistic) forecast results cover a horizon of two to three years. Due to the format and volume of the publication (scientific article), confidence intervals were not assessed for all models. The current market penetration of hydrogen-powered vehicles remains negligible, accounting for approximately 0.0246% of all alternative fuel vehicles. The authors' simulation of the projected share of the cars mentioned above in the alternative fuel vehicle market in 2030 indicates a slight increase in the share of hydrogen-powered vehicles to 0.0354%. The introduction of hydrogen-powered cars to the market presents two key challenges: technological issues and effective market communication. The three main technical aspects are the high cost of hydrogen production, high storage costs and inadequate refuelling infrastructure.

It is worth noting that the forecasts are based on current knowledge and advancements in technology. Intensive work on enhancing the efficiency and durability of fuel cells could lead to the development of more efficient powertrains and their widespread adoption in everyday life. Furthermore, although most of the hydrogen currently produced comes from natural gas, research is ongoing into alternative sources of hydrogen, such as water electrolysis using renewable energy, which could help to reduce greenhouse gas emissions associated with hydrogen production. As these efforts progress, hydrogen technology can be expected to become more competitive in the passenger car market. As a result, the number of hydrogen-powered vehicles is expected to increase. This is a key direction in the context of global policy goals aimed at reducing air pollution and greenhouse gas emissions.

In this context, an attempt can be made to formulate policy recommendations – actions that would ultimately contribute to accelerating the commercialisation of hydrogen technology in Europe:

1) Targeted investment subsidies – in this case, support should cover not only hydrogen and vehicle manufacturers, but also end users. Subsidies for the purchase of hydrogen cars (similar to subsidies for electric vehicles) could increase demand and stimulate economies of scale (Helbin, 2023).
2) Creation of infrastructure corridors – instead of scattered construction of individual stations, it would be worthwhile to develop a project for transport routes (e.g. TEN-T corridors) that would provide drivers with certainty of access to refuelling on major roads (Genovese, Fragiacomo, 2023). This approach would reduce user risk and increase the attractiveness of vehicles.
3) Integrated regulatory support – it is necessary to harmonise technical and legal standards across the EU. Discrepancies in funding levels and safety regulations make it difficult for manufacturers to scale their businesses. The European Hydrogen Bank could act as a coordinator of national activities.
4) Fuel cost reduction mechanisms – in the initial phase of development, the market requires subsidies for green hydrogen production in order to bring its price closer to that of competitive fuels (A hydrogen strategy for a climate-neutral Europe…, 2020). The Contracts for Difference system can be an effective tool in this regard.

5) Public communication and education – according to the recommendations of Bogel et al. (2018), it is necessary to adapt the narrative to the target groups. For innovators and early adopters, prestige and innovation are more important than low price. Appropriate campaigns could increase public acceptance and improve the safety image of the technology.
6) Integration of transport and energy policies – the development of hydrogen mobility needs to be synchronised with plans for the development of green hydrogen production and storage. Only then will it be possible to ensure stable fuel supplies and gradually reduce costs.

The above considerations demonstrate that the development of hydrogen technology in transportation requires multi-level actions that combine financial support, infrastructure development, regulatory stability, and informed communication. If such recommendations were implemented over the next few years, Europe would have a real chance of avoiding marginalisation relative to non-EU leaders and accelerating the transition to low-carbon mobility.

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