THE ROLE OF HYDROGEN IN URBAN MOBILITY

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Executive summary

In Europe, initiatives such as the EU's European Hydrogen Strategy and the Sustainable and Smart Mobility Strategy signal the centrality of hydrogen for tomorrow's economy. In this context, EIT Urban Mobility partnered with Eurecat, the technology centre of Catalonia, to better understand the implication of this transition in the transport sector in general and in urban mobility in particular.

The present study **aims to identify the main use cases for hydrogen in urban mobility**, considering aspects such as competitiveness, market size, and investments needed per segment of the value chain. It looks at both the infrastructure and vehicle dimension and as such provides insights into the implications of transitioning to hydrogen in the transport sector.

Thanks to literature review, stakeholder engagement via EIT Urban Mobility's Special Interest Group on energy, and interviews with practitioners, **the study combines three complementary approaches to fulfil its objectives**: it identifies the subsectors with the greatest potential for hydrogen within urban mobility ecosystems; it evaluates market opportunities for each subsector; and it looks in detail at the value chain enabling the different subsectors. The main findings are summarised below:

- The high costs of renewable hydrogen production and the current maturity-level of fuel cell technology are **hampering hydrogen scaling and implementation**. Accordingly, public funding (EU and member states) for RD&D in hydrogen and fuel cell technologies is expected to grow from €5,6bn to €18bn.

- Given the limited industrial interest in fuel cell vehicles (FCVs), the lack of infrastructure and high associated costs, widespread deployment of FCVs in the passenger car segment is unlikely. **FCV deployment may rather occur on segments such as trucks and commercial vehicles**: by 2030 these markets are expected to be quite balanced between hydrogen-powered and battery electric vehicles, with hydrogen trucks expected to represent a €13bn market in Europe. In a similar vein, the **hydrogen bus market is expected to grow steadily in the coming years**, although market size forecasts for this segment strongly vary.
- To cater for this demand, **the market for hydrogen refuelling stations (HRS) is expected to grow until 2030**, although with a significant uncertainty as to its total market size (estimated between €151M to €495M). This will ultimately depend on the speed of HRS deployment across Europe.
- With multiple sectors electrifying across the economy, energy storage with batteries or hydrogen is poised to become even more important in years to come. In fact, the market for **hydrogen storage and distribution systems in Europe is expected to reach an estimated €10bn by 2030**.

Based on the key findings above, it appears that **a conducive policy environment** can facilitate the uptake of clean hydrogen solutions for transport , for instance by **facilitating HRS implementation** and establishing clear, distinctive rules that prioritise hydrogen produced from renewable energy sources over non- renewable hydrogen.

Public-private partnerships are required to unlock targeted investments that can accelerate the establishment of a comprehensive refuelling infrastructure network. To optimize hydrogen production technologies and make them cost-effective and sustainable, collaborative research and development efforts are essential. These initiatives should focus on enhancing the **scalability, efficiency, and environmental sustainability** of hydrogen production methods.

Overall, segments with the highest potential for hydrogen in (urban) mobility turn out to be **public transport** - mainly buses – as well as **logistics trucks and commercial delivery vehicles**. In contrast, the value proposition of hydrogen cars and hydrogen-powered trains and trams **fail to match the efficiency exhibited by electric cars and trains**. The analysis shows that facilitating the uptake of hydrogen in urban mobility is not a linear process. **It requires cross sector collaboration** to ensure informed public participation, targeted safety communications, strategic infrastructure development and a strong supply chain. **More research and development is needed** to address the main disadvantages of hydrogen fuel cells, such as the cost of (green) hydrogen production, transportation, storage, and distribution.

Introduction

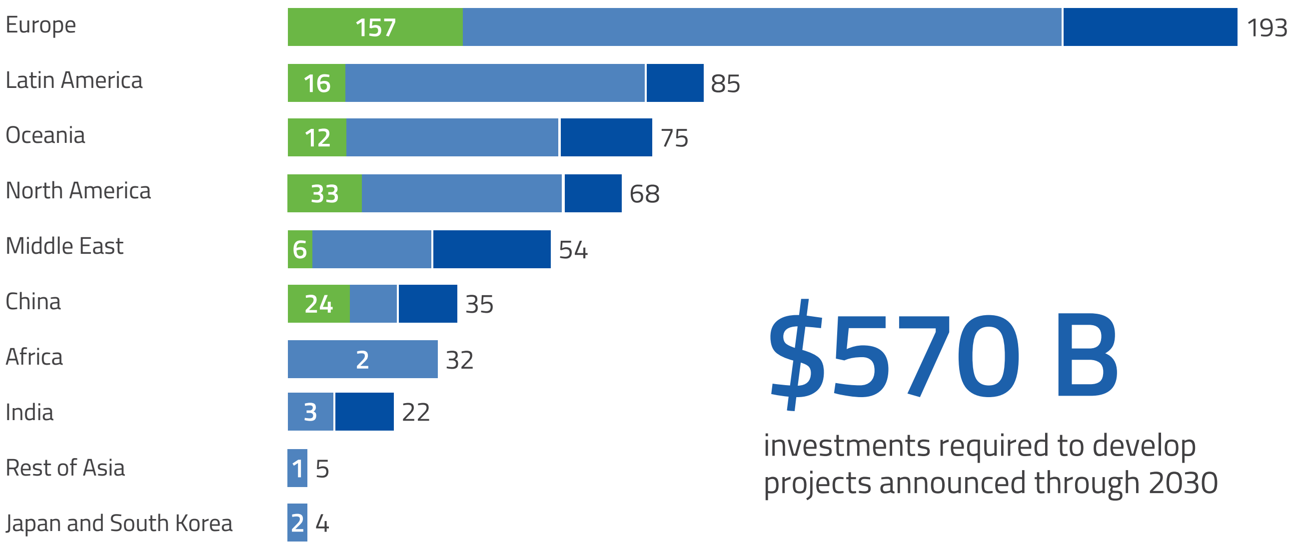
A. Background

As the transport sector in the European Union and globally needs to decarbonise, alternatives to fossil fuels such as hydrogen have increasingly been in the spotlight. In the current political and economic context, innovation around hydrogen applied to mobility has become a strategic priority for many countries and organizations as shown by the International Energy Agency (IEA) or International Renewable Energy Agency (IRENA). In this study, we take a closer look at the use cases and relevant appliances for hydrogen in urban mobility.

In this context, it is critical to understand the political and economic landscape driving innovation around hydrogen in mobility, and how this may influence the adoption and deployment of these solutions in the future. EIT Urban Mobility, as an initiative of the European Institute of Innovation and Technology (EIT), facilitates collaboration between cities, industry, academia, research and innovation and puts urban mobility challenges at the centre of its activities. In 2022, it has set up an expert group (Special Interest Group, SIG) composed of public and private sector practitioners to discuss the role and perspectives for hydrogen in urban mobility. In September 2023, EIT Urban Mobility organised a workshop with 19 participants to collect insights for this study. In addition, Eurecat conducted ten interviews with experts to gather further data and information about the role of hydrogen in urban mobility.

Governments and international organizations are promoting the transition towards a low-carbon economy and supporting the development of hydrogen technologies. This is reflected in the implementation of policies, regulations, and financing programs that seek to drive the adoption of hydrogen vehicles and associated infrastructure.

Globally, the industry has announced 1,418 (256 are mobility projects) clean hydrogen projects as of October 2023



Source: Project & Investment tracker, as of Oct 2023

Figure 1. Project and Investment tracker (Oct 2023).

Hydrogen is a versatile and clean energy carrier that can be produced from a variety of renewable sources such as solar, wind, and hydroelectric power, as well as from non-renewable sources like natural gas through reforming processes. It is an efficient energy storage vector, making it an attractive option for storing intermittent renewable energy for use when needed. Additionally, hydrogen can be transported and distributed through existing infrastructure such as pipelines and tanker trucks, facilitating its use in a wide range of industrial and consumer applications.

The EU Hydrogen Strategy posits that hydrogen represents a promising alternative within the domain of transportation, especially in cases where electrification encounters practical challenges. In essence, this perspective reflects a preference for the electrification of vehicles, with hydrogen reserved for scenarios where electrification is not the most feasible solution.

From an economic point of view, hydrogen applied in mobility opens new opportunities for job creation, the development of new industries and the promotion of competitiveness in the global market. In addition, it is expected that the production and use of renewable and low-cost hydrogen can play a fundamental role in diversifying the energy matrix and reducing dependence on fossil fuels.

B. Objectives

The study aims to:

- Identify the main use cases for hydrogen in urban mobility and their implications for a local value chain and stakeholders.
- Evaluate the technology's opportunities linked to competitiveness and vehicle innovation and identify regulatory and societal bottlenecks for wider deployment in cities and metropolitan areas, including their hinterland.
- Evaluate the required magnitude of investments needed for hydrogen infrastructure deployment in urban areas by 2030 in different scenarios and evaluate the energy needs and CO_2 emission reduction potential of the different uptake scenarios.
- Understand the implications of shifting to H2 buses for infrastructure planning at city level.

C. Methodology

The study uses a mixed-methods approach applied to different representative selected cases studies, that combines qualitative and quantitative data collection and analysis techniques.

Throughout the study, three approaches are developed to cover the entire ecosystem affected by the role of hydrogen in urban mobility. The **three approaches** have many points in common and allow to obtain an in-depth analysis of all stakeholders, sectors, sub-sectors, organisations, and stakeholders relevant to the hydrogen (urban) mobility supply chain.

- The first thread will be the subsectors with the greatest **potential** within the urban mobility ecosystem. Based on the meta-study of numerous reports, the systematic analysis of technologies and the market, seven potential topics were listed.
- The next thread that has been used is the **economic-market** one; The main existing market segments in the combined field of hydrogen and urban mobility have been analysed, resulting in six market opportunity niches.
- The third thread is the analysis of the ecosystem through the detailed development of the **value chain** structured in five links.

1 The role of hydrogen in urban mobility today and tomorrow

This section focuses on the role of hydrogen in urban mobility, exploring its potential to transform the way we move in our cities.

The following subsections analyse the hydrogen strategies adopted at global and European level, the current role of hydrogen in urban mobility, and how it compares with electricity as an energy source for urban mobility. This part also examines the infrastructure required for hydrogen, the hydrogen value chain in urban mobility, and the opportunities that the technology offers to improve and expand the use of hydrogen in urban mobility.

1.1 EU hydrogen strategies

The European Union (EU) hydrogen strategy[1], adopted in 2020, has become a concrete policy framework through the Fit-for-55 package presented in July 2021. This legislative package translates the original strategy into specific actions and proposals for the adoption of renewable hydrogen in industry and transport until 2030 [1].

The EU's comprehensive approach covers key areas, including investment support, promoting hydrogen production and demand, establishing a dedicated market and infrastructure, as well as coordinated efforts in research and international cooperation.

Financial support at European level is manifested through the NextGenerationEU recovery plan, enabling investments in hydrogen projects across the value chain. Furthermore, specific investment support has been provided through Important Projects of Common European Interest (IPCEI) on hydrogen, such as the IPCEI Hy2Tech[2], which seeks to decarbonize industrial processes

[1] European Commission. (2020). *A hydrogen strategy for a climate-neutral Europe.* Available at: EUR-Lex - 52020DC0301 - EN - EUR-Lex (europa.eu)

[2] European Commission. (2022). *Remarks by Executive Vice-President Vestager on Important Project of Common European Interest in the hydrogen technology value chain.* Available at: Remarks by Executive Vice-President Vestager (europa.eu)

and mobility, and the subsequent IPCEI Hy2Use[3], focused on infrastructure and integration of hydrogen in industry.

The Commission has also strengthened the policy framework by creating the Clean Hydrogen Partnership in November 2021, successor to Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU), dedicated to supporting research and innovation in the hydrogen ecosystem.

The regulatory framework has been further consolidated with the formal approval, in June 2023, of two delegated acts[4] applicable to renewable hydrogen under the 2018 Renewable Energy Directive. These acts address renewable fuels of non-biological origin (RFNBO) and set out criteria for "renewable hydrogen", as well as detailed schemes for calculating life cycle emissions, thus strengthening the EU's commitment to a transition towards a more sustainable hydrogen economy. In this context, several low-carbon production technologies are being considered, mainly focusing on electrolysis.

1.1.1 Drivers of the European hydrogen strategy

The deployment of technologies for low-carbon hydrogen production has featured prominently in government strategies, with electrolysis being the dominant technology featured in the targets. The European Union adopted targets to deploy electrolysis capacity of 40 GW[5] by 2030. Many countries in the European Union have adopted national targets, which represent between 70% and 75% of the EU Hydrogen Strategy target[6]. While individual countries are making substantial commitments to green hydrogen development, there is a need for coordinated efforts and policy alignment at the EU level to ensure that all member states collectively meet the ambitious targets set out in the EU Hydrogen Strategy.

The European Commission reinforces the EU's hydrogen strategy with the implementation of the REPowerEU[7] plan in May 2022, seeking to expand renewable hydrogen ambitions and reduce dependence on fossil fuels, especially from Russia. Through a Hydrogen accelerator[8], it is intended to produce 10 million tonnes and import 10 million tonnes of renewable hydrogen in the

[3] European Commission. (2022). *State Aid: Commission approves up to €5.2 billion of public support by thirteen Member States for the second Important Project of Common European Interest in the hydrogen value chain.* Available at: State Aid (europa.eu)

[4] European Commission. Renewable hydrogen. Available at: Renewable hydrogen - European Commission (europa.eu)

[5] The EU H2 Alliance, a public-private partnership that has identified a portfolio of projects in the European Union, announced that more than 50 GW of electrolysis could be deployed by 2030, of which 85% would be renewable. The 40 GW does not reflect the new REPowerEU targets.

[6] Including the provisional target of 5 GW of electrolysis capacity by 2030 of the Italian Hydrogen Strategy would increase this value to 83-86%.

[7] European Commission. *REPowerEU Plan.* Available at: EUR-Lex - 52022SC0230 - EN - EUR-Lex (europa.eu)

[8] European Commission. *Hydrogen accelerator.* Available at: Hydrogen (europa.eu)

EU by 2030, boosting its adoption in sectors that are difficult to decarbonize, such as transport and energy-intensive industries. The strategy highlights the expansion of infrastructure and investment support as key elements to facilitate the integration of hydrogen into the European energy matrix, positioning it as a central player in the transformation towards more sustainable energy [2] [3].

On the other hand, the deployment of hydrogen production capabilities using fossil fuels with carbon capture, utilization and storage (CCUS) has attracted less global attention [2].

Several governments have outlined cost targets for low-carbon hydrogen by 2030, ranging from $1/kg (United States) to $3/kg (Japan). The United States has initiated the Hydrogen Earthshot, with the goal of reducing the cost of low-carbon hydrogen to $1 per kg by 2030 [2].

As part of measures to accelerate the adoption of hydrogen, the European Commission has proposed the creation of the European Hydrogen Bank[9]. The communication on the European Hydrogen Bank, published in March 2023, mentions that this bank, managed internally by the Commission services, will not be a physical entity, but a financing mechanism. Its main objective is to catalyse private investments in hydrogen value chains, both nationally and internationally, connecting renewable energy supply with EU demand and overcoming initial investment challenges. The bank is expected to establish an initial market for renewable hydrogen, generating growth and employment opportunities. Thanks to pilot auctions and partnerships on green hydrogen, the aim is to promote the production and import of renewable hydrogen, thus contributing to decarbonization and guaranteeing equitable conditions between domestic production and imports from third countries.

Furthermore, the Hydrogen Energy Network positions itself as an informal group that brings together representatives of the energy ministries of the European Union countries. Its main objective is to support national energy authorities in exploring opportunities related to hydrogen as an energy vector. It functions as a platform for exchanging information, experiences, and advances in hydrogen technologies, in addition to facilitating collaboration on specific issues.

[9] European Hydrogen Bank. Available at: EUR-Lex - 52023DC0156 - EN - EUR-Lex (europa.eu)

1.1.2 EU hydrogen initiatives

The European Union has launched and supports various initiatives to boost the development and adoption of hydrogen in the region. The European Clean Hydrogen Alliance[10], launched in 2020 together with the hydrogen strategy of the EU, is a collaboration that brings together industry, local authorities, civil society, and other interested parties. It aims for an ambitious deployment of hydrogen technologies by 2030, covering hydrogen production, transport, use and distribution. It hosts key thematic roundtables and the 'Electrolyser Partnership' to boost electrolyser manufacturing in Europe.

The Clean Hydrogen Partnership[11], which operates until 2027, is a public-private partnership supported by the Commission through Horizon Europe. This partnership, building on the success of its predecessor, focuses on the research, development and deployment of renewable hydrogen technologies and is linked to the Hydrogen Valleys Platform.

The Hydrogen Public Funding Compass[12] is an online guide that facilitates stakeholders to identify public funding sources for hydrogen projects, and provides information on EU programs and funds (2021-2027) relevant to the sector. These initiatives reflect the EU's commitment to moving towards a more sustainable hydrogen economy.

1.2 Hydrogen value chain in urban mobility

Currently, more than 120 initiatives dedicated to the transmission of hydrogen, more than 50 projects focused on its distribution, and more than 60 projects focused on its storage are underway in Europe. In addition, more than 20 projects have been identified for hydrogen terminals and ports, along with more than 20 projects to meet hydrogen demand[13] [4]. In terms of production, the region is promoting more than 160 projects to generate hydrogen, marking a significant step towards a comprehensive and sustainable hydrogen infrastructure. These figures reflect Europe's active and expansive commitment to building a hydrogen value chain that spans from production to final demand [3].

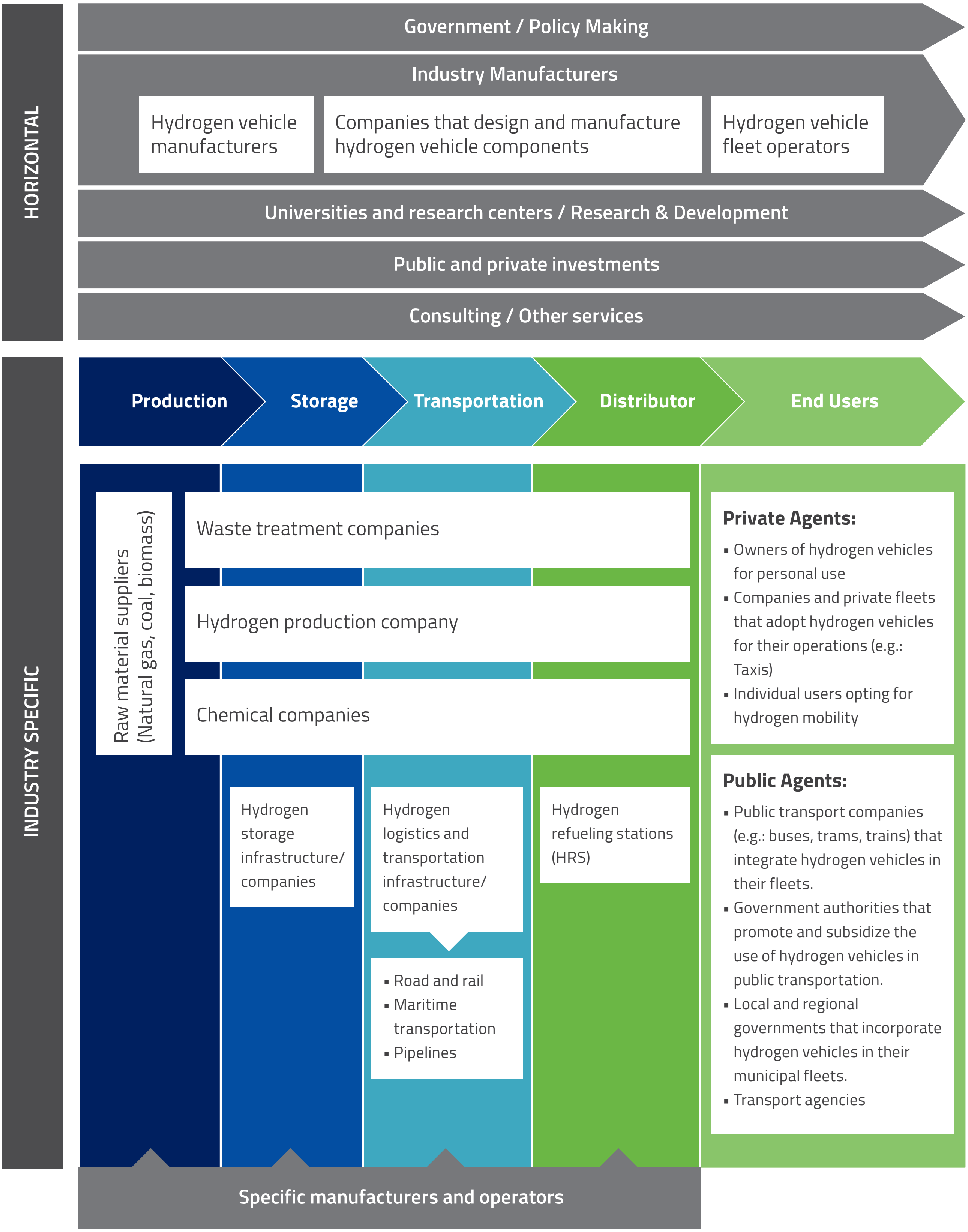
10 European Clean Hydrogen Alliance. Available at: European Clean Hydrogen Alliance - European Commission (europa.eu)

11 Clean Hydrogen Partnership. Available at: Homepage - European Commission (europa.eu)

12 Hydrogen Public Funding Compass. Available at: Funding guide - European Commission (europa.eu)

13 Demand projects refer to initiatives that have not yet started, and that seek to satisfy the demand for hydrogen, with a view to 2030 and 2040.These projects can be production plants, storage, distribution, among others, and can involve a variety of sectors, including industry, transportation, heating and others.

Figure 2. Hydrogen value chain in urban mobility.



1.2.1 Production

Hydrogen is an energy vector that is gaining unprecedented political and business momentum, with demand having grown more than three-fold since 1975 [4]. Current hydrogen equivalent production, amounting to approximately 95 MtH2eq, is mainly based on fossil fuels, such as natural gas and coal, through processes such as steam reforming or gasification. This production generates more than 1 Gt of CO_2 emissions per year, which is equivalent to 2.5% of annual global emissions, placing it at the same level as the entire aviation sector [5].

For hydrogen technologies to contribute to carbon neutrality, the United Nation Economic Commission for Europe (UNECE) recommends that current hydrogen production transitions from fossil fuel-based methods to fossil fuels with Carbon, Capture, Utilisation and Storage (CCUS), renewable electricity, nuclear energy, or grid-tied electricity via electrolysis using low-carbon electricity [6].

Renewable, low-carbon hydrogen has continued to grow since 2020 but remains less than 1% of global hydrogen production. Total hydrogen production worldwide was 95 Mt in 2022. Low-carbon and renewable hydrogen production is expected to reach between 70 and 125 Mt/year by 2030 [6] [7]. Hydrogen market growth is mainly driven by growing demand from the transportation and power generation sectors. Depending on assumptions and the prices users will pay for hydrogen, the market potential could total between 22 and 41 million metric tons annually [4].

Regarding urban mobility, hydrogen can be one of the main players in the mobility transition and will be important for the future of energy systems and for our society. With the EU committing to having hydrogen stations every 200 km on major roads, the industry sees a positive sign to drive the development of a hydrogen mobility ecosystem [8]. By 2030, CO_2 emissions reductions from clean hydrogen in the transportation sector are expected to reach 180 metric tons of CO_2. This positive impact will be driven mainly by medium-duty (MD) and heavy-duty (HD) vehicles [9] [10].

Factors such as production costs, product variety and other inputs will influence the dynamics of hydrogen trade in the future. In Europe, high-demand areas could have limited surplus energy for hydrogen production, while other regions would have production potential that exceeds local demand. Looking forward to 2050, several countries are expected to produce hydrogen at competitive costs, around $1.50 per kg, even falling to $1.20 per kg. By contrast, nations with limited clean energy resources could face significantly higher costs, exceeding $3.50 per kg [11].

Local production, when possible, could be more profitable than transportation from distant locations, despite lower costs in the latter. Transporting hydrogen over long distances presents logistical challenges and additional costs, but derivatives such as ammonia and synthetic kerosene could be competitive in long-distance trade due to their higher volumetric densities and relatively low transportation costs [11].

1.2.2 Storage and transport infrastructure

Establishing a robust hydrogen market requires the development of a well-knit infrastructure capable of delivering hydrogen to end users and facilitating cross-border trade. The vision for 2030 foresees an initial network of 11,600 km of pipelines, expanding to 39,700 km by 2040, supported by an estimated investment of 43 to 81 billion euros. The initiative, although with slightly higher transportation costs, is presented as an attractive and profitable option for long-distance transportation of hydrogen, especially considering the estimated future production costs. However, it is highlighted that the final configuration will depend on the dynamics of supply and demand in the integrated energy system [2].

Regarding hydrogen refuelling station (HRS) infrastructure, globally, targets are around 4,100 HRS by 2030 and will exceed 5,600 HRS by 2040. Notable developments include the Alternative Fuels Infrastructure Regulation adopted in 2023, which foresees at least one HRS every 200 km along the main transport network and in each urban node from 2030 onward, a fundamental step towards fostering an hydrogen-focused transport in the European Union [2].

The vision of incorporating hydrogen blending into the gas grid has been supported by several countries as a strategy to establish reliable demand for hydrogen during its initial implementation phases. This approach seeks to trigger significant reductions in costs associated with low-carbon hydrogen production technologies. In line with this approach, four European Union countries - Hungary, the Czech Republic, Slovakia and Portugal - have made commitments with specific objectives for the integration of hydrogen into their gas networks [2] [4].

The European Hydrogen Backbone (EHB)[14] emerges as an ambitious initiative led by gas transmission network operators in Europe. This project proposes to take advantage of the existing natural gas pipeline infrastructure through necessary adaptations to create an extensive hydrogen transportation network. Based on the conclusions of the 36th European Gas Regulatory Forum, ENTSOG, GIE, CEDEC, Eurogas, GEODE, GD4S, in cooperation with European Hydrogen Backbone, developed an interactive and publicly accessible map[15] (*H2 Infrastructure Map Europe*) gathering all relevant hydrogen infrastructure projects, which can be used by stakeholders and policy makers. The map brings together the hydrogen perspective and projects of gas transmission network operators (GRT), distribution network operators (DRG), storage system operators (SSO) and LNG system operators (LSO), as well as third-party promoters who develop projects in consortia throughout the entire value chain [3].

[14] The European Hydrogen Backbone (EHB) initiative. Available at: The European Hydrogen Backbone (EHB) initiative | EHB European Hydrogen Backbone

[15] Available at: H2 Infrastructure Map Europe (h2inframap.eu)

1.2.3 End use in urban mobility

In the global urban mobility landscape, fourteen countries have committed to deploying fuel cell electric vehicles (FCEV). Government policies remain the key driving force for global electric car markets, tailoring specific targets to different vehicle segments, with a particular focus on medium- and heavy-duty buses and trucks [2]. Their dynamism is also reflected in the automotive industry: announcements, objectives and launches of new models have helped strengthen the vision that the future of automobiles is electric [12].

Between 2020 and 2021, numerous governments and automakers set goals to phase out internal combustion engine vehicles over the next two decades. Electric vehicles have become the preference in road transport, with the EU Commission proposing to reduce the CO_2 emissions standard for new cars to zero by 2035. Manufacturers such as Volkswagen and Ford announced electrification targets, and Toyota, the largest automobile manufacturer in the world announced investments to reach sales of 3.5 million electric cars annually by 2030 [12].

Projections indicate the creation of a fleet of 1.5 million FCEVs worldwide by 2030, possibly reaching 4.8 million by 2040 [2]. Notably, the European Union has been an early adopter of hydrogen in captive uses, including city buses, taxis, and specific sections of the railway network.

In the non-road transport landscape, the potential of hydrogen has attracted substantial attention within national hydrogen strategies, despite only a handful of countries within the European Union having articulated specific objectives for these sectors. This can be attributed to the relatively nascent state of hydrogen technologies in these areas. In particular, only France, Portugal, the Slovak Republic, and Spain have committed to adopting hydrogen in railway applications and foresee the deployment of several dozen hydrogen-powered trains by 2030. In the maritime sphere, Portugal and the Slovak Republic stand out as the only pioneers with articulated objectives to the use of hydrogen. Norway is setting a goal of establishing five maritime hydrogen clusters by 2030. In the aviation sector, Germany emerges as the only nation to announce targets for hydrogen-based fuels [2].

In a crucial moment, the European Commission, in July 2021, proposed two directives awaiting approval. Firstly, a revision of the Renewable Energy Directive sets a binding transport target, requiring 2.6% of all fuels to come from renewable hydrogen by 2030 in all EU Member States. Secondly, the ReFuelEU Aviation initiative outlines the goal of achieving a 0.7% share of synthetic fuels in aviation by 2030, with a long-term target aiming to raise this share to 28% by 2050. These proposals signal a concerted effort to integrate hydrogen at a key pillar of the European Union’s priorities for sustainable aviation [2].

Zero emission vehicles for urban mobility

The European Commission has set targets to reduce CO_2 emissions from new vehicles in line with the objectives of the Paris Agreement. A 55% reduction in car emissions is sought by 2030 compared to 2021, and the goal is for all newly sold vehicles to be zero emission from 2035 onwards. In addition, the Commission promotes the use of zero emission vehicles (ZEVs) through investments in the necessary charging infrastructure, establishing pollution prices, encouraging the use of cleaner fuels and investing in clean technologies [13].

ZEVs generate no internal combustion engine exhaust emissions or other carbon emissions. Currently, there are only two types of ZEVs available: battery electric vehicles (BEVs) and fuel cell vehicles (FCVs). Unlike BEVs, which rely solely on a large battery for energy storage, FCVs use a much smaller battery in addition to a fuel cell stack [14].

Electric vehicles (EVs) stand out for their high energy efficiency and their ability to reduce air and noise pollution, in addition to reducing greenhouse gas emissions (although this depends on the entire supply chain). To obtain the full environmental benefits of EVs, it is essential to decarbonise the electricity grid, for instance thanks to renewable energy sources (RES) [14].

Zero-emission mobility can also be achieved through the use of hydrogen and fuel cell vehicles (FCVs). Similarly to BEVs, their full environmental benefits can only be unlocked by using hydrogen produced from carbon-neutral sources. Although the idea of using H_2 in the transportation sector is not new, the high costs of hydrogen production by renewable sources and fuel cells maturity of the technology for producing components at industrial scale are hampering H_2 implementation [15]. The massive investments needed for the required infrastructure, and some technical obstacles, such as the reliability and durability of fuel cells, have hindered the penetration of this technology. The successful implementation of FCVs will largely depend on public support and policy framework, as currently these vehicles are expensive mainly due to low production volumes and high manufacturing costs [14].

Although barriers to faster adoption of FCVs remain, recent progress in green hydrogen production has increased interest in these vehicles, as part of strategies to achieve net-zero carbon emission targets by 2050 [4]. With the increased use of variable renewable energy sources such as solar and wind, and an increase in electrolysis operating hours, green hydrogen production costs could decrease significantly in the future [14]. However, most automakers are focused on EVs, and only a few, such as Toyota, Hyundai and General Motors, are also heavily oriented toward FCVs. Given the limited industrial interest, lack of infrastructure and high associated costs, widespread deployment of FCVs is unlikely, and FCV deployment may rather occur on segments such as long-haul trucking [14].

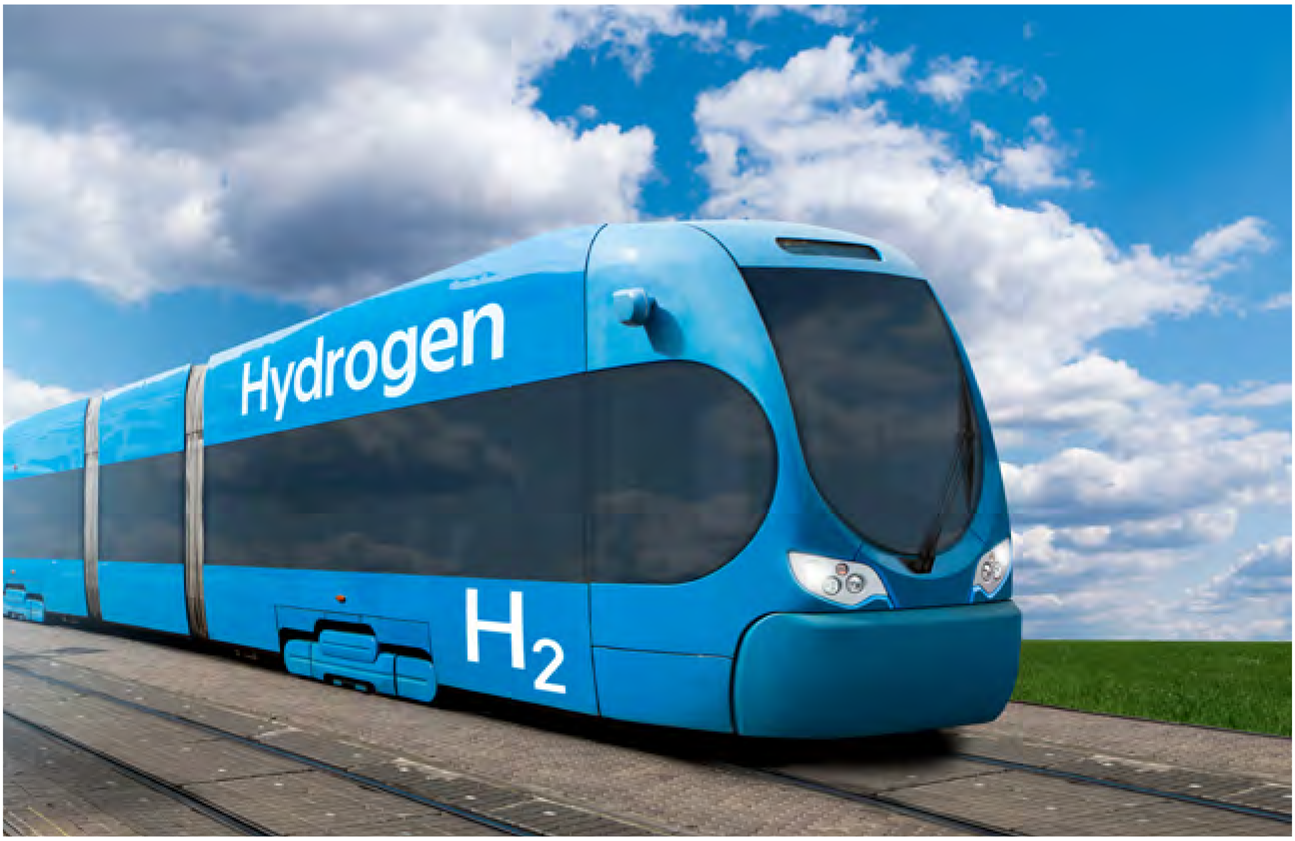
Electricity and hydrogen are emerging as complementary energy vectors to transform and decarbonize the transportation sector. As illustrated in Table 1, both exhibit distinct advantages and share common challenges that must be addressed for future advancements.

	BEVs	FCVs
Major advantages	▪ High energy efficiency ▪ Charging infrastructure is expanding rapidly due to major policy support ▪ Relatively low operating costs, but could be impacted by increasing energy prices ▪ Using electricity from RES, could significantly contribute to GHG emission reduction ▪ Contribution to the energy supply security and reduction of fossil fuel import dependency ▪ Improvement of air quality ▪ Reduction of noise level in comparison to combustion engine	▪ Relatively short refueling time, 5-10 min ▪ Application to sectors where electrification is too expensive or impossible, e.g. long-haul trucking, ships, airplanes ▪ Higher energy density of hydrogen in contrast to batteries ▪ Using green hydrogen, FCVs could significantly contribute to GHG emission reduction ▪ Contribution to the energy supply security and reduction of fossil fuel import dependency ▪ Improvement of air quality ▪ Reduction of noise level in comparison to combustion engine ▪ Lighter vehicles ▪ Less critical materials involved ▪ Complete decoupling of the place and time of hydrogen production and supply, without the need for local energy production ▪ Hydrogen vehicles with a low impact on electrical networks
Major Challenges	▪ Cost reduction ▪ Low battery energy density ▪ Slow charging process ▪ Limited driving range and range anxiety ▪ Battery weight ▪ Dependency on critical materials, and limited availability of these ▪ Battery supply chain bottleneck risks ▪ Environmental and social material mining concerns ▪ 'Thermal runaway' safety concerns ▪ Development of charging infrastructure, especially fast chargers ▪ Reduction of the overall life cycle emissions ▪ Battery recycling	▪ High associated costs: high hydrogen costs, high operating costs, high vehicle costs ▪ Fuel cell stack complexity ▪ High fuel cell technology costs ▪ Infrastructure costs ▪ Less efficient than BEVs ▪ Relatively low support from car industries ▪ Durability, reliability, and robustness of fuel cells ▪ Handling hydrogen safely requires proper training, procedures, and equipment ▪ Only a few vehicle models on offer

Table 1: Major advantages and challenges for BEVs and FCVs [16] [17] [18]

A main merit shared by both electricity and hydrogen lies in their potential to collaborate with BEVs and FCVs to improve air quality, reduce noise pollution and raise the overall quality of life in urban environments. Furthermore, their ability to be produced from a wide range of primary energy sources positions them as contributors to reducing dependence on energy imports and reinforcing the security of energy supply. Currently, both BEVs and FCVs are beneficiaries of policies aimed at reducing emissions and promoting clean and sustainable mobility.

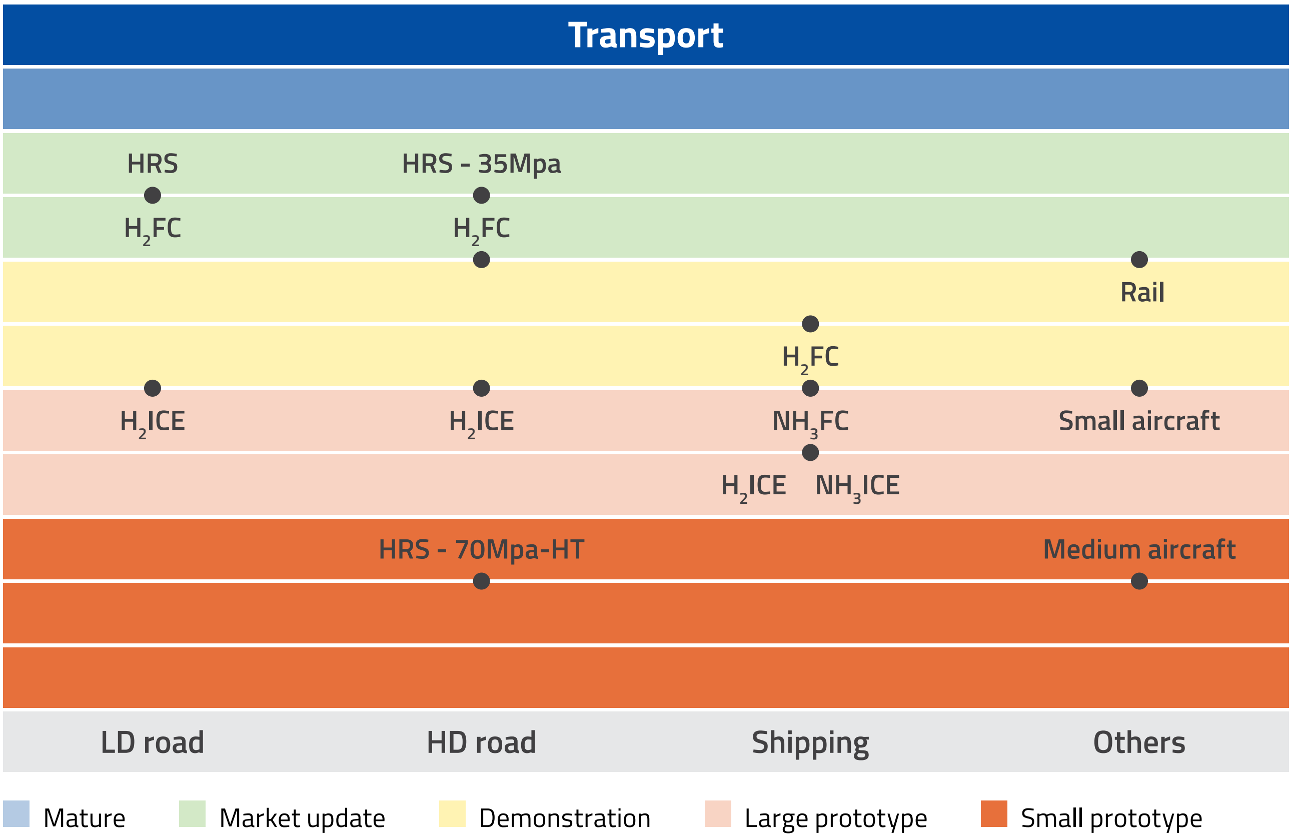
Comparing the two technologies, BEVs currently maintain an advantage over FCVs in terms of commercialization and infrastructure development. Furthermore, the overall efficiency of BEVs, from electricity generation to mileage, surpasses that of FCVs. However, FCVs present certain advantages, including fast refuelling times, high energy density and extended driving range. These distinctions underscore the multifaceted considerations necessary when navigating the transition to cleaner, more sustainable transportation solutions.



1.3 Technology opportunities

The main opportunities hydrogen offers to companies transitioning to more sustainable operations relate to fuel diversification and emission reduction.

To map these opportunities, figure 3 provides a brief overview of the state of the main hydrogen production technologies for transportation, both on roads and water, among other contexts. The mapping is based on the international Technology Readiness Level (TRL) system.



Notes: FC = fuel cell. HRS = hydrogen refuelling station. HD = heavy-duty. ICE = internal combustion engine. LD = light-duty.
Source: Clean Energy Innovation (2020), p. 67. Source: IEA, 2022.

Figure 3. TRL classification of the main hydrogen production technologies for transportation.

2 Uptake potential

2.1 Assessment of adoption potential

As social-environmental awareness and urbanization increases, cities face growing challenges related to pollution, congestion, and carbon emissions. Hydrogen vehicles are possible solutions to these problems. This section explores the potential for hydrogen adoption, examining key factors such as the state of infrastructure, availability of hydrogen supply, social acceptance, and alignment with the demand for sustainable urban mobility.

The pathway to hydrogen's potential in urban mobility

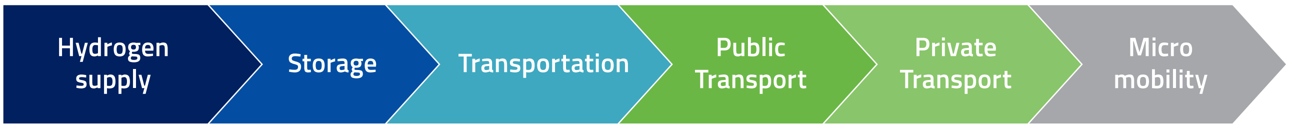


Figure 4. Hydrogen application for transport.

Hydrogen demand in transport totalled over 30 kt in 2021, more than 60% higher than the previous year. As a share of total hydrogen demand, however, transport represents only 0.03%, across all modes.

Following the effects of the global pandemic in 2020, the global number of fuel cell system shipments increased by 75.7% in 2021, accounting for 2,330.4 MW. The number of shipments to Europe grew by 33% to 197.8 MW from 149 MW in 2020. Similarly, after a period of slow growth in 2020, HRS deployment in Europe rebounded, with 170 stations in operation by the end 2021, an 11% increase from 2020. In the same direction, 3,885 new FCEVs were registered in Europe in 2021, an increase of 36% from 2020. Following a sharp decline in the number of electrolysers commissioned in 2020 (only 2 units totalling 1.5 MW), 2021 saw 14 new units in Europe, with a total capacity of 27 MW. The Clean Hydrogen Partnership expects these numbers to grow significantly over the coming years [19].

Road vehicles, by far, are the major source of hydrogen demand in transport. Most of this hydrogen is consumed in trucks and buses due to their high annual mileage and heavy weight. The number of heavy-duty hydrogen trucks increased significantly in 2021 (up over 60-fold from 2020), as has the estimated hydrogen demand from commercial vehicles, i.e. vans and trucks. In 2021, hydrogen demand for commercial vehicles exceeded that from buses for the first time, reaching 45% of total hydrogen demand in the transport sector.

Hydrogen offers a solution to decarbonise diesel rail lines where electrification is difficult, and the distances are too far to be covered by battery electric trains [20]. Given the limited deployment of hydrogen trains, hydrogen consumption for rail was less than 0.1 kt in 2021. However, based on industry announcements [21], hydrogen's role in rail transport is expected to rise in the near term.

Interest is also increasing in the use of hydrogen and hydrogen derived synthetic fuels in the maritime and aviation sectors, though the technologies are less mature than those for road and rail. There are several projects and orders for vessels that can operate on hydrogen, ammonia and methanol that will be realized in the coming decade. Similarly, the use of hydrogen-derived synthetic fuels for aviation is not expected to make inroads in the short term.

However, a widespread network of hydrogen refuelling stations is crucial for the uptake of hydrogen powered vehicles.

Hydrogen supply

Hydrogen's versatility as an energy carrier is a significant advantage. It can be produced through various methods, like steam reforming from different hydrocarbons using carbon or coal; from biomass; using thermochemical processes or by electrolysis of water using renewable energy sources like wind and solar power. This last one is called green hydrogen. Nowadays the most widespread process to obtain hydrogen is through steam methane reforming, which is the traditional process to obtain hydrogen from natural gas. This flexibility in production allows hydrogen to align with diverse energy strategies.

Storage potential

Building a comprehensive infrastructure network is essential to produce, distribute, and store hydrogen efficiently. This involves establishing production facilities, transportation methods, and storage solutions such as compressed gas, liquefied hydrogen, or the uses of solid carriers, most notable chemical hydrides from light metals such as Li, Na, Mg, Al, B and Be, or liquid carriers, which are molecules organic substances that serve to adsorb and release hydrogen known as LOCHs.

Moreover, hydrogen storage plays a critical role in integrating renewable energy sources into the energy mix. Excess energy generated from wind or solar during peak production periods can be converted into hydrogen and stored for later use, thereby enhancing grid stability, and reducing curtailment of clean energy. To fully unlock the potential of hydrogen infrastructure and storage, concerted efforts in cost reduction, stringent safety measures, and public awareness campaigns are necessary.

Transportation potential

Hydrogen can be transported using containers or blended with a small percentage of natural gas, can be also transported using the public pipe gas network. Governments and private sector entities are actively investing in expanding hydrogen refuelling infrastructure, particularly in regions where hydrogen mobility is gaining momentum.

Public transport potential

Hydrogen's zero-emission profile makes it an ideal candidate for reducing air pollution and enhancing urban air quality, a critical concern in densely populated areas. Hydrogen-powered buses, trams, and trains offer similar ranges to conventionally powered equivalents and swift refuelling, ensuring efficient and reliable public transport services. Moreover, these vehicles operate quietly, minimizing noise pollution and contributing to more peaceful urban environments.

Hydrogen's scalability allows it to cater to a variety of public transport needs, making it a versatile option for cities. Its capability to store excess energy from renewable sources further enhances its appeal, helping cities utilize clean energy efficiently. While initial infrastructure costs are a challenge, many cities are already piloting hydrogen-based solutions in public transport, expecting operating cost reduction over time. This will be detailed in the next section.

Private transport potential

Hydrogen fuel cell vehicles (FCVs) are gaining attraction as a clean and sustainable alternative to traditional gasoline and diesel-powered cars, according to the International Energy Agency's (IEA) Global EV Outlook 2023 report. One of the primary advantages of hydrogen in private transport is its long driving range and rapid refuelling times. FCVs can cover substantial distances on a single tank of hydrogen, typically exceeding the range of battery-electric vehicles, and refuelling takes just a few minutes, similar to the convenience of refilling a gasoline car. This addresses "range anxiety" concerns and provides a more familiar driving experience for consumers.

In addition, hydrogen FCVs produce no exhaust emissions, as they only emit water vapour as a by-product. This makes them an environmentally friendly option, helping to reduce air pollution and greenhouse gas emissions. If car manufacturers continue to invest in hydrogen technology and expand their hydrogen vehicle offerings, FCVs can become a contributing leg to a more sustainable and environmentally friendly transport future for trips that cannot be done with public transport. However, to fully realise this potential, challenges such as the need for a more extensive hydrogen refuelling infrastructure and cost competitiveness with conventional vehicles still need to be addressed.

Micromobility potential

Transport by very light vehicles such as electric scooters, electric skateboards, shared bicycles and assisted bicycles such as the bicilec/pedelec are modes of transport that are very likely to be coupled with new alternative transport technologies such as electric vehicles, reducing emissions through their use, especially in urban areas.

Local governments promote incentives for the use of electric two-wheeled vehicles, such as bicycles, in large city centres and, in fact, some countries are already trying to adopt this transition. A potential use-case, being trialled in various pilot projects, is the use of hydrogen fuel cells in micro-mobility to increase their range with short refuelling times.

2.2 Market opportunities and specific niches

Through the analysis of the meta-studies, identification of use cases and interviews with hydrogen and urban mobility experts, a short classification has been developed with the six main market opportunities and their corresponding specific niches. The segmentation has been done on two levels: first, the six most relevant growing market segments around the hydrogen value chain in urban mobility and down a step, the specific niches of each market segment.

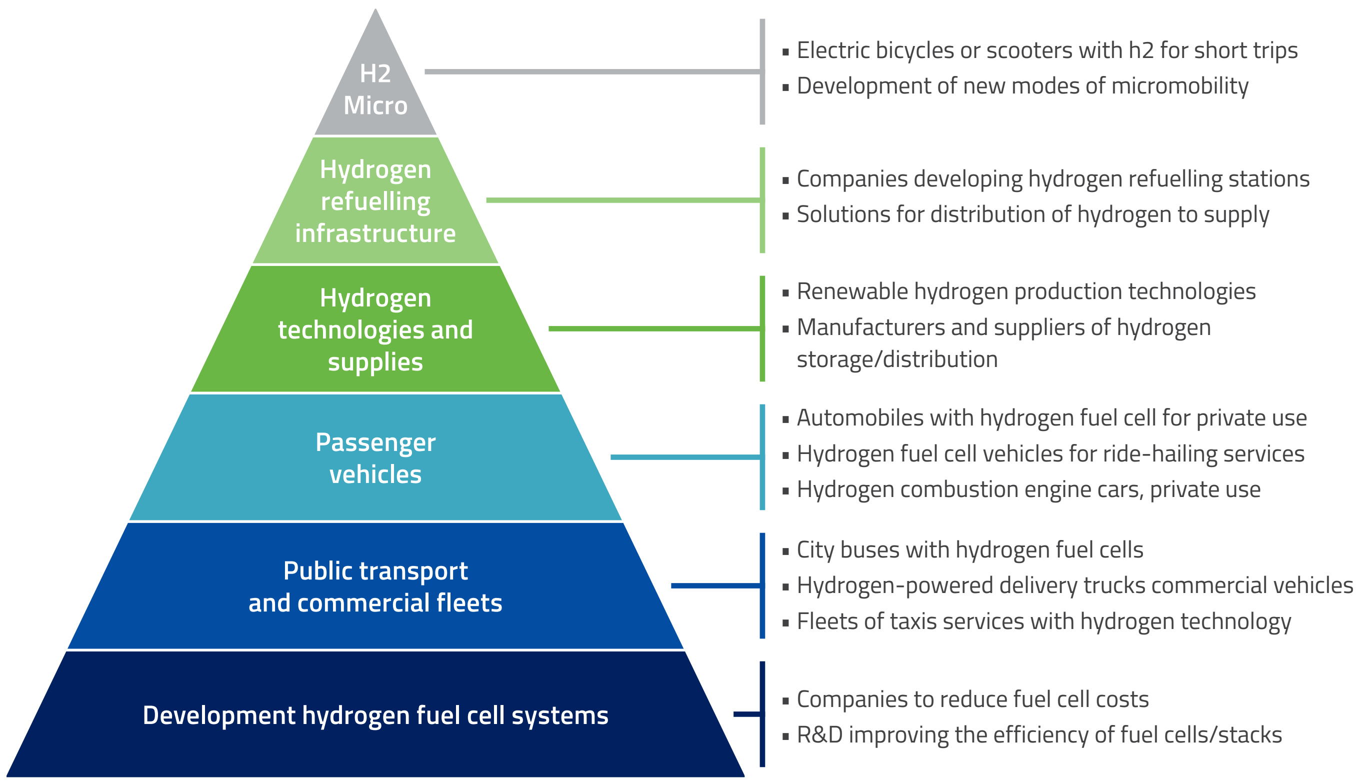
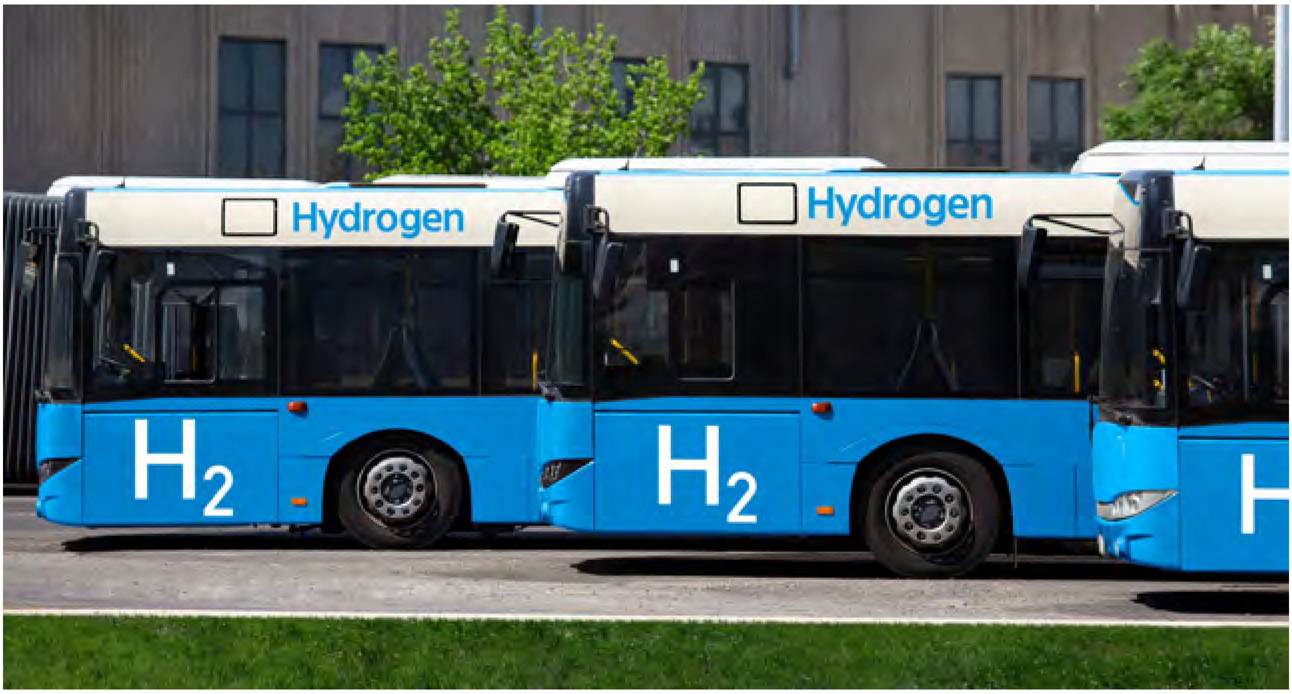


Figure 5. Market segments (by size) and specific niches



Public transport and commercial fleets in the EU

Cities are looking for ways to reduce carbon emissions and improve air quality. City buses, taxis, delivery trucks and other hydrogen-powered fleet vehicles can play an important role in reducing pollution and noise in densely populated urban areas. The most important market segments are analysed below:

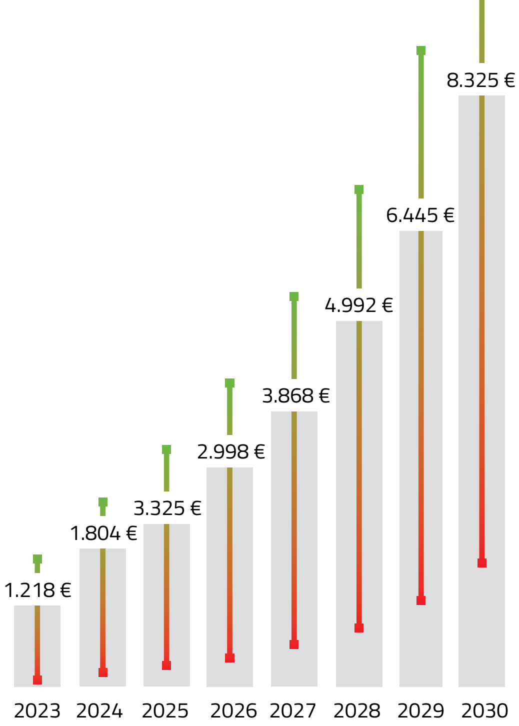
Urban buses with hydrogen fuel cells			1.218 M€
YEAR 2030	Conservative 1.747 M€	Realistic 8.325 M€	Optimistic 11.471 M€

To analyse the market size of the hydrogen bus market for public transport, a series of assumptions are made based on three different current and prospective market sources: Future Market Insight [22], Coherent Market Insight [23] and Straits Research [24].

As well as analysing the hydrogen sector, a comparisoni with Battery Electric Vehicles (BEV) and Plug-in hybrid electric vehicle (PHEV) are established. Despite remaining smaller than the BEV and PHEV market, the hydrogen bus market is expected to grow steadily in the coming years. Interestingly, market size forecasts for this segment strongly vary (see error bar below).

Hypothesis and assumptions

Market size of hydrogen buses for public transport in Europe 2023-2030. Shown in millions.



Now

There are different trends and starting points from different studies which range from **0.8** to **10kM€**.

Outlook

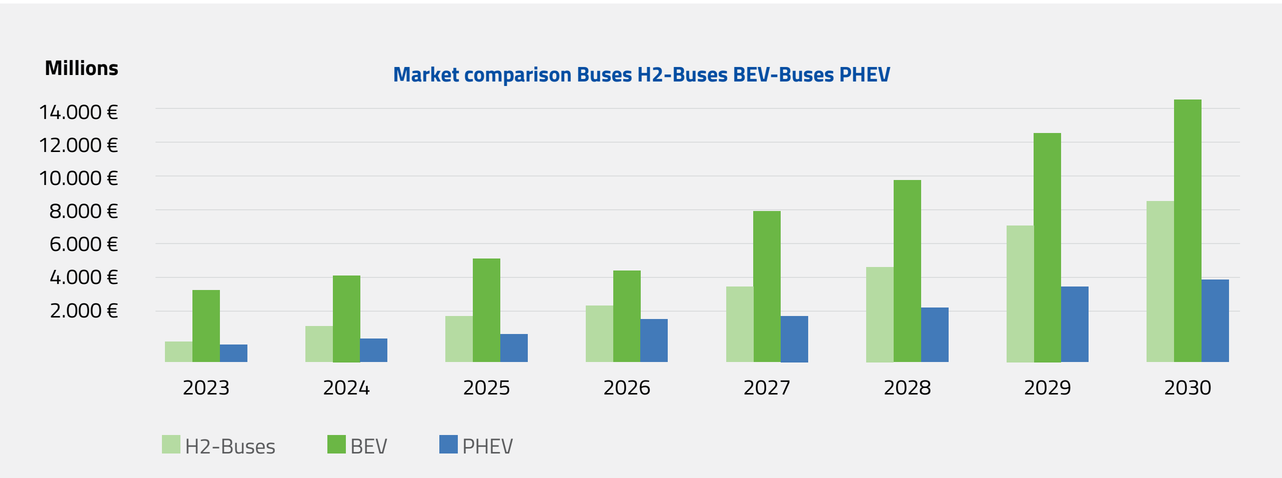
Growing demand for environmentally friendly and energy efficient vehicles. Major initiatives by government agencies to promote vehicles that reduce dependence on oil set to provide vehicles that reduce dependence on oil set growth ranges of a CAGR between **46%** and **67%**.

Application

The studies analysed detail all bus technologies, however, we would like to focus on buses dedicated to public transport. It is assumed that **70-90%** of bus production is dedicated to public transport.

Location

The market niche that we want to estimate is Europe, for which we have averaged the weight estimated by the 3 studies **25-39%** of the global total.



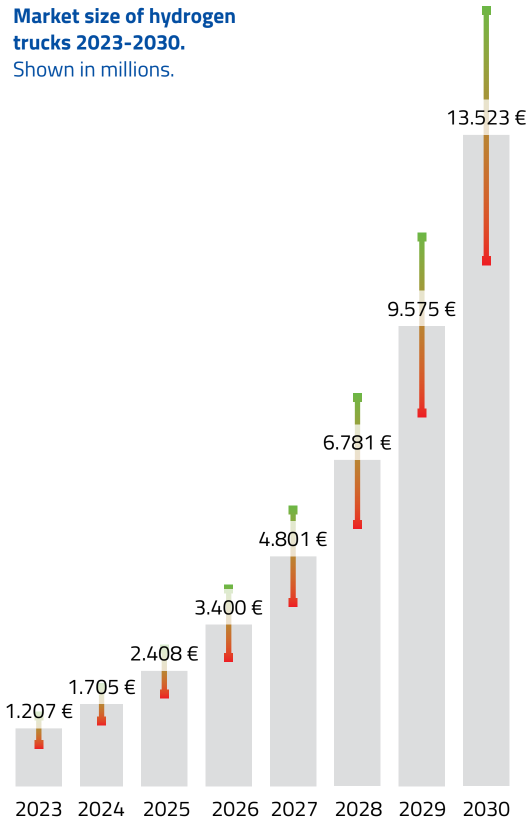
Delivery trucks and commercial vehicles powered by hydrogen — **1.207 M€**

YEAR 2030	Conservative	Realistic	Optimistic
	11.325 M€	13.523 M€	15.719 M€

To analyse the market size of hydrogen trucks we have relied on three reports: Precedent Research [25], Future Market Insight [26] and Allied Market Insight [27].

In the case of the electric trucks market, a Mordor Intelligence report [28] was used to establish comparison between markets. These markets are expected to be quite balanced between hydrogen-powered and BEV, while PHEV represent a marginal revenue of the market.

Hypothesis and assumptions



Size

Studies have been collected looking at the three main size divisions; heavy, medium and small.

Outlook

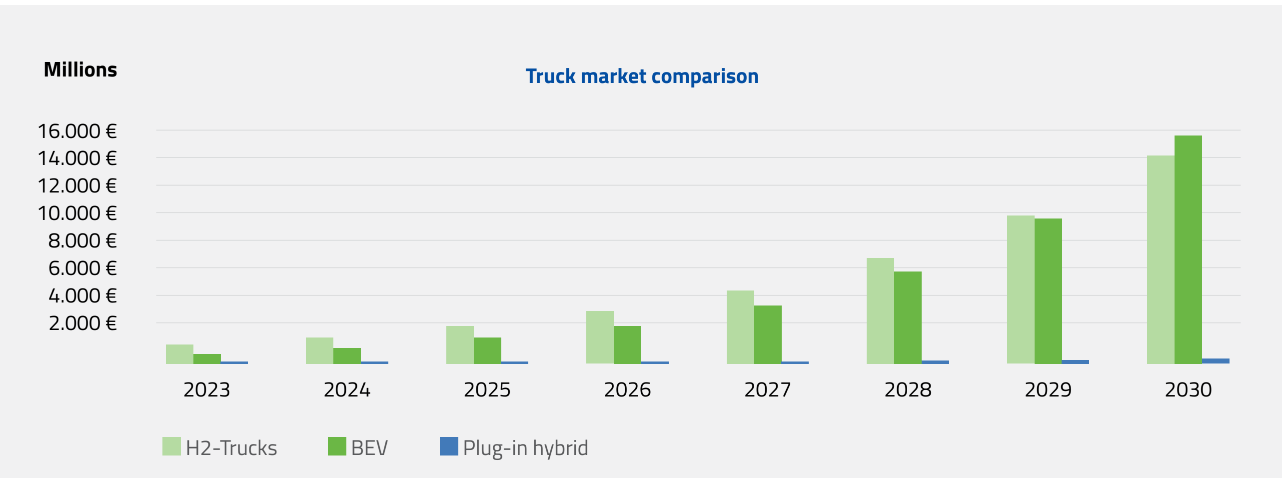
Growth, thanks to recharging times as fast as petrol and a long range on a single tank. Lighter than electric vehicle batteries, making them suitable for carrying heavy loads. Set growth ranges of a CAGR between **41%** and **42%**.

Application

The estimate includes logistics trucks and those assigned to municipal services (maintenaince, gardening, collection, etc).

Location

We simply focus on Europe, using an analogy with electric trucks per region in 2021 (IEA), with Europe accounting for **28.57%**.



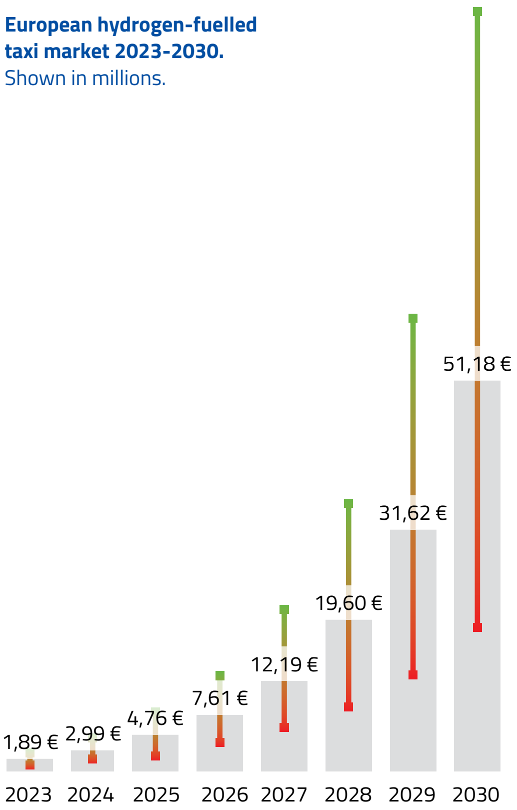
Fleets of taxis services with hydrogen technology				1,89 M€
YEAR 2030	Conservative 19,40 M€	Realistic 51,18 M€	Optimistic 99,15 M€	

Three different sources were reviewed to determine the European market size of hydrogen-fuelled taxis services: Globe Newswire [29], Market Research Future [30] and Coherent Market Insight [31]. In addition, an extra source, a report by the International Energy Agency [32] was reviewed to compare it with the electric taxi market.

In the case of hydrogen-fuelled taxis there's still a long way to go to become mainstream. Tendency shows BEV and PHEV increasing with an important market share. Similar to the bus segment, there are strong variations between lowest and highest estimates, reflected in the error bar below.

Hypothesis and assumptions

European hydrogen-fuelled taxi market 2023-2030.
Shown in millions.



Now

Hydrogen-fuelled taxis is still an incipient market that in Europe generates **1,89 € million** in 2023 but is expected to reach **51 € million** in 2023.

Outlook

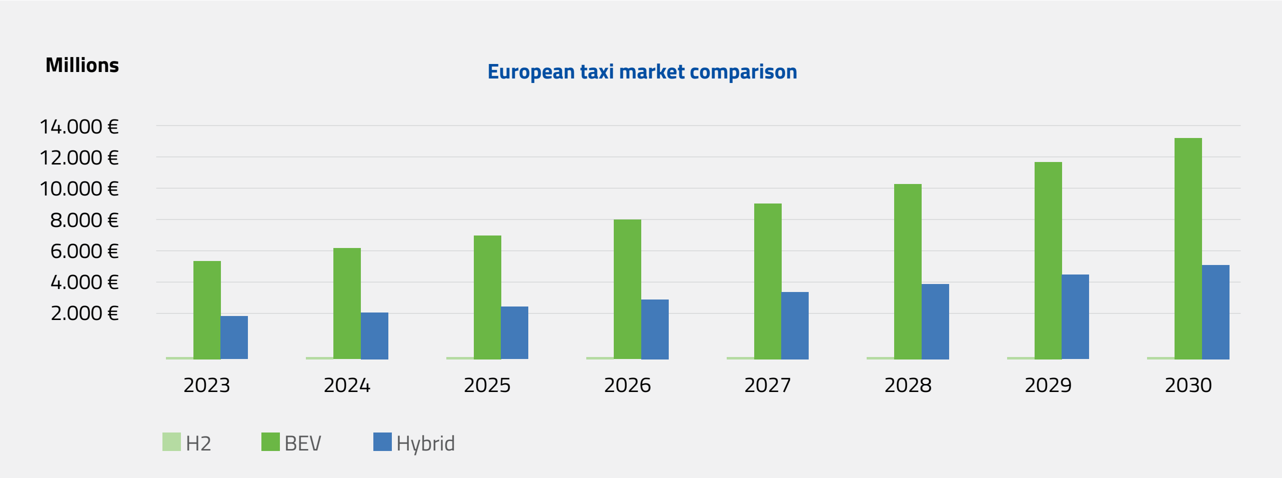
The average CARG provided by different market researchers is situated in **55%** for the period 2023-2030. Paris, Copenhagen, London and Hamburg pioneered this technology.

Application

Only licensed taxis are considered, excluding ride hailing companies such as Uber, Bolt or Cabify.

Location

Europe accounts for **25%** of the hydrogen-fuelled cab market, being the second region behind the United States.



Passenger vehicles

While battery electric vehicles have gained popularity, hydrogen fuel cell vehicles offer an attractive alternative in terms of range and refuelling time. In urban areas with adequate infrastructure, fuel cell vehicles could offer sustainable mobility without compromising.

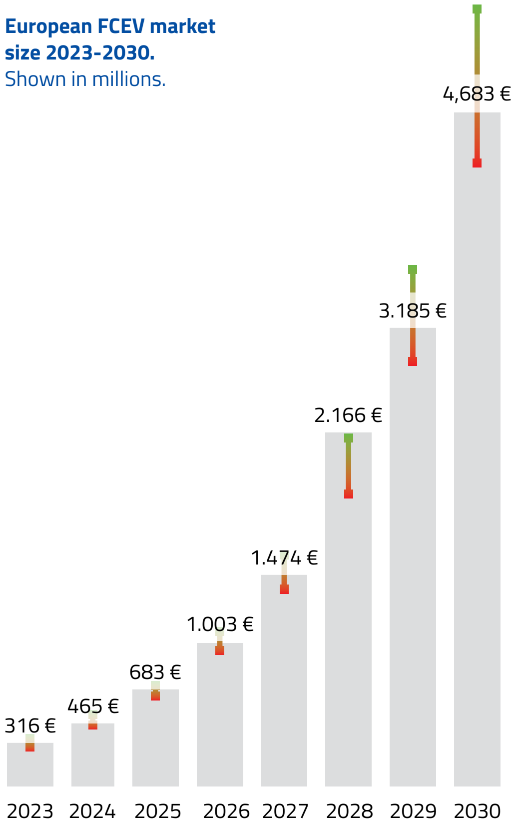
Automobiles with hydrogen fuel cell for private use			316 M€
YEAR 2030	Conservative 4.336 M€	Realistic 4.683 M€	Optimistic 5.361 M€

To estimate the size of the European market for privately owned hydrogen fuel cell cars, a variety of sources were examined, namely Allied Market Research [33], Polaris Market Research [34] and Grand View Research [35].

In order to ascertain the market size and percentages of BEV and PHEV, a Markets & Markets [36] report and an article from McKinsey were also examined. Public policies are tending to boost electric vehicles for private use, as it can be seen with both types of electric cars during this decade. Hydrogen powered vehicles still represent a low market share, as processes in the entire hydrogen value chain are less mature than in the electric car value chain.

Hypothesis and assumptions

European FCEV market size 2023-2030.
Shown in millions.



Size

75% of the global fuel cell vehicles market corresponded to passenger cars. Almost all of them **(95%)** are given by their owners a private use.

Outlook

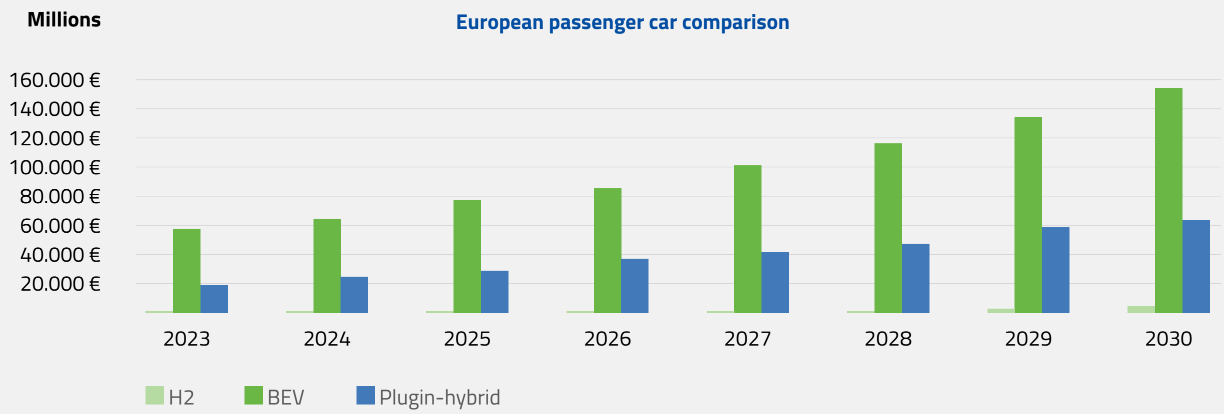
It us expected that the expansion of the hydrogen refuelling stations will boost the acquisition of the FCEV for private use. The CAGR until 2030 is estimated in **45%**.

Application

Passenger cars for private use, designed to seat no more than 9 persons, including the driver, are considered in this study.

Location

The study focuses on European market, where Denmark, France, Netherlands, England and Germany are one step ahead of the rest of the countries.



Hydrogen fuel cell vehicles for ride-hailing services

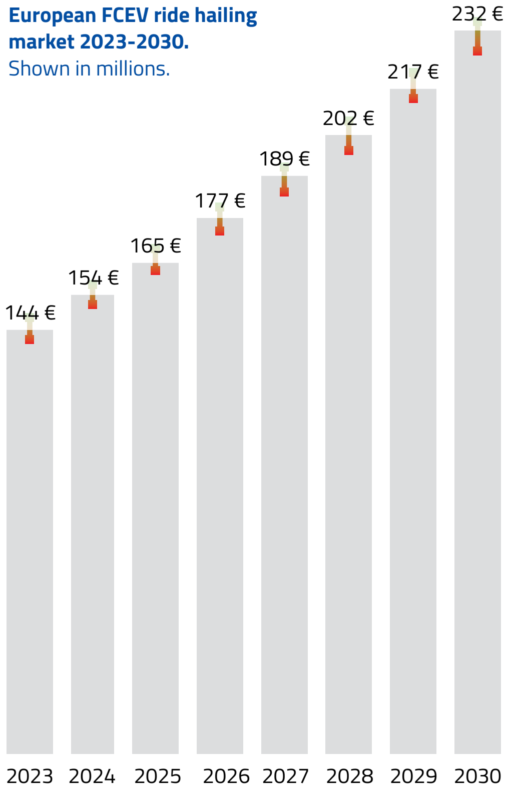
144 M€

YEAR 2030	Conservative	Realistic	Optimistic
	220 M€	232 M€	235 M€

Two reports focused specifically on the European ride-hailing market were reviewed in order to analyse this market: Business Market Insight [37] and Statista [38]. To get specific data of electric ride-hailing market, an article of World Resource Institute [39] was reviewed. The predominance of electric cars in this section has to do with the objective of different companies such as Uber, to provide the service with 100% of its fleet in Europe being electric [40].

Hypothesis and assumptions

European FCEV ride hailing market 2023-2030.
Shown in millions.



Expectations

This category includes companies that provide passenger transfer services with a hired person. The market size is expected to reach in Europe **232 € million** in 2030.

Outlook

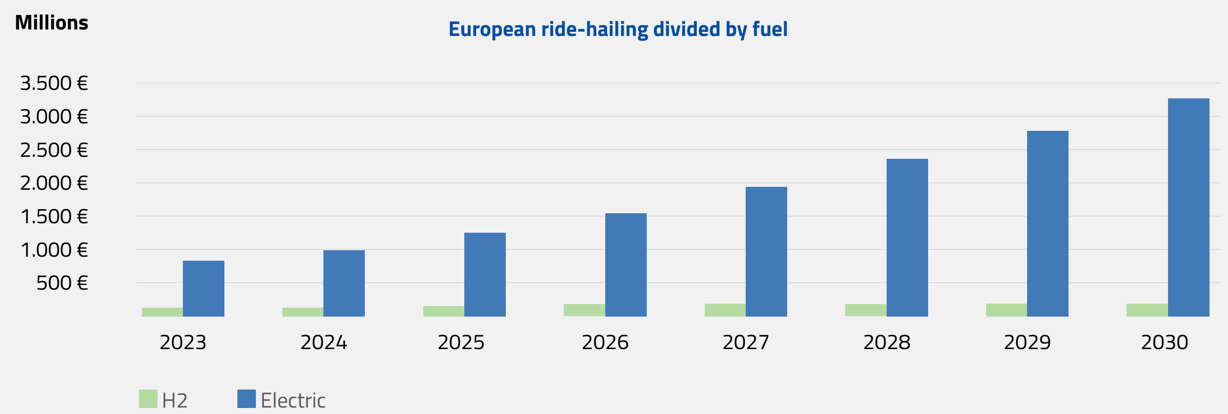
The users are expected to increase every year, reaching **84 million** in the European market in 2027. It is assumed that **1%** of the automotive fleet in hydrogen-powered.

Application

The expansion of ride-hailing in Europe is a component of the continent's larger digitalization trend as well as the introduction of new mobility services.

Location

The study is focused on Europe, the third biggest market worldwide, after North America and Asia.



Hydrogen combustion engine cars, focused on private use

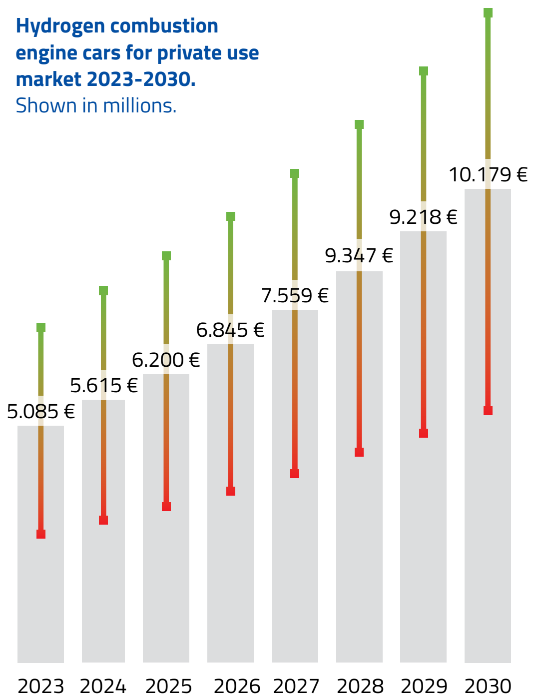
5.085 M€

YEAR 2030	Conservative	Realistic	Optimistic
	5.505 M€	10.179 M€	13.927 M€

The size of the hydrogen combustion engine vehicle market in Europe, with a concentration on private use, was estimated using three different sources: Future Market Insight [41], Business Research [42] and Verified Market [43]. Compared to private hydrogen fuel cell cars, the uncertainty range shown by the error bar is higher.

Hypothesis and assumptions

Hydrogen combustion engine cars for private use market 2023-2030.
Shown in millions.

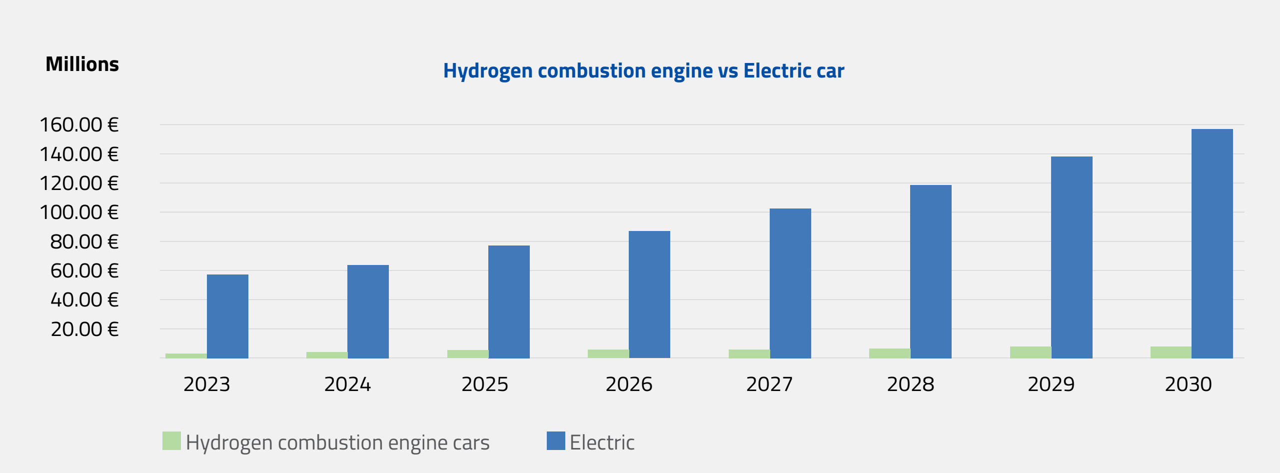


Forecast
By 2030, hydrogen combustion engine cars, focused on private use, is expected to double its size compared to 2023.

Outlook
The market is expected to increase **10%** each year until 2030.

Application
The increased need for fuel cells in automotive and transportation, is expected to drive the global hydrogen combustion engine market size.

Location
European market represents half the size of North American market, who has around **45%** of the market share.



Hydrogen refuelling infrastructure

The establishment of a network of hydrogen refuelling stations is a market opportunity in itself. The lack [44] of a well-developed refuelling infrastructure has been one of the main obstacles to the mass adoption of hydrogen vehicles. Companies investing in the creation of a network of hydrogen stations could gain competitive advantages in this emerging market.

The recharging infrastructure is yet to be determined between large hubs or small distributed hydrogen refuelling stations; however, the following niches stand out; Hydrogen stations and distribution to these stations.

Investment companies in the development and operation of hydrogen refuelling stations.			127 M€
YEAR 2030	Conservative 151 M€	Realistic 365 M€	Optimistic 495 M€

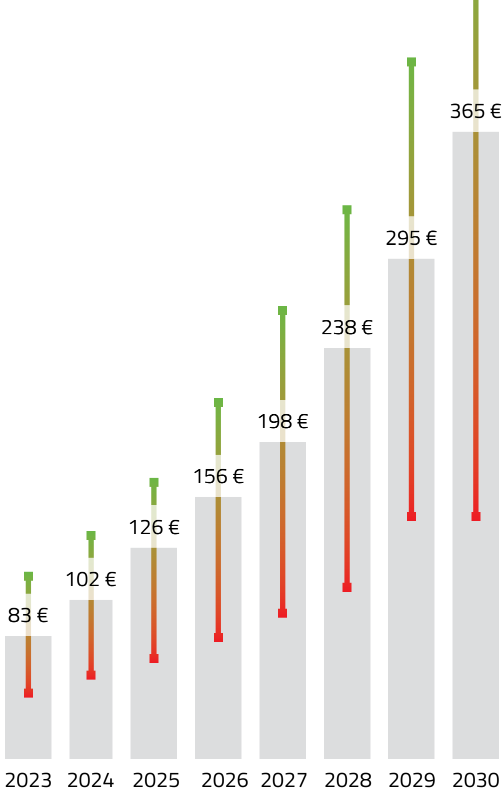
A variety of sources were examined in order to calculate the size of the hydrogen refuelling station market: Markets & Markets [45], Fortune Business Insight [46] and Grand View Research [47].

For this indicator, a parallelism was drawn with the plug-in charging system for electric cars, relying on a Global Market Insight [48] report.

Plug-in charging system is currently the main charging source of electric cars and is expected to increase with the expansion of electric cars. Despite being more common than off-site stations, the on-site hydrogen stations are still very low in comparison with plug-in systems.

Hypothesis and assumptions

European on-site hydrogen stations market size 2023-2030.
Shown in millions.



Drivers

These stations eliminate the need for fuel transportation and storage by offering a dependable and localized supply of hydrogen.

Outlook

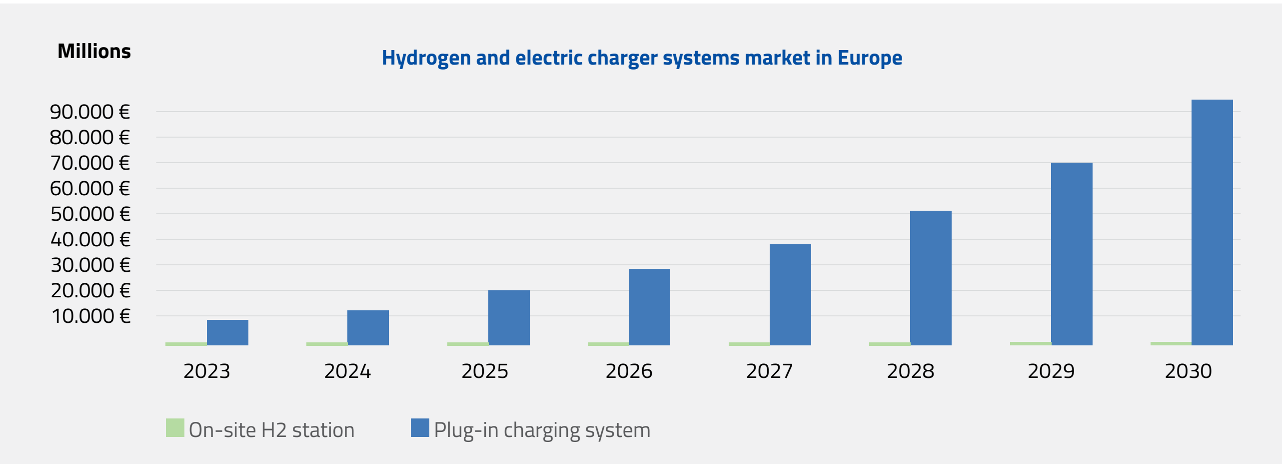
The rising demand for zero-emission vehicles as well as government programs and policies designed to boost the use of hydrogen fuel cell vehicles are the main factors propelling the market's expansion.

Application

The on-site hydrogen stations produce and dispense hydrogen fuel for cells. The main advantage is that they provide a convenient and efficient way to refuel hydrogen-powered vehicles.

Location

Europe accounts for around **25%** of the hydrogen stations global market. In 2030 the European market is expected to reach **365 € million**.



Hydrogen technologies and supplies

The development of hydrogen production, storage and distribution technologies is key to the growth of hydrogen use in urban mobility. In addition, renewable and sustainable hydrogen supply is also a promising area for companies involved in green hydrogen production or electrolysis powered by renewable sources.

Engineering and development companies working on renewable hydrogen production technologies. **1.344 M€**

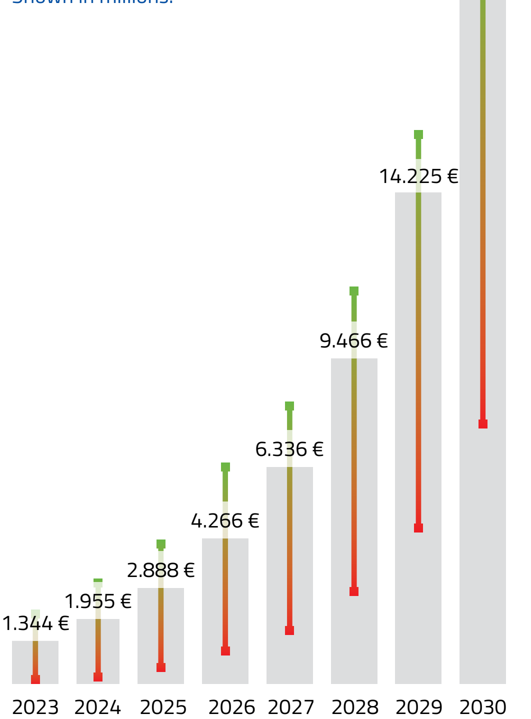
	Conservative	Realistic	Optimistic
YEAR 2030	7.711 M€	20.906 M€	22.263 M€

For this niche, the information was collected from two global studies, Precedence Research [53] and Grand View Research [54] and an additional study focused on the European market, Markets & Markets [55]. In relation to solar PV energy production, Global Market Insight report was revised.

Despite the fact that solar PV is a widespread technology around Europe, an exponential increase in renewable hydrogen production is expected – although estimates vary widely between the analysed reports.

Hypothesis and assumptions

Market size of European renewable hydrogen production 2023-2030.
Shown in millions.



Now

According to the studies examined, the present size of the global market situates in around **5,5 billion €**.

Outlook

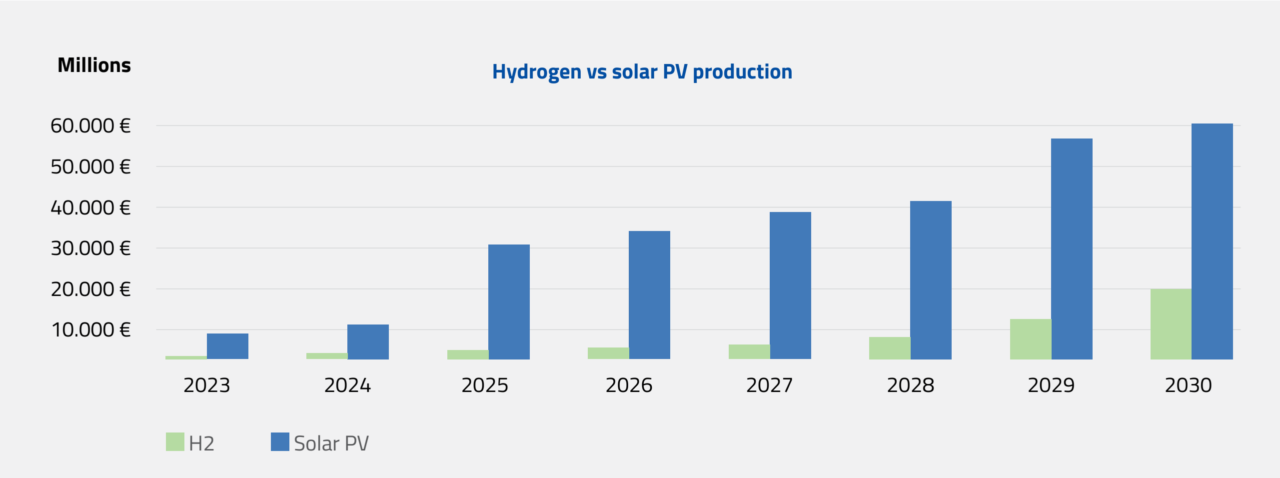
Despite high initial production cost, forecasts estimate CAGR between **24%** and **50%** worldwide, boosted by increasing demand of FCEVs expected.

Application

Mobility ans industrial production are the two main industries for renewable hydrogen application.

Location

The study focuses on Europe, one of the key players in renewable hydrogen technologies. During the last decade, according to IAE, **28%** of the patents related to renewable hydrogen were registered.



Manufacturers and suppliers of hydrogen storage and distribution systems.

334 M€

YEAR 2030	Conservative	Realistic	Optimistic
	791 M€	1.161 M€	1.344 M€

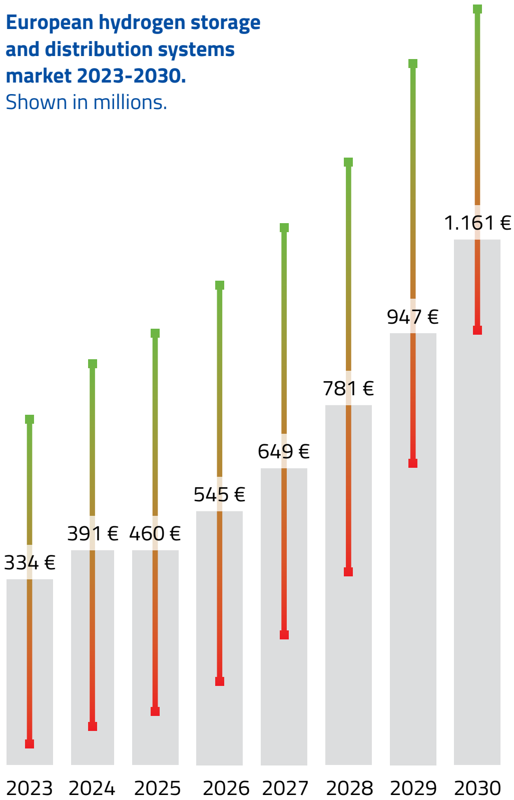
To analyse this market, we rely on three different global reports: Transparency Market Research [56], Markets & Markets [57] and Market Business Insight [58]. In the case of battery energy storage systems (BESS) which are used in renewable's industry, the Markets & Markets [59] report was reviewed.

Every link in the value chain is important for improving the efficiency, safety and potential of hydrogen deployment in urban mobility.

Due to the increasing use of clean energy sources, BESS (Battery Energy Storage System) have turned an important player. As Europe has ambitious plans towards non-fossil fuels fonts of energy, there is an emerging market which is expected to overpass € 40 billion by the end of the decade. The market for hydrogen storage and distribution systems is expected to reach in 2030 a 25% share of BEES market.

Hypothesis and assumptions

European hydrogen storage and distribution systems market 2023-2030.
Shown in millions.



Size

According to the International Energy Agency, hydrogen production is being lowered than expected. The hydrogen storage and distribution system market is still incipient.

Outlook

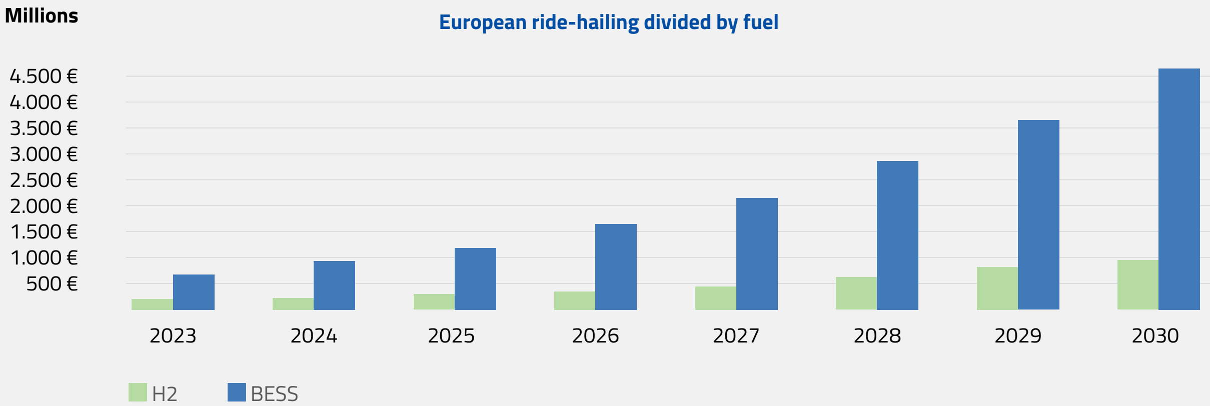
CAGR varies considerably according to different studies averaging **21%** growth.

Application

Hydrogen storage systems encompass a range of technologies and solutions, including compressed gas storage, liquid storage, metal and chemical hydride storage, and solid-state storage.

Location

We simply focus on Europe, whose market share is approximately **1/5** of the world's revenue.



Fuel cell and hydrogen fuel cell system development

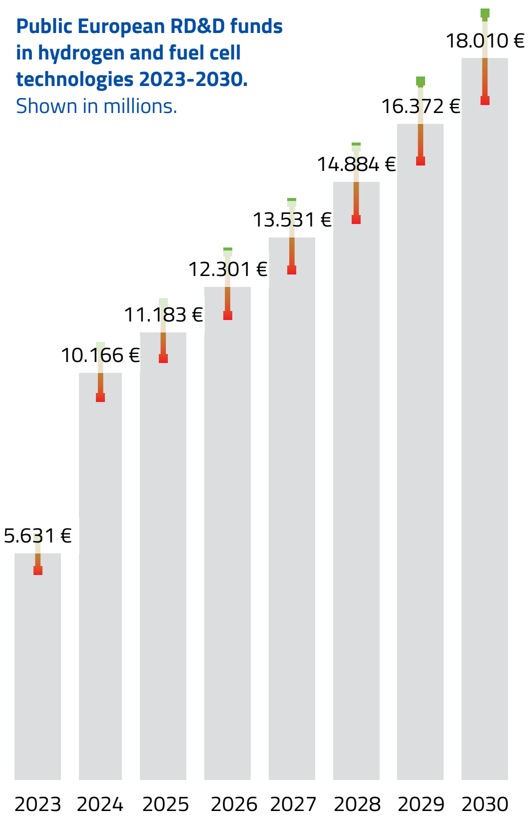
Continuous improvement of fuel cell technology is crucial to make vehicles more efficient and cost-effective. Three niche markets stand out within this opportunity:

Public RD&D spending in hydrogen and fuel cell technologies	Year 2023	5.631 M€

International Energy Agency's (IEA) database [60] of Energy Research, Development & Demonstration (RD&D) activities was reviewed to analyse European public spending (European Union and Member States) in hydrogen and fuel cell technologies. Another IEA's database was used to analyse the European public spending in clean energies R&D activities. In this case, given that hydrogen is still an emerging technology, it will receive much more funding for R&D activities than the other clean energies which are already well established in the market.

Hypothesis and assumptions

Public European RD&D funds in hydrogen and fuel cell technologies 2023-2030.
Shown in millions.



Leaders

France, Germany, Netherlands and Sweden are the countries who have allocated most resources to RD&D in hydrogen and fuel cell technologies during the last five years.

Outlook

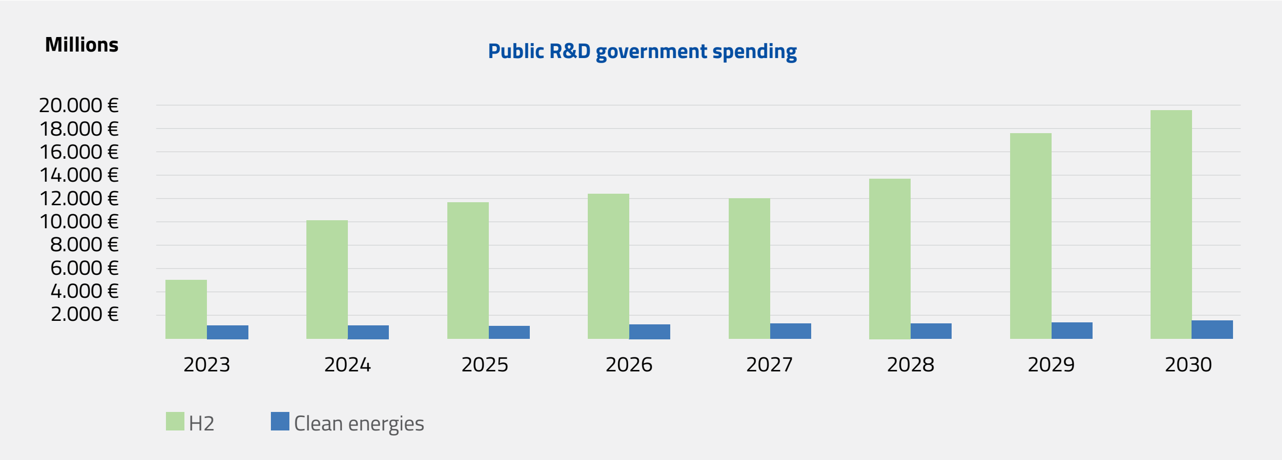
Although in early stages of a disruptive technology there is a strong support from public institutions in R&I activities, private investments take the lead when the technology has already matured.

Application

The study focuses on public RD&D spending in hydrogen and fuel cell technologies.

Location

IEA's studies counts the 43 European countries RD&D public spending.



Hydrogen applications in micromobility

In addition to larger vehicles, there could also be some niche opportunities in the micromobility space, such as hydrogen fuel cell electric scooters and bicycles. These vehicles could offer advantages in terms of range and faster charging times, making them more attractive to urban users. The uncertainty about this market is quite significant, as shown by the error bar in the chart below.

Engineering and development companies working on renewable hydrogen production technologies. 234 M€

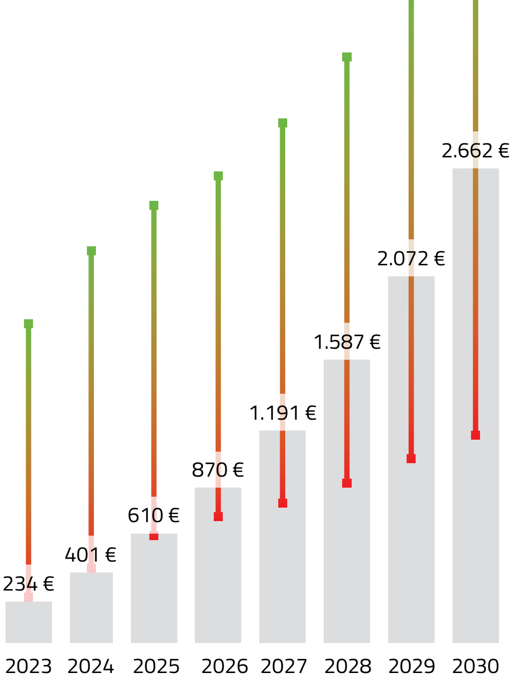
YEAR 2030	Conservative 1.184 M€	Realistic 2.662 M€	Optimistic 4.185 M€

Three different sources were analysed to study the European micromobility market: Business Wire [61], Grand View Research [62] and Market Research Future [63]. As for electric micromobility market, two reports of Markets and Markets [64] [65] have been considered.

Although hydrogen micromobility is still an emerging market, it is expected to increase ten times its size by 2030. Still, electric micromobility is much more settled among consumers.

Hypothesis and assumptions

European hydrogen-powered micro mobility market 2023-2030.
Shown in millions.



Leaders

European hydrogen powered micro mobility market is expected to overcome **2.500 € million** in 2030.

Outlook

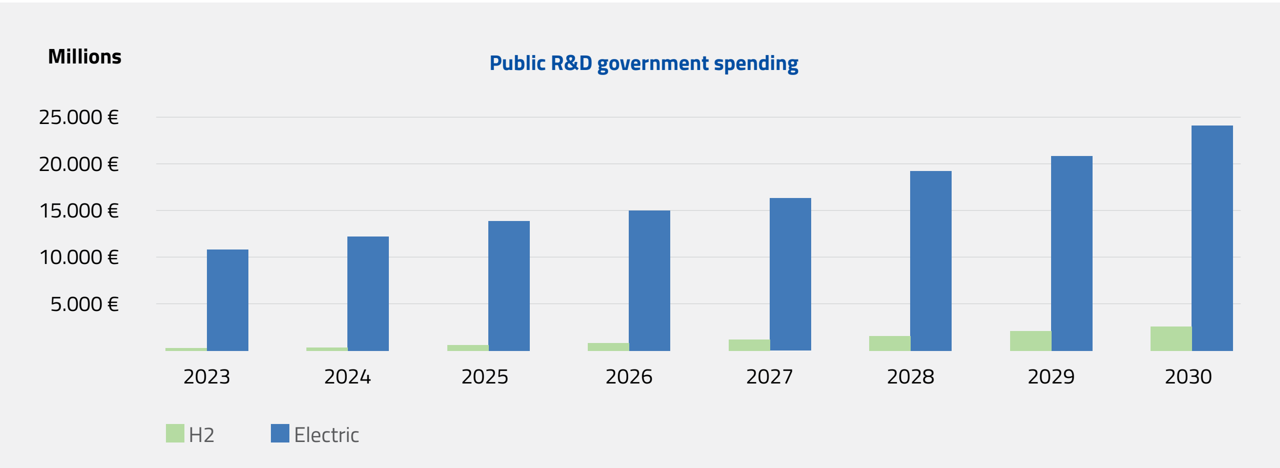
Despite representing a small proportion in micro mobility, hydrogen is expected to increase worldwide, accounting a **25%** in 2050.

Application

Bicycles, tricycles, scooters, skateboards, electric motorbikes, segways and motorcycles are considered in this study.

Location

European market represents **21%** of the global hydrogen micro mobility market.



Analysing the market potential of hydrogen in urban mobility shows that the technology's role within this sector will remain limited to a few applications. While there is a growing consensus that hydrogen will not be the go-to technology for light duty vehicles, there seems to be more opportunities for the technology in the trucks and buses segment. In addition, the research shows that hydrogen as energy storage can play a role in advancing mobility electrification in urban areas.

3 Use cases in urban mobility

To understand the key factors allowing the deployment of hydrogen solutions in urban areas, it is essential to analyse practical cases.

3.1 Case studies identification

Identifying and selecting relevant case studies is of utmost importance for stakeholders in the mobility sector. A systematic evaluation process is used to assess the suitability of each case study. Factors such as project scale, technological advances, cost-effectiveness, replicability, scalability, potential CO_2 emission reductions, energy requirements and social acceptability are considered during the selection process.

Through a thorough analysis of these case studies, policy makers, researchers and industry practitioners can gain valuable insights into some of the applications of hydrogen technologies in urban mobility.

Fourteen projects have been identified for study. A quantitative and qualitative prioritisation matrix (Annex A) has been drawn up to define the projects that best encompass use cases for hydrogen in urban mobility. To this end, a series of variables have been used: mode of transport, production, transport and storage infrastructure, station typology, characteristics of the region or the capacity for scalability and replicability.

3.2 In-depth case studies

Quantitative analysis

The following table provides an analytical framework for the use cases:

QUANTITATIVE ANALYSIS	Parameters	
i. Infrastructure deployment	CAPEX	Type of Technology
		Performance (Energy requirement & production capacities)
	OPEX	Maintenance costs of the technology
ii. Energy needs and CO_2 emission reduction potential	Energy needs	
	CO_2 emission reduction	
iii. Economic and environmental Impact	Economics Benefits	
	Environmental Benefits	

Table 2: Quantitative analysis for the use cases.

Below is a detailed explanation of each KPI, formula and variable to carry out the analysis.

Infrastructure deployment

CAPEX

Capital expenditures (CAPEX) represent significant expenditures that are not meant for day-to-day operational expenses but rather for long-term strategic investments in a business or project. CAPEX is a critical aspect of financial management for businesses and organizations as it plays a significant role in shaping their long-term growth, competitiveness, and operational capabilities. In the case of HRS it will be expressed in €/kWh or just directly €/kW assuming a determined number of working hours. Designing and building a hydrogen refuelling station involves several CAPEX that contribute to its overall functionality and efficiency. While the importance of each investment can vary based on specific circumstances and goals, here is a general ranking of CAPEX for a hydrogen refuelling station, from most important to least important:

1	**Hydrogen Production System**
	Electrolysis or other methods for hydrogen production
	High-quality and efficient hydrogen production equipment is crucial for the overall performance
2	**Compressor and Storage Systems**
	Compression systems for storing hydrogen at high pressure & storage tanks
	Components to ensure a continuous and reliable supply of hydrogen to the dispensers
3	**Dispensing Equipment**
	High-pressure dispensers for fuelling vehicles
	Safety features and user interfaces for smooth and secure fuelling operations
4	**Site Preparation and Installation**
	Groundwork, civil engineering, and site preparation
	Installation of all equipment and infrastructure
5	**Safety Systems**
	Safety measures such as leak detection, emergency shutdown systems, and ventilation
	Compliance with safety standards is paramount for public and environmental safety
6	**Utilities and Power Supply**
	Adequate power supply for the electrolysis process and station operations
	Connection to local utilities and backup power systems
7	**Hydrogen Purity and Quality Control**
	Equipment for monitoring and ensuring the quality and purity of the hydrogen produced.
	This is essential for meeting industry standards and ensuring vehicle performance
8	**Environmental Compliance and Permitting**
	Costs to obtaining necessary permits and ensuring compliance with environmental regulations
	Environmental impact assessments and mitigation measures
9	**Land and Real Estate**
	Cost of acquiring or leasing the land for the station
	Real estate costs can vary significantly depending on location
10	**Government Incentives and Subsidies**
	Costs associated with obtaining any available incentives, grants, or subsidies
	This may include incentives for promoting the use of hydrogen as a clean fuel source
11	**Operational and Maintenance Training**
	Training costs for staff responsible for operating and maintaining the station
	Proper training is essential for the safe and efficient operation of the facility

Table 3: Capital expenditures (CAPEX) factors ordered by order of magnitude.

It is important to note that the specific circumstances of each hydrogen refuelling station project can influence the relative importance of these investments. Additionally, technological advancements and changes in the hydrogen industry may impact the prioritization of certain CAPEX components over time. Finally, the hydrogen retail price strictly depends on the hydrogen production method, compression, storage, and distribution costs.

Hydrogen Production Method	Approximate Cost (EUR)	Notes
Steam Methane Reforming (SMR)	€1.50 - €2.50 per kg	Costs can vary based on natural gas prices, carbon capture implementation, and scale of the facility.
Electrolysis (PEM)	€4.50 - €6.50 per kg	Costs are influenced by electricity prices, capital costs of the electrolyser, and utilization rate.
Electrolysis (Alkaline)	€4.00 - €6.00 per kg	Costs can vary based on electricity prices, electrolyser, capital costs, and operational parameters.
On-Site SMR with Carbon Capture	€2.00 - €3.50 per kg	Capital and operational costs depend on the size of the SMR unit and the effectiveness of carbon capture technology.
Off-Site Hydrogen Supply	€2.00 - €3.00 per kg	Costs depend on the distance of hydrogen transport, compression, and storage requirements.

Table 4: Approximate cost of hydrogen according the production method
(Colour depending on the production method)

Type of Production Technology

Classical methods of hydrogen production such as SMR (Steam Methane Reforming), coal gasification and electrolysis are highly energy intensive and have a significant environmental impact. Thermochemical methods (reforming, gasification, pyrolysis) of hydrogen production result in emission of carbon dioxide to the atmosphere directly or indirectly through consumption of energy from emission sources [67]. The least energy-intensive method of producing hydrogen is electrolysis, in which water is broken down by an electric current. Hydrogen produced during electrolysis has a high purity of up to 99.99%. There are three main techniques used in electrolysis which include alkaline electrolysis, proton exchange membrane (PEM) electrolysis and solid oxide electrolysis (SOE). Alkaline electrolysis is the most widely used and has been commercially available for many years, but it is less efficient than PEM electrolysis. Alkaline electrolysers have lower capital costs than those with a proton exchange membrane, but lower electrical efficiency, which results in higher electricity costs. The third SOE technology is at the testing stage [68].

Performance (Energy requirement & production capacities)

The cost of producing hydrogen by electrolysis depends on many technical and economic factors, such as the number of hours the electrolyser is in operation per year, the efficiency of the process, and the price of electricity. The cost of the electrolyser stack (combined electrolyser cells) alone represents 50% of the capital cost of alkaline electrolysers and 60% of PEM-type electrolysers. It is assumed that as the operating time of the electrolyser becomes longer at full load, capital costs are less important, so the cost of purchasing electricity becomes the main component for the average cost of hydrogen production [4].

OPEX

Operational expenditures (OPEX) refer to the ongoing, day-to-day expenses that a company or organization incurs to maintain its regular business operations. Unlike CAPEX (Capital Expenditures), which involve investments in long-term assets, OPEX represents the costs necessary to run a business, keep it operational, and generate revenue in the short term. For a hydrogen refuelling station it represents the ongoing costs associated with the station's day-to-day operations and maintenance, which used to be expressed as a % of initial CAPEX/Year. Several variables can impact the OPEX of a hydrogen refuelling station, and it's essential to consider these factors when planning for the operational costs of such infrastructure.

1	**Electricity Costs**
	Energy costs for hydrogen production through processes like electrolysis
	Influenced by the electricity pricing structure
2	**Maintenance and Repairs**
	Regular maintenance of equipment, including compressors, dispensers, and storage systems
	Budget for unexpected repairs to ensure the continuous and reliable operation of the station
3	**Labour Costs**
	Salaries for station operators and maintenance personnel
	Skilled staff is crucial for smooth station operation and customer service
4	**Hydrogen Supply Costs**
	Costs associated with purchasing or producing hydrogen for the station
	Hydrogen supply costs can be influenced by production method, sourcing, and market conditions
5	**Insurance**
	Insurance premiums to cover potential liabilities, property damage, and other risks
	Comprehensive coverage is essential to protect against unforeseen events

6	**Utilities**
	Ongoing costs for utilities such as water, gas, and additional power supply
	Regular utility expenses for day-to-day operations
7	**Monitoring and Control Systems**
	Maintaining and upgrading systems that monitor hydrogen production, storage, and dispensing
	Ensures efficient and safe station operation
8	**Compliance and Regulatory Costs**
	Costs associated with complying with safety, environmental, and other regulations
	Regular audits and inspections to ensure adherence to industry standards
9	**Training and Certification**
	Ongoing training for staff to stay updated on safety protocols and operational procedures
	Certification and recertification costs for compliance with industry standards
10	**Waste Management**
	Costs related to the proper disposal or recycling of waste generated during station operations
	Compliance with environmental regulations regarding waste management
11	**Marketing and Outreach**
	Budget for promoting the station and encouraging the use of hydrogen vehicles
	Marketing expenses to attract and retain customers
12	**Lease or Land Use Fees**
	Ongoing fees associated with leasing the land or using the station location
	Lease agreements and associated costs for maintaining the property

Table 5: Operational expenditures (OPEX) factors listed by order of magnitude.

The ranking of OPEX components can vary based on factors specific to each hydrogen refuelling station [69]. Local market conditions, regulatory requirements, and advancements in technology may also influence the ongoing costs associated with operating and maintaining a hydrogen refuelling station [70]. It is important to conduct ongoing monitoring and cost management to optimize OPEX for a hydrogen refuelling station.

Maintenance costs of the technology

Maintenance costs in a Hydrogen Refuelling Station (HRS) have a significant impact on its OPEX and are crucial for ensuring the station's reliability and safety. Effective maintenance practices help prevent costly breakdowns, downtime, and potential safety hazards, reducing unexpected repair expenses. Regular maintenance activities, such as equipment checks, system inspections, and preventive servicing, not only extend the operational lifespan of the HRS components but also enhance its overall efficiency.

Estimating the annual maintenance costs for a hydrogen refuelling station (HRS) involves considering various factors such as equipment types, sizes, and local conditions. For instance, the maintenance of compressors, vital for station operation, may range from €9 000 to €27 000 or more annually. Hydrogen storage tank maintenance costs can be approximately €4 500 to €13 500 or more per year, depending on tank size and material. Dispenser maintenance, including routine checks and calibration, might incur costs ranging from €4 500 to €13 500 or more annually per dispenser. Electrolysers, if part of the station, could have maintenance costs ranging from €18 000 to €45 000 or more each year, based on technology and capacity. Monitoring and control systems may require €4 500 to €13 500 or more in annual maintenance costs, depending on system complexity. Piping and connection maintenance costs could be in the range of €4 500 to €13 500 or more per year, contingent on the extent of the network. Safety systems, crucial for compliance and emergency situations, might incur €4 500 to €13 500 or more in annual maintenance costs. General site maintenance, including landscaping and lighting, could range from €4 500 to €18 000 or more annually, depending on the size and location of the site. These estimations provide a broad overview, and actual costs may vary based on specific circumstances and local market conditions. It can therefore be estimated that the **maintenance costs** for one year of a hydrogen refuelling station approximate to the amount of **€220 000.**

Energy needs and CO_2 emission reduction potential

Energy needs

Energy is a central factor influencing both the Operational Expenditure and Capital Expenditure of a Hydrogen Refuelling Station. In terms of OPEX, ongoing expenses tied to electricity or other energy sources required for hydrogen production and dispensing can be substantial. Efficient energy management becomes crucial for controlling operational costs and ensuring the station's long-term profitability. On the CAPEX side, the choice of energy infrastructure and technology during the station's design phase significantly shapes the initial investment. Opting for more energy-efficient equipment and renewable energy sources may entail higher upfront costs but holds the potential for lower long-term operational expenses. Striking a balance between these considerations is essential for the economic viability and sustainability of the HRS, emphasizing the pivotal role of energy cost considerations in the planning and management of hydrogen infrastructure projects.

CO_2 Emission Reduction Potential

The CO_2 emission reduction potential of a hydrogen refuelling station quantifies the environmental benefits derived from transitioning to hydrogen as a cleaner energy source compared to conventional fossil fuels. Using carbon dioxide equivalent (CO_{2e}) emissions as the unit of measurement, this potential is calculated through a protocol based on the UNE-EN ISO 14064-1, widely recommended for the European Union[16]. This approach ensures a comprehensive assessment of environmental impact by considering the potential influence of other greenhouse gases. The expression of reduction potential in CO_{2e} units provides a standardized and meaningful way to communicate the environmental advantages of hydrogen, crucial for environmental impact assessments, policy decisions, and the overall sustainability evaluation of hydrogen infrastructure. The reduction potential varies based on factors such as the hydrogen production method, energy sources, transportation methods, and the overall efficiency of the hydrogen production and distribution process.

Economic and environmental Impacts

Economics Impacts

A hydrogen refuelling station can offer several economic benefits, including job creation, reduced operating costs for vehicles, and diversification of energy sources. By providing clean and efficient fuelling options, these stations can stimulate economic growth through infrastructure investments, create employment opportunities in the hydrogen industry, and ultimately contribute to a more sustainable and resilient urban transportation system.

Environmental Impacts

The adoption of hydrogen as a fuel can lead to lower fuel price volatility, reduced healthcare costs due to decreased air pollution, and enhanced energy security by diversifying away from fossil fuels. Overall, hydrogen refuelling stations can play a role in promoting economic sustainability, environmental stewardship, and energy resilience in urban mobility.

[16] The protocol involves determining a baseline of CO_2 emissions that would occur with conventional fossil fuels, calculating the actual emissions associated with hydrogen production and usage, and expressing the reduction in CO_2 emissions in CO_{2e} units.

3.3 Case studies

Buses feeded by the HRS in Hafencity Hamburg

QUALITATIVE

H2: Green Hydrogen

Mode: 20 buses

Hydrogen generation system

On-site production (335kg/day) plus pipeline under construction to increase supply.

Location

The hydrogen refuelling station will be located at the eastern entrance of HafenCity Hamburg, allowing production within the city and easy access to transport.

Property & stakeholders

Linde Engineering, commissioned by Hamburger Hafen und Logistik AG.

Typology of the storage system

Two storage tanks are available; a Medium pressure tank with a maximum capacity of 500 kg and a High pressure tank with a maximum capacity of 300 kg.

Affected population

This innovative hydrogen initiative directly impacts a population of 1,841 million inhabitants and It is estimated that they have carried more than 3.5 million passengers.

QUANTITATIVE

I		II		III	
Infrastructure deployment		**Energy needs and CO2 emission reduction potential**		**Economic and environmental benefits**	
CAPEX	**OPEX**	**Energy**	**CO2**	**Economic**	**Environmental**
3.700.000 €	720.000€/y	11 GWh	4961 Tons/y	2.525.250 €	1.529.009 €

Occitanie H2 Corridor

QUALITATIVE

H2: Green Hydrogen

Mode: 40 trucks
62 refrigerated units
15 regional inter-urban buses

Hydrogen generation system

The production of 6 tonnes of hydrogen per day by electrolysis (and possibly biomass).

Location

The successful outcome for the Corridor H2 project is due to the commitment of the Region Occitanie to drive the project (at political and technical level).

Property & stakeholders

Lhyfe and AREC Occitanie (the regional energy and climate agency). Co-financiers are the EU and the European Investment Bank

Typology of the storage system

2 production sites for 8 stations producing between 600 and 1200 kg per day.

Affected population

This innovative hydrogen initiative directly impacts a population of 5,933 million inhabitants.

QUANTITATIVE

I	II	III
Infrastructure deployment	**Energy needs and CO2 emission reduction potential**	**Economic and environmental benefits**
CAPEX / **OPEX**	**Energy** / **CO2**	**Economic** / **Environmental**
114.000.000 € / **14.420.000€/y**	**75 GWh** / **3140 Tons/y**	**40.515.000 €** / **20.976.000 €**

Inclusion of hydrogen-powered vehicles in the TMB fleet

QUALITATIVE

H2: Green Hydrogen

Mode: 8 Buses

Hydrogen generation system

Utilizing Green Proton Exchange Membrane (PEM) technology, the system can produce an impressive annual output of 300 tons of green hydrogen.

Location

It has been implemented in the city of Barcelona in urban and interurban areas (connection with the airport).

Property & stakeholders

Operated in public-private collaboration.
Key entities include; Transportes Metropolitanos de Barcelona (TMB) and Iberdrola.

Typology of the storage system

Employing high-pressure compression techniques, hydrogen is stored at pressures ranging between 450 and 500 bar, maintaining a gaseous state for efficient storage and distribution.

Affected population

This innovative hydrogen initiative directly impacts a population of 1.6 million inhabitants and is estimated to have carried more than one million passengers.

QUANTITATIVE

I	II	III
Infrastructure deployment	**Energy needs and CO2 emission reduction potential**	**Economic and environmental benefits**
CAPEX / **OPEX**	**Energy** / **CO2**	**Economic** / **Environmental**
4.000.000€ / 13.330€/y	2.4 GWh / 209 Tons/y	1.200.000 € / 139.470€

4 Framework conditions for hydrogen deployment

4.1 Regulatory framework

The European Union (EU) has set clear objectives to reduce greenhouse gas emissions and become carbon neutral by 2050, adopting a set of policies to reach this goal, including the European System Integration Strategy [71], the European Hydrogen Strategy [72], the Sustainable and Smart Mobility Strategy [73]. These policies, approved by the European Commission in 2020, include the transport sector as one of the end-use sectors in which the EU should promote the use of hydrogen, as an energy vector - especially renewable hydrogen - to contribute to the objectives of decarbonising the energy system. In particular, transport was considered one of the sectors to decarbonise and where the use of hydrogen as a fuel would be appropriate, together with the use of other renewable and low-carbon fuels, in cases where electrification is not feasible, either for a lack of technical and/or financial viability, and subject to the energy-efficiency-first principle.

The regulation applicable to hydrogen production, transport, storage, and end-use supply sets the conditions to the deployment of hydrogen for mobility usage and for complying with the renewable energy targets, albeit the regulatory challenges will differ depending on the design of the infrastructure. It is also important to consider that the regulation applicable to the whole hydrogen value-chain is largely defined at a national level and may vary from country to country, depending on the transposition or implementation of the European regulatory framework. This report presents the main regulatory barriers identified in each stage of the hydrogen value-chain – production, transport and storage, and end-use supply – at a European level.

Production

First regulatory barrier: lack of a dedicated regulatory framework for hydrogen production:

> Hydrogen remains currently treated, from a regulatory point of view, as an industrial gas. With the adoption of the new EU Hydrogen and Decarbonised Gas Market Package, it will also be regulated as an energy carrier. Consequently, at present, all forms of production of hydrogen, either at small or large scale, will require permitting as an industrial activity.

Recommendation:

> The establishment of a proper regulatory framework for hydrogen that specifically addresses different types of hydrogen production for energy uses, clearly distinguishing

between renewable and low-carbon hydrogen from hydrogen produced from fossil sources and prioritise the production and use of the former.

Second regulatory barrier: urban land restriction for hydrogen refuelling stations (HRS):

Hydrogen production is usually considered as production of inorganic gas, included in the chemical industry. This has important consequences from an urban planning perspective, since its classification as industrial often requires these types of plants to be located only within industrial areas, limiting the location of any hydrogen producing facility. HRS where hydrogen is produced on-site (from small scale electrolysers), may find some restrictions to establish and operate in cities and other urban areas.

Recommendation:

Where relevant, exemptions for hydrogen could be considered at national level, as the European Union has limited competences on land planning.

Third regulatory barrier: undifferentiated environmental regulatory requirements for large chemical installations and small-scale hydrogen production:

According to Directive 2011/92/EU ("Directive on environmental assessment") and Directive 2010/75/EU ("Industrial Emissions Directive"), projects, and activities to produce basic inorganic chemicals, such as hydrogen production, must obtain a favourable environmental assessment (EIA) and an environmental permit. The concept of "integrated chemical installations" depends on the scale of production, which is not defined at the European level. Currently, criteria for EIA and permitting differ between Member States, creating an uncertain regulatory environment even for small scale projects.

Recommendation:

Considering a *de minimis* exception to explicitly exclude small-scale hydrogen production sites from the scope of the aforementioned directives.

Transport and storage

Regulatory barrier: lack of a regulatory framework for dedicated hydrogen networks and storage facilities:

The development of hydrogen refuelling infrastructure is, on one hand, highly dependent on the deployment of hydrogen transport and storage infrastructure, and on the second hand, on the regulatory framework that governs them. The development of this infrastructure will be determinant on the success of HRS with no *in situ* production, as transport through pipelines could be the most cost-efficient way to obtain the supply of hydrogen. This is why clear access rules to transport, and distribution networks is necessary to ensure that small and retail consumers, such as HRS, receive their hydrogen supply in the most cost-efficient way.

The efforts for establishing a regulatory framework dedicated to the development of EU hydrogen markets finally reached an agreement [75] with the Hydrogen and Decarbonised Gas Market Package ("Hydrogen Package")[17] [76].

Recommendation

A close follow-up on the development of the transitory regulatory framework will be necessary to evaluate if it incentivises investment and competition and access to the transport networks to all interested third parties.

End-use supply

First regulatory barrier: lack of a coherent alignment between the Trans-European Networks for Energy (TEN-E) and the Trans-European Transport Network (TEN-T) to ensure the flow of investments needed to meet the new Alternative Fuels Infrastructure Regulation (AFIR) infrastructure targets.

Recommendation:

A coherent alignment, at European level, between the TEN-E and the TEN-T to ensure the flow of investments. This alignment rests on the foundation of sound infrastructure planning, informed by the ten-year network development plans (TYNDP).

Second regulatory barrier: no differentiation between types of HRS:

When it comes to HRS, it should be noted that the AFIR does not distinguish between stations that produce on-site hydrogen for refuelling and stations that only store hydrogen for refuelling. It could be problematic if Member States' national regulations were to establish differentiated permitting procedures depending on whether the refuelling station generates on-site or only stores hydrogen.

Recommendation:

A more detailed definition within the AFIR framework in order to facilitate implementation and ensure consistency at Member State level.

[17] The package includes a *Proposal for a Directive of the European Parliament and of the Council on common rules for the internal markets in renewable and natural gases and in hydrogen (recast)* and the *Proposal for a Regulation on the internal markets for renewable and natural gases and for hydrogen (recast)*.

4.2 Exogeneous factors

At a generic level, literature, own expertise, and discussions with experts have identified the main concerns about hydrogen adoption in urban mobility:

Public perception and social acceptance

Public awareness and perception of green hydrogen shows limited awareness, especially in regions like Eastern Europe [77].

Research shows that social acceptance is essential for the widespread adoption of green hydrogen applications, influenced by factors such as energy transition policies, sociodemographic elements, psychological factors, costs, technical aspects, and familiarity with the technology [80]. Positive experiences, especially with fuel cell vehicles, contribute to greater acceptance by minimising concerns about hydrogen safety. These experiences enhance knowledge, promoting pro-environmental attitudes that favour the acceptance of green hydrogen [81].

Cost and affordability

The predominant focus of research on costs has centred around the transportation sector, particularly private vehicles. Studies suggest that while cost remains a crucial factor[3], individuals are willing to pay more for emission-free fuels, especially if they match conventional vehicles in performance [82]. For potential consumers, environmental awareness distinctly influences the intention to purchase and utilize green hydrogen and its associated technologies [83] [84].

However, scant attention has been given to the acceptance of green hydrogen in public transportation. Since environmental concern remains a pivotal variable [85], providing technical information on the potential environmental impacts of technologies can enhance the acceptance of green hydrogen [86].

Safety concerns

Research on the safety of green hydrogen has primarily aimed to understand public perceptions, acknowledging the common view of hydrogen as a highly explosive substance [87].

Major safety apprehensions are directed toward the storage and transportation of green hydrogen rather than its end use in the transportation sector, with safety concerns in hydrogen storage being significantly overlooked [88]. Trust emerges as a pivotal variable, influencing safety perceptions and acceptance. For instance, in Taiwan, trust in local industry and adherence to safety standards have alleviated safety concerns [89].

This underscores the importance of addressing safety perceptions of technologies associated with green hydrogen, particularly in storage, transportation, and pipeline use sites. Building trust, ensuring technology availability, and establishing legitimacy in implementation are crucial in managing risk perceptions in this domain [80].

Supply chain and procurement

The use of hydrogen in urban mobility faces supply chain and procurement bottlenecks, mainly related to the infrastructure for hydrogen production, storage and transportation. The lack of ubiquitous hydrogen refuelling stations is a major obstacle to the adoption of hydrogen in mobility. Each filling station requires considerable investments, and a value chain that supplies hydrogen is also needed [80].

More and more cities support technological innovation in the production, storage and transportation of hydrogen, but there is a lack of support for R&D to promote the use of hydrogen in the energy, industry and construction sectors [90]. The high costs associated with the use of hydrogen and fuel cells in the transport sector, as well as the need for significant investments in infrastructure, are also mentioned as main challenges [14].

In addition, the importance of overcoming obstacles to the production of green hydrogen and the importance of transportation infrastructure in the development of the clean hydrogen value chain are emphasized [91].

5 Conclusions and recommendations

5.1 Analysis of the results

A comprehensive examination of hydrogen adoption in urban mobility leads to a landscape with many social, technological, and economic variables.

The assessment of prominent projects has brought to light suitable applications for hydrogen in urban mobility, albeit with significant variations across modes of transportation. The most widespread use cases for hydrogen are related to busses, which have, for the most part, demonstrated a positive impact, as well as for vehicles (vans and trucks) integrated into the municipal fleet. In contrast, both hydrogen cars and hydrogen-powered trains and trams fail to enhance the efficiency exhibited by electric cars and trains.

The overall conclusion is that the uptake of hydrogen in urban mobility is not a linear process. Successfully deploying the technology requires a multi-faceted strategy that includes informed public participation, targeted safety communications, strategic infrastructure development and a strong supply chain. The value chain, with its intricate web of connections, serves as a guide and underlines the need for an integrated and holistic approach to navigate the complexities inherent in developing a sustainable hydrogen ecosystem in urban mobility.

5.2 Implications and relevance

The study underlines the importance of targeted interventions by public and private funding entities, strategically designed to fill the existing infrastructure gaps.

The main advantages of using hydrogen fuel cell vehicles are their fast charging, long autonomy, and minimal emissions. However, research and development of advanced technologies are necessary to address the main disadvantages of hydrogen fuel cells, such as the cost of (green) hydrogen production, transportation, storage, and distribution. Additionally, hydrogen must overcome challenges inherent to new technologies, such as the lack of scalability, infrastructure, and efficiency improvement. As mentioned earlier, these advantages and disadvantages vary significantly depending on the mode of transportation and its application.

Regarding rail vehicles, based on the analysed projects, there appears to be a growing consensus on the greater cost-benefit efficiency of electric trains compared to hydrogen trains. However, not all cities have interconnected catenary systems, which opens a niche for hydrogen trains.

5.3 Recommendations

This study recommends practical and actionable strategies to enable the adoption, where relevant, of hydrogen-based solutions for urban mobility. The multifaceted challenges require a comprehensive and strategic response, addressed holistically by the following recommendations:

1. The development of a conducive policy environment is pivotal in fostering an ecosystem that encourages and supports the adoption of hydrogen-based solutions in the context of the transition to zero-emission transportation, with a particular focus on public transportation fleets.

2. Public-private partnerships are required to address safety issues, ensure widespread accessibility to refuelling stations, optimise hydrogen production technologies, etc. Strategic investments can accelerate the establishment of a comprehensive refuelling infrastructure network. Policy-makers and industry stakeholders should collaborate to identify strategic locations and deploy resources efficiently, ensuring widespread accessibility to refuelling stations.

3. Safety concerns can be effectively addressed through a concerted effort to build trust, adhere rigorously to safety standards, and communicate effectively with the public. Transparent communication regarding safety measures and adherence to stringent standards can assuage concerns. Collaborative initiatives involving industry players, regulatory bodies, and local communities can play a pivotal role in establishing safety as a non-negotiable priority.

4. To optimise hydrogen production technologies and make them cost-effective and sustainable, collaborative research and development efforts are essential. Public-private partnerships, academic-industry collaborations, and international cooperation can drive innovation and efficiency in hydrogen production. These initiatives should focus on enhancing the scalability, efficiency, and environmental sustainability of hydrogen production methods. Collaborative efforts, such as hydrogen valleys, are already being implemented.

5. Robust public awareness campaigns and targeted educational initiatives stand as cornerstones in overcoming the prevailing lack of awareness and perception hurdles. A concerted effort to inform, engage, and empower the public is crucial. Collaborative endeavours involving governmental bodies, educational institutions, and advocacy groups can play a pivotal role in disseminating information about the role hydrogen can play in urban mobility.

In essence, these recommendations provide a roadmap for stakeholders, including policymakers, industry players, and advocacy groups, to navigate the intricate landscape of hydrogen adoption in urban mobility. The successful implementation of these recommendations can contribute to the wider shift towards sustainable and cleaner urban transportation systems.

Annex A

Case Studies	TYPOLOGY MATRIX							TARGET LEVEL
	Transport application	Hydrogen production type	Transport infrastructure	Storage infrastructure	Refuelling Stations	Region Size & density	Replication and Scalability	Adequacy
H2 HafenCity	Buses, 10-20 units 3 Ships (ferries)	Green Approx. 355 kg/day	Hydrogen gas pipeline under construction receiving H2	Medium pressure tanks: max. 500 kg, High pressure tanks:300 kg	Located at a highly frequented place and in an urban zone	1,8 M. inhabitants 2500 inhab/ km2	Medium	★★★★★
Clean Energy for All Europeans (CE4A)	35 cars (taxi fleet)	Green	N/A	N/A	The nearest station is in Rhoon, 35 km away.	0,5 M. inhabitants 5890 inhab/ km2	Low	★★
H2 Aberdeen	28 cars, 15 bus, 2 waste trucks, 3 sewer, 9 vans	Green	Aberdeen's onsite production ensures no transportation	N/A	2 publicly accessible (HRS)	202 k inhabitants 1000 inhab/ km2	High	★★★
Occitanie H2 Corridor	40 trucks, 62 trailers, 15 buses	Green	Fleet of trucks	N/A	2 HRS with 6 tn day	5.93 M inhabitants 82 inhab/ km2	High	★★★★★
Coradia iLint.	Train, 1 unit	Electrolysis & Steam reforming	N/A	Storage at 35 Mpa (on board)	Mobile refuelling station	7,98 M inhabitants 167 inhab/ km2	Over	★★
Hydrogen Viking	1 vessel	Electrochemical reactions with the LNG	c-type insulated tanks	storage 40' ISO c-type container	N/A	492 k inhabitants 57,3 inhab/ km2	Medium	★★★
In-der-City-Bus GmbH (ICB)	Buses, 13 units	TBD	N/A	It is stored in gas form, in roof-mounted composite tanks	Capacity to refuel at least 22 fuel-cell buses per day	760 k inhabitants 1780 inhab/ km2	Medium	★★★★
Caetano-TMB	Buses, 6 units, 1 in operation and 5 in testing phase	Green (PEM) can generate 300 tons of green H2 year	The electrolyzer is on site	Hydrogen is compressed to pressures of between 450 and 500 bar	One exclusive refuelling station for buses	1.6 M. inhabitants 15900 inhab/km2	High	★★★★★

Case Studies	TYPOLOGY MATRIX							TARGET LEVEL
	Transport application	Hydrogen production type	Transport infrastructure	Storage infrastructure	Refuelling Stations	Region Size & density	Replication and Scalability	Adequacy
Dinamarca	Fuel cell Buses, 200 units	Green – Plant in Herning to supply stations	N/A	Underground hydrogen storage and compressed air energy storage	Various service stations	5.9 M inhabitants 138 inhab/km2	Low	★★★
ZEFER and H2ME	Cabs, 100 units	Green- A 2 MW electrolysis facility 1000 kg of H2/day	N/A	N/A	One hydrogen refuelling station (HRS)	1.366.301 inhabitants 4,4 inhab/km2	Medium	★★★
HYPE	Cabs, 700 units	Green – One electrolyzer 1 ton/day	Hydrogen with on-site production	N/A	7 hydrogen refuelling station (HRS)	2.25 M inhabitants 20,64 inhab/km2	High	★★ ★★
ENGIE	Vans, 50 units	Green - Electrolyzer with a capacity of 20 kg/day	Hydrogen with on-site production	N/A	One hydrogen refuelling station (HRS)	12.4 M inhabitants 1,03 inhab/km2	Low	★★★
FEBUS	Eight 18m-long fuel cell-powered buses	Green - 268 kg hydrogen produced on site per day	8 distribution points, 70t of hydrogen distributed	1 storage capacity of < 1t equivalent	1 operational hydrogen station	162.000 h 2,46 inhab/km2	High	★★ ★★
MTPF	Taxis, 1000 units	Green – 10MW by 20MW Solar Plant	The recharging point is in the production plant	N/A	HRS with capacity at 700 bar/Mpa, up to 10kg of hydrogen day	6.9 M inhabitants 862 inhab/km2	Low	★★★

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