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Too Fast and/or Too Furious?
BMW's Commitment to Fuel Cell Technology

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CASE STUDY

Abstract

This case study examines the emergence of hydrogen as an alternative fuel in Germany and Europe, with a particular focus on BMW's strategic bet on fuel cell electric vehicles (FCEVs). In response to stringent environmental regulations and changing consumer awareness following the Volkswagen diesel emissions scandal, automakers such as BMW are being forced to explore more sustainable fuel options. This analysis allows students to apply key strategic concepts to evaluate BMW's hydrogen strategy within the competitive landscape of the automotive sector. The case study not only highlights BMW's strategic responses to regulatory pressures, but also encourages students to consider the broader implications for the future of vehicle fueling. By analyzing the resources and capabilities required to play a leading role in the transition to alternative fuel systems, students gain insight into the long-term strategic maneuvers necessary to secure a competitive advantage in this evolving market.

Both individual parts aim to identify on value creation in different segments of the automotive sector. While one study assesses the environmental impact and sustainability opportunities of FCEVs throughout their life cycle (life cycle assessment), from production to disposal, the other study compares the "traditional automotive value chain" with that of battery electric vehicles (BEVs) and FCEVs and elaborates the disruptive trends.

Keywords: Corporate Strategy, Fuel Cell Electric Vehicles, BMW, Technology Strategies, Innovation, Network Externalities, Sustainable Competitive Advantages, Value Creation

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Introduction

In June 2023, Oliver Zipse, Chairman of the Board of Management of the BMW Group, stood in his office on the 22nd floor of the company's iconic four-cylinder headquarters in Munich, Germany, and gazed thoughtfully into the future. His vision for the company included an expanded range of powertrain options with a particular focus on hydrogen fuel cell vehicles (FCEVs) to complement existing diesel and gasoline internal combustion engines (ICEs), plug-in hybrid electric vehicles (PHEVs) and pure battery electric vehicles (BEVs).

Zipse believed that by prioritizing the reduction of carbon emissions throughout the lifecycle of its products, BMW could redefine the definition of luxury mobility and combine it with exceptional sustainability. This strategic move would increase BMW's influence in the market and strengthened the company's economic resilience.

However, investors were cautious, as reflected in a price-to-earnings ratio of only four times earnings and a market-to-book ratio of 0.7. These figures indicated that the investment community was not very optimistic about BMW's prospects.

Hydrogen had already established itself as a valuable commodity in the EU in mid-2023. Experts predicted that demand in Europe could grow to nearly 70 million tons by 2050, driven by the chemical and manufacturing industries and the transportation sector.

Frank Weber, Board Member for Development at BMW, captured the company's commitment succinctly when he said: "We want to be there when something new is created". *But is BMW's strategy of betting on FCEV technology too fast and furious?*

Company Overview

Bayerische Motoren Werke AG (BMW) traces its roots back to 1916, when two companies, "Flugmaschinenfabrik Gustav Otto" and "Bayerische Flugzeug Werke AG (BFW)", merged in response to a government directive. Originally founded by Karl Rapp and Gustav Otto, the company was officially renamed Bayerische Motoren Werke GmbH in 1917 and became a

stock corporation in 1918 (BMW, 2024a). BMW originally focused on manufacturing aircraft engines before moving into automobile production in the 1920s.

In the 1970s, BMW introduced the 3 Series, 5 Series, and 7 Series, which formed the core of BMW's heritage and established its image of luxury and performance (Mahmoud, 2023). The acquisition of the Rover Group followed in 1994, which BMW later sold in 2000, retaining only the MINI brand. To further expand its luxury segment, BMW acquired the Rolls-Royce brand in 1998 and began production of Rolls-Royce-branded vehicles in 2003 (BMW, 2024b). Today, BMW is one of the largest companies in Germany, employing approximately 154,950 people and generating revenues of 155 billion euros in fiscal year 2023, with Europe, the U.S., and China representing the largest market segments (BMW Group, 2024b; Statista, 2024a) (*Appendices 1 and 2*). Globally, it is one of the top 15 automakers, assembling 2.56 million cars and 215,900 motorcycles per year and capturing a 4.24% market share (Statista, 2023a, 2023b, 2024a).

Financial Performance BMW has experienced financial volatility over the decades, most notably in 1959 when it narrowly avoided acquisition by Mercedes-Benz thanks to a critical \$1 million investment from the Quandt family. The threat of acquisition in the late 1950s spurred BMW to prioritize cutting-edge vehicle technology, culminating in the introduction of the “New Class”¹ in the early 1960s. BMW's commitment to pioneering innovation has been a driving force behind its strategic initiatives, resulting in several major technological breakthroughs (BMW Group, 2024a; BMW, 2024) (Appendix 3).

By the end of 2023, the Quandt family owned 42% of the company and was BMW's largest shareholder, followed by established asset, insurance and portfolio management firms such as Vanguard and Amundi (Forbes, 2024; MarketScreener, 2024). These long-term investors focus

¹ Introduced in the 1960s, BMW's New Class was a series of compact, powerful mid-size cars with a modern design and advanced engine technology that shaped BMW's reputation as a manufacturer of driver-oriented premium vehicles. It marked a bold new beginning and laid the foundation for the future direction and development of the company's entire model portfolio.

on dividends rather than short-term share price fluctuations. Zipse noted that high profitability and growing market share are key performance indicators for the company, as they are also the basis for a positive share price performance and a high dividend payout, which is what most investors are looking for (BMW Group, 2022). BMW utilized the issuance of bonds as a primary method of financing its operations and has consistently maintained an “A” credit rating from S&P, the best among European automakers (Paul & Ferraris, 2023).

A summary of financial data is provided in *Appendices 4 and 5*.

Environmental Sustainability With the appointment of its first environmental officer in 1973, the company has been rewarded for its approach to innovation and environmental sustainability by being ranked among the top three automakers in the Dow Jones Sustainability Group Index² since its inception in 1999 (BMW Group, 2024a).

BMW's commitment also extends to the global stage, as demonstrated by its participation in the United Nations Climate Change Conferences starting in 1992. Another important step was joining the United Nations Global Compact in 2001, in which BMW endorsed the ten core principles in the areas of human rights, labor standards, environmental protection and anti-corruption (BMW Group, 2024a). In 2000, BMW defined sustainability as a guiding principle of its corporate strategy and published its first Sustainable Value Report in 2002.

In 2008, BMW launched Project i³ marking a strategic pivot towards sustainable mobility. This initiative led to the release of the BMW i3 in 2013, which featured innovative production techniques and the use of lightweight materials like carbon fiber-reinforced plastic to reduce vehicle weight significantly (BMW Group, 2020). By joining the Science Based Targets Initiative's Business Ambition for 1.5°C⁴ in 2021, BMW set a precedent as the first German

² It represents the top 10% of the largest 2,500 companies in the S&P Global BMI based on long-term economic, environmental and social criteria.

³ Project i focused on reducing CO₂ emissions, promoting circular economy and fulfilling the Paris Climate Agreement, with the ultimate goal of offering a portfolio of all-electric models across all major market segments.

⁴ The Science Based Targets initiative (SBTi) develops standards and tools for companies to set emissions reduction targets aligned with limiting global warming, aiming for net-zero by 2050.

automaker to align with the goals of the Paris Agreement⁵. This move was indicative of a broader trend towards sustainability in the automotive industry, particularly in Europe (BMW Group, 2020).

As the early 2020s unfolded, BMW was advancing its sustainable mobility strategy with a significant expansion in its electric vehicle (EV) lineup. This development was a cornerstone of BMW's goal to achieve carbon neutrality by 2050. The company not only diversified its portfolio with numerous new electric models but also rigorously enhanced its manufacturing processes to reduce carbon emissions. In parallel, recognizing the potential of emerging technologies, BMW was investing in hydrogen fuel cells as a complementary solution to battery electric vehicles. In 2022, the company underscored this commitment by launching a pilot fleet of hydrogen-powered vehicles. This initiative served to refine the technology through real-world applications and prepare for its broader adoption in future mobility ecosystems (Agora Verkehrswende, 2022).

Accordingly, Oliver Zipse underlined in the beginning of 2024 the dual pursuit of environmental sustainability and financial performance as cornerstones of BMW's strategy: "Sustainability and economic success go hand in hand at the BMW Group. As a premium manufacturer in particular, we aspire to lead the way when it comes to sustainability" (Wermke, 2024)

The Landscape of the Automotive Industry

The automotive industry is one of the largest and most diverse sectors in the world, comprising numerous entities such as manufacturers, suppliers, dealers and service providers. As a key player in the global economy, it contributes significantly to the economic growth of many countries and has created multiple employment opportunities. The industry is continuously shaped by dynamic trends including technological advancements, regulatory requirements,

⁵ The Paris Climate Agreement of the United Nations is intended to ensure that global warming is limited to well below 2° C compared to pre-industrial times; the states even want to try to limit warming to 1.5° C.

consumer preferences and macroeconomic factors (iggrabs, 2019; Reichert, 2020; Trang Rausch-Phan & Siegfried, 2022). These factors are forcing the industry to constantly evolve and adapt to changing consumer demands and environmental regulations.

In Germany, where BMW is headquartered, the automotive industry is a cornerstone of the economy, generating significant industry revenues of €54.2 billion in 2023 (Reichert, 2020; Statista, 2024d). Germany has dominated the global automotive market for the past two decades, particularly in the premium vehicle segment, which accounted for 5% of the German economy (Dmitracova, 2023; Krzywdzinski, 2022).

Premium vehicles represent a key segment of the industry, as they not only satisfy global consumers aspirations, but also serving as a significant revenue stream for manufacturers. These vehicles are often at the forefront of the introduction of cutting-edge innovations and playing a critical role in the industry's growth (Julian Felipe Munoz, 2023). In 2018, they accounted for just 13% of total market sales, but generated about 40% of automakers' profits. However, the emergence of autonomous driving, increased connectivity, electromobility, and new mobility services, the factors that determine success in the industry are on the cusp of a major shift (Hatstrup-Silbererg, 2019; Köstring et al., 2019).

Historically, BMW's main competitors in the luxury car market have been Mercedes-Benz and Audi. Tesla's entry changed the market by making EVs technically feasible. At the end of 2021, Tesla led the electric car market with a 13.8% share, while BMW was in seventh place with 4.8%. Tesla's market capitalization was 36 times higher than its book value, but its free cash flow was only 20% of its market value and it paid no dividends. In contrast, BMW and Mercedes-Benz had lower market-to-book ratios, generated higher cash flow and paid dividends (S&P Global Market Intelligence, 2022) (*Appendix 6*). Transitioning to 2024, the brand VW leads the German automotive industry with 18.7% of all newly registered passenger

cars in the first quarter. Mercedes came in second with 9.1%, followed by BMW with 7.7% (Statista, 2024a).

In the premium segment, however, BMW was the global leader: in 2023, BMW sold more premium vehicles than its competitors (2,101,000 BMW; 2,020,000 Mercedes; 1,900,000 Audi), generating a 9% increase in sales over the previous year and €2 billion more than Mercedes-Benz. For years, BMW and Mercedes were the fiercest competitors in premium car sales, often alternating at the top (Fasse & Hubik, n.d.; Statista, 2022; Impey, 2024).

BMW's strong financial position enabled it to also be leader in the development of fuel cell technology. "BMW is the only European manufacturer to believe in a future with hydrogen cars," the German car magazine "Automobilwoche" stated at the beginning of 2024 (Wermke, 2024). Oliver Zipse positioned himself as open to new technologies, noting that while China is mostly focused on electric vehicles, FCEVs also play an important role. He added that "there is no 'one-size-fits-all' solution for the mobility of today and tomorrow" and that "for a global premium manufacturer" like BMW, such a technology orientation "remains the right way to decarbonize mobility for the near future" (Frankfurter Allgemeine Zeitung, 2024).

Mercedes-Benz Mercedes-Benz is known in the automotive industry for luxury and quality vehicles. With a long history dating back to 1926, they strove to combine high comfort, sophisticated design and innovative technology (Mercedes-Benz Group AG, 2024). As part of Mercedes-Benz's commitment to sustainability, Daimler Truck AG, one of its subsidiaries, was actively involved in the dual pursuit of battery electric and fuel cell technologies. An important example of Mercedes-Benz's innovation in this area is the Mercedes-Benz GenH₂ truck, which consisted of a fuel cell system and a liquid hydrogen tank system. This prototype truck achieved a groundbreaking distance of 1,047 km on a single tank, roughly the distance from Stuttgart, Germany to Rome, Italy, demonstrating the viability of hydrogen fuel technology for long-distance travel. While this dual focus was prominent in the truck sector, Mercedes-Benz

continued to prioritize EVs in the passenger car segment such as the VISION EQXX⁶ (Wilkens, 2023; Mercedes-Benz Group AG, 2024; Bergmann, 2023).

Audi AG Headquartered in Ingolstadt, Bavaria, Audi had been a member of the Volkswagen Group since the 1960s and earned its reputation as a premium manufacturer since the early 2000s (Audi AG, 2024; Statista, 2022). In a strategic move, Audi discontinued its hydrogen fuel cell development program, which ran until the end of 2020 with a dedicated team of 150 highly qualified experts (Amariei, 2023). Although this program developed a fuel cell with an exceptionally high energy density, the Audi brand's strategy was in line with the VW Group's focus on 100% electric mobility, as announced by Herbert Diess in 2021: “We can continue to work on e-fuels and fuel cells, as we are doing in the VW Group. For road traffic, however, it is nonsense on a broad scale [...] electromobility is the only way to reduce CO₂ emissions from individual mobility quickly and efficiently” (Ecomento, 2021). Yet Audi had not completely abandoned its commitment to fuel cells. From 2020, Audi had been working with Ballard Power Systems to further research the technology for advanced fuel cell stacks for automotive applications, both for its own brand and for the group (Henßler, 2020).

Foreign Competitors⁷ FCEVs were critical to Asia’s environmental and energy strategies in the early 2020s. Countries such as Japan, South Korea, and China were using FCEVs to meet stringent CO₂ reduction targets, increase energy independence through domestically produced hydrogen, and improve urban air quality. By making significant investments in hydrogen infrastructure, these countries were not only promoting greener transportation, but also taking a leading role in FCEV technology (NOW - GMBH, 2020). With a turnover of €221,6 billion⁸ in 2023, the Japanese car manufacturer Toyota was the largest in the world (Baumann, 2024; Impey, 2024; Statista, 2024e). Since sales began in Germany in 1971, the company has

⁶ The Vision EQXX is an e-concept car from Mercedes Benz that is extremely economical and efficient. It has a very low flow resistance by design and can cover up to 1200 km on one charge (Pfeiffer, 2022).

⁷ For the sake of simplicity and space, only a small selection of Asian competitors is discussed here.

⁸ 37,15 Trillion Yen, 1 Yen= 0,006€ (Exchange rate on the 9th of May 2024)

continued to innovate, launching one of the first commercial hydrogen cars, the Mirai (Toyota, 2024). Despite Elon Musk's criticism of fuel cells as “fool cells”, Toyota had supported and embraced the technology. However, the Toyota Mirai, the world's first and best-selling fuel cell electric car, which was launched in 2015, had only been purchased by about 11,000 customers worldwide as of 2020 (Toyota, 2020, 2021).

Hydrogen as an Alternative Fuel

Hydrogen has a rich historical association with fueling mobility, dating back more than two centuries. Initially, it was used in the earliest internal combustion engines, similar to the use of gasoline today. However, its adoption faced challenges due to safety concerns and its relatively low energy density. In today's context, hydrogen functions as an energy carrier in fuel cells, where it reacts with oxygen to produce electricity, offering an alternative approach to its use in mobility solutions (Deloitte, 2020).

The fuel cell can be traced back to 1839, when it was first invented by a Welsh scientist named William Grove (Andújar & Segura, 2009). However, it was not until the oil embargoes of the 1970s that alternative power systems came into the international spotlight. In response to the effects of the embargoes, the EU and the US initiated several policies to combat dependence on foreign oil. The need for smaller, more fuel-efficient vehicles was first highlighted (Andújar & Segura, 2009; Deloitte, 2020). While some policies were seen as incentives for increased research and development of the prototype electric car, in 1990 the U.S. government released the Hydrogen Research, Development and Demonstration Act, which outlined a five-year plan for hydrogen energy research and development. Another significant development occurred in 2003 when the U.S. government allocated \$1.3 billion for research into hydrogen vehicle technology. Curiously, at the same time, Congress approved significant tax incentives that allowed buyers of gas-guzzling SUVs to benefit from an accelerated depreciation tax break of

up to \$100,000. In contrast, buyers of electric cars were eligible for a much smaller tax break, capped at \$4,000 (Rothaermel & King, 2015).

Over the past few decades, automakers around the world have pursued the development of FCEVs with varying degrees of intensity. In 1994, for example, Daimler broke new ground by unveiling the NECAR 1, an advanced fuel cell vehicle powered by Ballard⁹ power stacks. This era marked a growing enthusiasm for alternative propulsion, fueled by environmental concerns and the unpredictable nature of oil prices, forcing the automotive industry to make significant investments in this direction (Deloitte, 2020).

In 2000, the establishment of the European Research Area (ERA) by 25 European countries marked a significant step in fostering collaboration between industry leaders and government agencies. This initiative focused on research and development of hydrogen and fuel cell technologies, complementing other EU efforts such as the public-private partnership known as the Fuel Cells and Hydrogen Joint Undertaking (FCHJU) (Deloitte, 2020).

However, the prospects for widespread market adoption of FCEVs were limited during this period as diesel-powered vehicles dominated the European market. By the mid-2000s, diesel vehicles accounted for approximately 50% of all new car sales in Europe, a trend driven by tax incentives and regulatory policies that favored diesel over gasoline due to its lower greenhouse gas emissions per kilometer¹⁰ (EUR-Lex, 2019; Miravete et al., 2018).

Impact of “Dieselgate” Scandal

In September 2015, the automotive industry was rocked by the revelation that Volkswagen had programmed its diesel vehicles to cheat on emissions tests (NDR, 2020).

⁹ Ballard Power Systems is a leading manufacturer of proton exchange membrane fuel cells (PEM fuel cells) used in FCEVs. These stacks are efficient, produce only water vapor as an emission, and offer high power density, making them ideal for various types of vehicles, including buses and trucks.

¹⁰ The initial preference for diesel engines in Europe was mainly due to the fact that early emissions regulations focused primarily on reducing CO₂ emissions. Diesel engines, which are more fuel efficient, tend to emit less CO₂ per kilometer than gasoline engines. However, these regulations initially overlooked other critical pollutants such as nitrogen oxides (NOx) and particulates, which are more prevalent in diesel engines and have significant environmental and health impacts.

While Volkswagen bore the brunt of the legal and consumer backlash, the results for its industry peers were mixed. Although environmental experts claim to have found evidence in the engine control unit of a BMW diesel that the emission control system is shut down or completely disabled in certain situations, BMW was fined a modest €8.5 million for discrepancies in older diesel models, in stark contrast to Mercedes-Benz, which was fined a €870 million for similar violations (Hans Koberstein, 2023; Christina Kunkel, 2024). The scandal led to a sharp decline in diesel sales, from 1.5 million units in 2016 to less than 500,000 the following year and is therefore considered a tipping point that heralded the demise of the diesel engine (Kraftfahr-Bundesamt (KBA), 2023; Hans Koberstein, 2023) (*Appendix 7*). With this scandal, the German government was prompted to foster innovation in the industry and drive the adoption of EVs to regain customers' trust (Krzywdzinski, 2022).

Between 2023 and 2027, an estimated €250 billion was to be invested by private companies and public institutions in the electrification of vehicle fleets, according to the German Association of the Automotive Industry (2023). This significant inflow of capital was primarily driven by stringent environmental regulations, such as the commitments established by the Paris Agreement (2015), the European Green Deal (2019), and the EU's ambitious strategy to eliminate new registrations of internal combustion engine vehicles by 2035 (Kottasová, 2023; Niese et al., 2022).

At the same time, research into hydrogen fuel cell technologies was growing rapidly. Bosch, the world's leading automotive supplier, committed €2.5 billion to hydrogen research from 2021 to 2026 to drive the development of this alternative fuel source (Manager Magazine, 2023). These efforts for hydrogen were prevalent as the production of lithium-ion batteries for electric vehicles faced significant scrutiny: issues such as child labor and other exploitative labor practices were prevalent, and there were significant battery recycling challenges and

environmental concerns due to the extraction of rare earth minerals that needed to be addressed to improve the sustainability of the EV lifecycle (BMZ 2021; Backhaus 2021).

FCEVs and EVs

In an effort to decarbonize the transportation sector and reduce dependence on fossil fuels, the automotive industry has two salient solutions between battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) (Shafi, 2022). This transition is critical because passenger vehicles are a significant contributor to transportation emissions, accounting for 61% (Wu & McAllister, 2023).

FCEVs and BEVs serve as complementary solutions to the environmental challenges of the transportation sector. FCEVs are characterized by the fact that they generate their own electricity, unlike pure electric or plug-in hybrid vehicles that rely on externally charged batteries. These vehicles have an internal power plant, the fuel cell, that converts hydrogen into electricity, enabling on-demand power generation and significantly reducing dependence on large, heavy batteries. FCEVs work through a process called reverse electrolysis, which takes place within the fuel cell, which works in a fundamentally different way than conventional batteries. In a fuel cell (*see Appendix 8*), hydrogen enters the anode (colored red) where it is catalytically split and ionized into protons and electrons. The protons then pass through the polymer electrolyte membrane (colored green) and move by ionic conduction toward the cathode (colored blue). Simultaneously, the electrons travel through an external circuit, performing electrical work before also reaching the cathode. At the cathode, electrons, protons, and oxygen molecules react to produce water. The primary inputs to the fuel cell are hydrogen and oxygen, while the primary outputs are water, electricity, and heat (Crabtree & Dresselhaus, 2008).

Despite the dominance of BEVs in the early 2020s, which were favored by the existing infrastructure, FCEVs had potential for segments that require longer ranges and shorter

refueling times, especially in decarbonizing sectors such as long-haul and heavy-duty transport (Wu & McAllister, 2023) (*Appendices X5 and X6*).

The efficiency of a BEV is about 73%, while the efficiency of the FCEV using green hydrogen is only 22% (Onorino, 2023; Umweltbundesamt, 2022). Efficiency in this context refers to how effectively these vehicles convert the energy stored in their fuel (electricity for BEVs, hydrogen for FCEVs) into power that actually drives the vehicle. However, from that perspective, it is critical to evaluate not only the well-to-wheel (WTW)¹¹ efficiency, but also the specific energy source. The overall efficiency of FCEVs can be significantly improved if hydrogen is produced using renewable energy sources. This higher efficiency could potentially compensate for the relatively lower tank-to-wheel (TTW)¹² efficiency of FCEVs compared to BEVs.

Assessing the GHG emissions of FCEVs vs. BEVs in a renewable energy scenario yielded the following comparison: BEVs had lower emissions of about 1.35 kg per 100 km compared to FCEVs, which emitted over CO₂ per 100 km (Specht et al., 2022).

Beyond the automotive industry, hydrogen could enable the balancing of energy availability in renewable electricity, especially in regions with significant seasonal variations in renewable energy availability. Hydrogen could effectively bridge these gaps by enabling long-term storage and transportation of energy, balancing seasonal and intra-day supply and demand imbalances more efficiently than other storage solutions such as batteries or pumped storage (Vahlenkamp et al., 2021a) (*Appendix X5*).

In addition, the battery in a hydrogen car is much smaller and therefore lighter than the battery in an EV. A lighter vehicle is in turn much more efficient (Tattersall & Rohr, 2024) (*Appendices X1 and X2*). It has also been emphasized that the development of battery technology has been

¹¹ Refers to the analysis of the vehicle's energy consumption from the initial energy source ("well") to the vehicle's wheels. It includes all the steps involved in producing the fuel, delivering it to the vehicle and its final use in driving. The goal is to capture the total environmental impact and energy efficiency of the fuel life cycle.

¹² Describes the energy consumed from the time the fuel is stored in the vehicle's tank until the fuel is used to drive the vehicle's wheels. It focuses specifically on the efficiency of the vehicle in using the fuel to generate locomotion, without considering losses during the production and transportation of the fuel.

very quickly, which has given EVs a competitive advantage (Brügge & Wildberg, 2024). Yet, in early 2024 the widespread adoption of FCEVs was hampered by the lack of hydrogen infrastructure, a situation that could change with the expected investment in hydrogen production and distribution in the following decade (Shafi, 2022) (*Appendix X6*). However, for FCEVs to be truly sustainable, the long-term focus must be on the use of green hydrogen (Crabtree & Dresselhaus, 2008; Vahlenkamp et al., 2021a) (*see Appendix 9 for more details*).

A holistic study¹³ (von Bechtolsheim et al., 2020) found, that capital expenditures (CAPEX) for both BEVs and FCEVs will decrease as production volumes increase, with BEVs currently enjoying a cost advantage. This decrease in CAPEX primarily relates to the initial investment required to manufacture these vehicles, which will decrease per unit as production increases and fixed costs are spread over a larger output. Electricity is expected to be more cost effective than hydrogen in terms of operating expenses (OPEX). While hydrogen prices are expected to remain moderate, supporting CO₂ neutrality for applications that cannot be electrified, electricity is still a more economical option for most residential users. As a result, BEVs will have lower operating costs than hydrogen-powered vehicles. Current EU regulations support both types of vehicles and tightening these regulations would give them a further advantage over fossil-fuel vehicles. FCEVs have the potential to be more popular with consumers because they have many of the features of conventional combustion engines, such as quick refueling and long ranges (*Appendices 10, X2 and X5*). In contrast, consumers may become accustomed to the advantages of BEVs, including the ability to charge vehicles at home, which also promotes the acceptance of shorter ranges (Vahlenkamp et al., 2021; von Bechtolsheim et al., 2020). At the same time, the popularity of BEVs is increasing as falling costs for lithium-ion batteries and government incentives, combined with a steadily improving and denser network

¹³ Von Bechtolsheim et al., (2020) present a holistic framework for assessing the potential of hydrogen. Based on this, we compare the CAPEX (cost of application for manufacturing and installation, including incentives and recycling) and OPEX (cost of running the application, including infrastructure, taxes, and fees) for the two alternative fuels.

of electric charging stations, increase their attractiveness on the consumer market (Moseman, 2023).

The strategic direction of the industry is somewhat splintered between these two technologies. The future of the industry therefore remains exciting, as the major car manufacturers have different priorities. Some companies are focusing exclusively on BEVs, while others, such as BMW and Toyota, are including FCEVs in their strategic planning. This dichotomy illustrates that choosing the right technological path comes with high risks, as it can significantly impact a company's survival (Dr. Schmitz, 2021).

Cost is a critical factor in the adoption of FCEVs. Currently, the cost of hydrogen fuel is about €13.30 per 100 kilometers, significantly higher than electricity, which costs about 50% less. This raised important questions about the scalability of hydrogen production (*Appendix 11*). Looking to the future, the ability to produce hydrogen in sufficient quantities at competitive prices will be essential to making FCEVs a viable and economical alternative to conventional and electric vehicles (Wallner, 2022).

The environmental impact of FCEVs versus BEVs remains a topic of ongoing debate. Research suggested that hydrogen produced from renewable sources could be more environmentally friendly than using grid electricity for BEVs (Shafi, 2022). While hydrogen technology is already mature in some commercial applications, it has shown great promise for passenger cars and other mobile applications (von Bechtolsheim et al., 2020). As the automotive sector evolves, the industry's strategic choices, coupled with technological advances, would have a significant impact on sustainable mobility. The dynamic interplay between BEVs and FCEVs would shape the future transportation landscape, reflecting a collective effort to reduce environmental impacts and meet the diverse needs of global mobility (Dr. Schmitz, 2021).

A comparative performance assessment of FCEVs and BEVs is shown in *Appendix 12*.

BMW's Hydrogen Strategy

BMW's involvement with hydrogen fuel began in the 1970s, initially focusing on hydrogen internal combustion engines. In 1979, in partnership with the German Aerospace Center (DLR), BMW converted a 1975 BMW 520/4 (E12) into a hydrogen test vehicle to prove the feasibility of hydrogen as a viable fuel. This vehicle, although similar in appearance to its gasoline counterparts, was instrumental in demonstrating the practical application of hydrogen in internal combustion engines.

In 1980, BMW escalated its commitment by introducing the first European car powered by cryogenic liquid hydrogen, a modified 7 Series. This vehicle was powered by a hydrogen internal combustion engine and had a 93-liter tank that provided a range of approximately 300 kilometers. Although the hydrogen was derived from less sustainable sources such as crude oil, the technology demonstrated a significant reduction in emissions-burning hydrogen instead of gasoline produces only water vapor.

Throughout the 1980s and 1990s, BMW continued to refine hydrogen combustion technology. A landmark achievement was unveiled at the 1989 International Motor Show in Frankfurt: the world's first hydrogen-powered 12-cylinder engine. At the turn of the millennium, this technological prowess was embodied in the BMW Hydrogen 7, introduced in 2006. Based on the 760Li model, this vehicle featured a bivalent engine capable of running on both gasoline and liquid hydrogen, overcoming the infrastructure limitations of the time by ensuring reliability and convenience for the user.

Recognizing the efficiency limitations of hydrogen internal combustion engines, in the 2010s BMW began to shift its focus to hydrogen fuel cells, which convert hydrogen directly into electricity, offering higher efficiency and lower environmental impact. This shift was marked by a significant collaboration with Toyota in 2013 to develop a robust fuel cell system. This

partnership leveraged Toyota's expertise from the Mirai fuel cell vehicle and culminated in the presentation of a hydrogen fuel cell-powered BMW 5 Series GT at the 2017 Hannover Messe. In the 2020s, BMW stepped up its efforts to advance fuel cell technology. The company announced plans to launch a production fuel cell vehicle in the second half of the decade, supported by developments at its hydrogen competence center in Garching near Munich. At the time, Zipse, the CEO of BMW, also emphasized the enormous importance of the innovative drive system: “Hydrogen is a versatile energy source that has a key role to play in the energy transition process and therefore in climate protection. After all, it is one of the most efficient ways of storing and transporting renewable energies. We should use this potential to also accelerate the transformation of the mobility sector” (BMW Group, 2023).

The BMW iX5 Hydrogen, which began global testing as part of a pilot fleet starting in 2023, represented the culmination of decades of research and development in hydrogen technology. The pilot fleet would be used for test and demonstration purposes by various target groups around the world over 2024. BMW was supported by Toyota in this major project with joint fuel cells (BMW Group, 2023; H2 NEWS, 2023). The goal of the development team was to gain valuable practical experience with the vehicle and the everyday use of hydrogen fuel cell technology. In addition to technological analogies to the combustion engine, such as intercoolers, air filters, control units and sensors, BMW developed special hydrogen components for the new fuel cell system.

BMW also supported the EU Commission's efforts to develop infrastructure for alternative fuels, including hydrogen filling stations, under the Alternative Fuels Infrastructure Regulation (AFIR). In addition, BMW was committed to promoting hydrogen economy initiatives, particularly through its participation in key projects such as those outlined in the IPCEI (Important Projects of Common European Interest) (Schaefer, 2022).

Ingrid Muehlbauer, automotive historian, concluded, “The BMW Archive contains over 1,000 documents, publications and files on the subject of BMW and hydrogen. Over the decades and through various stages, BMW has developed the expertise required to put today’s iX5 Hydrogen pilot fleet on the road” (BMW Group Classic, n.d.).

Business challenges and opportunities

As Uwe Weichenhain, Senior Partner and Global Hydrogen Lead at Roland Berger, pointed out, the hydrogen economy holds considerable potential for companies that take a leading role early on (Weichenhain, 2022). These “first movers” could set market standards and secure lucrative positions along the entire value chain by leveraging network effects and government incentives. Network effects refer to the fact that as more people use hydrogen as a fuel, the value of the product itself increases. Thus, as more sectors and companies would adopt hydrogen technology, its value and utility increases, encouraging further adoption and integration. The transition to more sustainable drive systems had been significantly accelerated by government subsidies and stricter emission standards, which were also crucial for the development of hydrogen technology (*Appendix X2*). The European Union's “Fit for 55” initiative aimed to reduce emissions by 55% by the end of the decade and prepare the economy for the challenges of a low-carbon future in a cost-effective, competitive and equitable way (European Commission, 2024; European Union, 2023). Fiscal and policy support for hydrogen was an integral part of the EU's Green Deal, which aimed to achieve carbon neutrality by 2050. Due to its high energy content and adaptability, hydrogen was recognized as a critical pillar in Europe's energy transition under the Green Deal (Claeys et al., 2019; European Commission, 2024) (*Appendices X3 and X5*).

Key initiatives such as the “Hydrogen Strategy for a Climate Neutral Europe” and the “European Alliance for Clean Hydrogen” reflected this focus and aimed to close the gap

between supply and demand and build a comprehensive project pipeline along the hydrogen value chain (Hydrogen Europe, 2023; Weinberger, 2020).

In line with EU policy, there are also projects for “green corridors”, primarily intended to facilitate the import of green hydrogen. The Green Hydrogen Maritime Corridor would be established between the ports of Algeria and Rotterdam, another project aimed to streamline the transport of green hydrogen from Morocco to the port of Trieste (Klare, 2023; Meillaud, 2024).

The development of a hydrogen infrastructure was a major challenge for the establishment of hydrogen as a fuel and energy carrier. However, the resulting network effects of more people being using a more accessible infrastructure, could facilitate and promote the introduction and acceptance of hydrogen. The EU has been promoting the development of hydrogen as part of its “Hydrogen Strategy”. It has defined three phases (*Appendix 13*) with the aim of planning a hydrogen infrastructure by 2024, creating “hydrogen valleys”¹⁴ by 2025 and establishing an EU-wide infrastructure network by 2025 (Weinberger, 2020) (*Appendix X6*). Part of this hydrogen roadmap was that this infrastructure should include 3,700 fueling stations and 3.7 million fuel cell vehicles by 2030 (Deloitte, 2020). In addition, the development of the production, storage and distribution infrastructure would require continuous technological innovation and considerable investment. Experts therefore expected that hydrogen would gradually become established in Europe (Vahlenkamp et al., 2021a) (*Appendices 14 and X4*).

In Germany, the federal government's “National Hydrogen Strategy” specifically targeted the establishment of a hydrogen market, supported by billions in federal and state funding to promote hydrogen production and infrastructure (Federal Ministry of Economics and Climate Protection, 2024). By investing in local hydrogen production and technology, the country

¹⁴ A Hydrogen Valley is a defined geographical area where the entire hydrogen value chain is implemented, from production, storage and distribution to end-use in various sectors (energy, industry, mobility, housing, agriculture, etc.).

would reduce its dependence on external suppliers, foster a competitive edge through home-grown innovation, and position itself as a leader in the emerging hydrogen market (German Federal Ministry of education and research, 2023) (*Appendix X3*).

Germany was a leading example when it came to the density of H₂ refueling station compared to the hydrogen cars on the road (iea50, 2023). As of 2022, there were 254 H₂ refueling stations in Europe, 105 of which located in Germany (Gebhardt, 2023). The long-term benefits of a hydrogen infrastructure are shown in *Appendix 15*: Initially, the costs of the two powertrains are similar, but as the market grows to 20 million vehicles, the BEV infrastructure becomes more expensive at €51 billion, while hydrogen is cheaper at €40 billion. The hydrogen pathway includes the costs of the transition to renewables and storage, highlighting the need for seasonal storage solutions to ensure reliable supply (Robinius et al., 2018).

However, there have been challenges to the widespread adoption of hydrogen. For example, declining sales of the Toyota Mirai in the U.S. highlighted the inadequacies of the infrastructure, as there were only 57 hydrogen refueling stations nationwide, all in California. Without easily accessible refueling options, Toyota said that customer interest would wane (Donath, 2023; Lang, 2024).

Prospects for the use of hydrogen as an energy source had improved due to falling energy costs for the production of green hydrogen, specific government support programs, and the EU's more stringent decarbonization targets. Experts predicted that hydrogen would be used primarily in the industrial sector, followed by heavy-duty vehicles, and only in the distant future in passenger transportation (Vahlenkamp et al., 2021) (*Appendices 14, XI and X4*). However, economic viability remained a major challenge, especially for green hydrogen.

Cost-effective production methods and competitive fuel pricing are crucial for widespread market adoption of hydrogen technology. As research advances and consumer demand increases, it is anticipated that costs will decrease, as noted by (Wietschel et al., 2023)

(*Appendix X2*). However, achieving consumer acceptance and adjusting market structures are major challenges. Targeted public relations campaigns and incentives are essential to build consumer confidence and facilitate the integration of hydrogen as a mainstream energy source.

Future Outlook

Zipse was convinced that BMW's entry into hydrogen technology for passenger cars would give the company a unique position in the premium segment of the German automotive industry. This strategy not only reflected the company's historical commitment to hydrogen but is also a calculated bet on the future of sustainable mobility. Despite the still developing hydrogen infrastructure and the current focus on electromobility, Zipse was certain that BMW would use its heritage and expertise in this area to be an early player in the further spread of hydrogen technology (*Appendix XI*).

Given the potential of hydrogen beyond transportation in sectors such as the steel industry and high-temperature processes where electrification is not possible, BMW's strategy for the transport sector alone may have been premature, as other major car manufacturers are currently relying almost exclusively on EVs, and hydrogen still needs some technical breakthroughs before it can be used in large quantities for passenger transport. However, this approach aligned with their core competency in automotive innovation, positioning them strategically as the utility of hydrogen grows beyond transportation.

The public was generally receptive to hydrogen technology, perhaps even more so than battery-powered alternatives (*Appendix X3*). Zipse was confident that this acceptance was crucial, and this underlay BMW sticking with hydrogen despite the known challenges.

However, BMW's path is fraught with uncertainty. The success of the hydrogen initiative depended on several factors: the expansion of hydrogen production to meet EU targets, the development of an EU-wide infrastructure, and the possibility of being overtaken by rapidly advancing battery technology (*Appendix 6*). In view of the growing importance and success of

electric mobility, this is a race for BMW to establish hydrogen as a serious technological alternative in the automotive industry.

Outside of BMW, the singular focus of the other German automotive industry players on BEVs raised strategic questions. *Why was BMW sticking with hydrogen while the competition is focusing on battery power? Was BMW betting on future market shifts, or did BMW see hydrogen as a strategic diversification to reduce the risks associated with battery materials and production? Was it a visionary step toward a more diverse, sustainable future or a hedge against the unpredictable challenges of electromobility?*

Zipse seemed certain that BMW was not just advancing a particular technology but setting the direction for sustainable mobility. Still, outsiders wondered: *Was the bet on hydrogen a strategic stroke of genius or an expensive detour?* Only time would tell, but one thing is clear: the automotive landscape is changing, and BMW is moving toward a horizon that held both opportunities and uncertainties.

APPENDICES TO THE CASE STUDY

Appendix 1 *BMW Group Key Metrics – Non-financial performance indicators*

BMW GROUP

Key metrics - Non-financial performance indicators

	Q1		Q2		Q3		Q4		FY	
	2023	2022	2023	2022	2023	2022	2023	2022	2023	2022
BMW Group										
Workforce (end of period)									154,950	149,475
Share of women in management positions in the BMW Group									20,8%	20,2%
Spending on employee training and development (in million €) ¹									469	416
Automotive segment										
CO2 emissions of the new vehicle fleet in Europe (in g CO2 / km) ^{2,3,4}									102,1	105,0
Energy consumption per vehicle produced (in MWh) ⁵									1,97	2,13
Sales volume (deliveries to customers)										
BMW									2,252,793	2,100,689
MINI									295,358	292,922
Rolls-Royce									6,032	6,021
Total									2,554,183	2,399,632
Production volume										
BMW									2,340,547	2,089,801
MINI									315,196	286,265
Rolls-Royce									6,179	6,239
Total									2,661,922	2,382,305
Motorcycles segment										
Sales volume (deliveries to customers)									209,066	202,895
Production volume									221,988	215,932
Financial Services segment										
New contracts with retail customers	347,298	433,429	382,010	382,019	383,509	362,838	429,697	367,204	1,542,514	1,545,490

¹ Training for BMW Group employees and temporary staff at consolidated companies worldwide. Data is collated on the basis of direct input by participants and, to a small extent, by extrapolation. Data also includes e-learning formats

² EU-27 countries including Norway and Iceland; with effect from 2021, values are calculated on a converted basis in line with WLTP (Worldwide Harmonised Light Vehicles Test Procedure)

³ This is a preliminary internal calculation with a potential variation of +/- 0.5 g CO2/km, as official registration figures from the authorities are not available for all EU states. Figures officially published by the EU Commission are not expected to be available until November of the following year

⁴ Including an allowance for eco-innovations (amounts of clearly minor significance)

⁵ Efficiency indicator calculated from the absolute energy consumption (adjusted for CHP losses) of automobile production (BMW Group plants excluding partner plants and contract manufacturing) divided by the number of units produced (BMW Group plants and partner plants, excluding contract manufacturing)

Source: <https://www.bmwgroup.com/en/investor-relations/company-reports.html>

Appendix 2 BMW Group Key Metrics – Financial performance indicators

BMW GROUP

Key metrics - Financial performance indicators

in € million	Q1		Q2		Q3		Q4		FY	
	2023	2022	2023	2022	2023	2022	2023	2022	2023	2022
BMW Group										
Revenues	36,853	31,142	37,219	34,770	38,458	37,176	42,968	39,522	155,498	142,610
Profit before tax	5,129	12,227	4,222	3,929	4,063	4,100	3,682	3,253	17,096	23,509
PBT margin	13.9%	39.3%	11.3%	11.3%	10.6%	11.0%	8.6%	8.2%	11.0%	16.5%
Net profit	3,662	10,185	2,958	3,047	2,931	3,175	2,614	2,175	12,165	18,582
Earnings per common share in €	5.31	15.33	4.39	4.30	4.20	4.25	3.77	3.43	17.67	27.31
Earnings per preferred share in €	5.31	15.33	4.40	4.31	4.20	4.25	3.78	3.44	17.69	27.33
Capital expenditure ¹	1,328	1,098	1,903	1,831	1,847	1,751	3,758	3,111	8,836	7,791
Capital expenditure ratio ²	3.6%	3.5%	5.1%	5.3%	4.8%	4.7%	8.7%	7.9%	5.7%	5.5%
Research and development expenditure ³ (cash)	1,554	1,391	1,842	1,551	1,827	1,952	2,532	2,284	7,755	7,178
R&D Ratio ⁴	4.2%	4.5%	4.9%	4.5%	4.8%	5.3%	5.9%	5.8%	5.0%	5.0%
Gross Liquidity ⁵ (end of period)									19,497	20,308
Automotive segment										
Revenues	31,268	26,726	31,630	30,015	32,096	32,290	37,283	34,571	132,277	123,602
EBIT	3,777	2,367	2,898	2,463	3,135	2,873	3,171	2,932	12,981	10,635
EBIT margin	12.1%	8.9%	9.2%	8.2%	9.8%	8.9%	8.5%	8.5%	9.8%	8.6%
RoCE									20.2%	18.1%
Free Cash Flow ⁶	1,981	4,816	1,160	2,954	2,618	2,106	1,183	1,195	6,942	11,071
Net financial assets (end of period)									17,003	24,603
Motorcycles segment										
Revenues	933	799	988	864	650	822	643	691	3,214	3,176
EBIT	154	108	158	127	-4	87	-49	-65	259	257
EBIT margin	16.5%	13.5%	16.0%	14.7%	-0.6%	10.6%	-7.6%	-9.4%	8.1%	8.1%
RoCE									22.1%	24.9%
Financial Services segment										
Revenues	8,826	8,486	8,795	8,765	9,102	8,785	9,504	9,086	36,227	35,122
EBIT	958	966	751	982	740	679	606	536	3,055	3,163
RoE									17.2%	17.9%
Penetration rate									38.2%	41.0%
Other Entities										
Revenues	3	1	3	2	3	3	2	2	11	8
EBIT	-4	-32	-1	-142	-8	-13	0	-16	-13	-203
Eliminations										
Revenues	-4,177	-4,870	-4,197	-4,876	-3,393	-4,724	-4,464	-4,828	-16,231	-19,298
EBIT	490	-18	537	-4	489	56	684	113	2,200	147

¹Capital expenditure: investments in property, plant and equipment and other intangible assets (excluding capitalized development costs)

²Capital expenditure ratio: Capital expenditure divided by Group revenues

³Research and development expenditure: The sum of

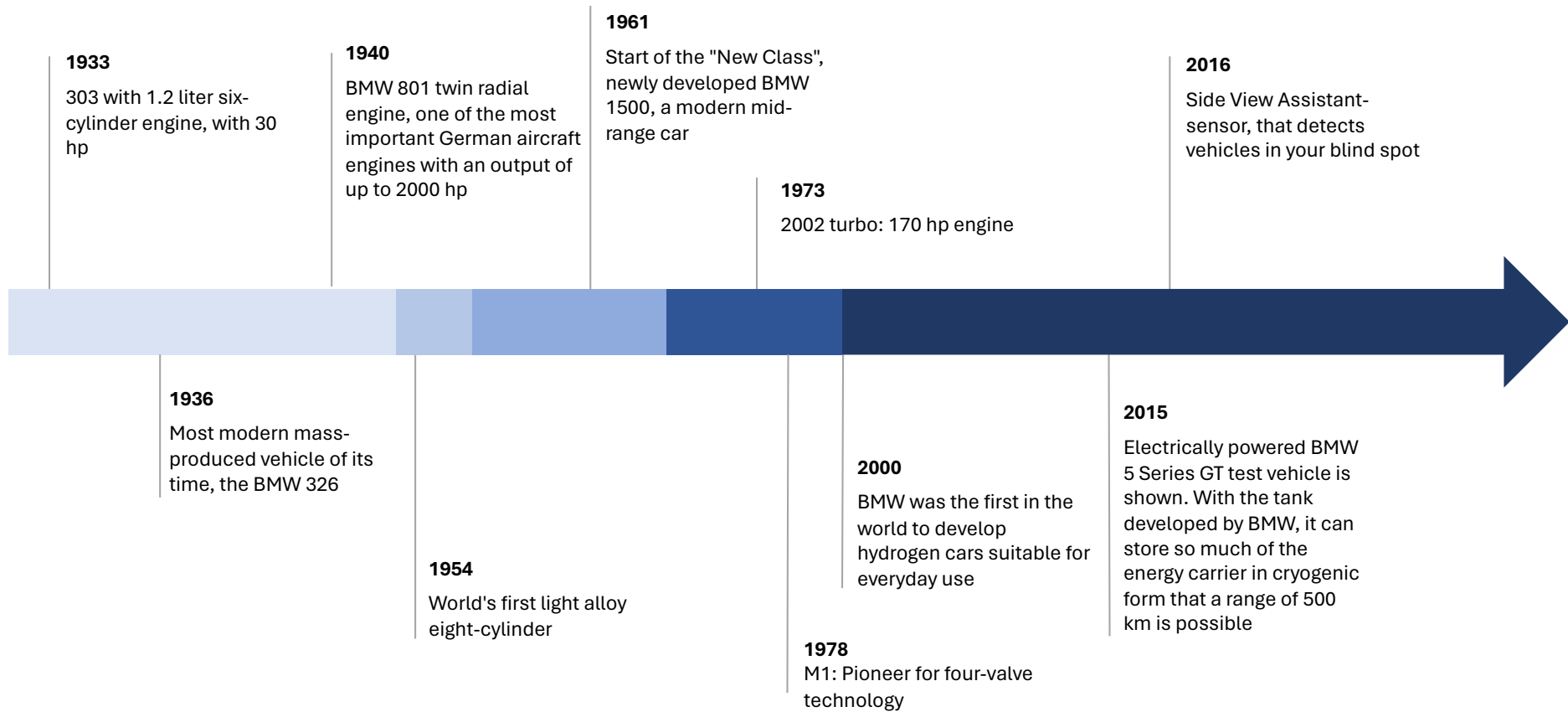
⁴R&D Ratio: Research and development expenditure divided by Group revenues

⁵Gross Liquidity: Cash & cash equivalents and marketable securities

⁶Free cash flow corresponds to the cash inflow from operating activities of the Automobiles segment less the cash outflow for investing activities of the Automobiles segment adjusted for net investment in marketable securities and term deposits

Source: <https://www.bmwgroup.com/en/investor-relations/company-reports.html>

Appendix 3 *Timeline of BMWs biggest innovations*



Source: Own illustration
 *hp = horsepower

Appendix 4 Balance Sheet for Group and Segments at 31 December 2023

BALANCE SHEET FOR GROUP AND SEGMENTS AT 31 DECEMBER 2023

in € million	Group		Automotive (unaudited supplementary information)		Motorcycles (unaudited supplementary information)		Financial Services (unaudited supplementary information)		Other Entities (unaudited supplementary information)		Eliminations (unaudited supplementary information)	
	2023	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023	2022
ASSETS												
Intangible assets	20,022	21,776	19,439	21,220	216	185	366	370	1	1	-	-
Property, plant and equipment	35,266	32,126	34,639	31,514	533	491	94	121	-	-	-	-
Leased products	43,118	42,820	-	-	-	-	50,415	49,867	-	-	-7,297	-7,047
Investments accounted for using the equity method	443	420	443	420	-	-	-	-	-	-	-	-
Other investments	1,197	1,351	14,697	14,775	-	-	28	28	23,084	23,020	-36,612	-36,472
Receivables from sales financing	50,517	50,368	-	-	-	-	50,657	50,482	-	-	-140	-114
Financial assets	1,387	3,073	588	1,522	-	-	256	481	643	1,191	-100	-121
Deferred tax	2,431	1,758	3,216	3,340	-	-	506	517	22	23	-1,313	-2,122
Other assets	1,537	1,030	2,296	2,612	18	25	2,852	2,325	35,249	38,315	-38,878	-42,247
Non-current assets	155,918	154,722	75,318	75,403	767	701	105,174	104,191	58,999	62,550	-84,340	-88,123
Inventories	23,719	20,005	22,121	18,679	905	802	693	524	-	-	-	-
Trade receivables	4,162	4,127	3,875	3,869	102	143	184	114	1	1	-	-
Receivables from sales financing	36,838	35,340	-	-	-	-	36,838	35,340	-	-	-	-
Financial assets	4,131	5,164	2,888	3,841	-	-	558	560	692	766	-7	-3
Current tax	1,199	1,096	911	547	-	-	102	134	186	415	-	-
Other assets	7,596	9,602	24,925	31,576	7	4	3,753	5,020	57,638	54,857	-78,727	-81,855
Cash and cash equivalents	17,327	16,870	13,590	13,109	36	21	3,090	3,530	611	210	-	-
Current assets	94,972	92,204	68,310	71,621	1,050	970	45,218	45,222	59,128	56,249	-78,734	-81,858
Total assets	250,890	246,926	143,628	147,024	1,817	1,671	150,392	149,413	118,127	118,799	-163,074	-169,981
EQUITY AND LIABILITIES												
Subscribed capital	639	663	-	-	-	-	-	-	-	-	-	-
Capital reserves	2,456	2,432	-	-	-	-	-	-	-	-	-	-
Revenue reserves	89,072	85,425	-	-	-	-	-	-	-	-	-	-
Accumulated other equity	-2,071	-117	-	-	-	-	-	-	-	-	-	-
Treasury shares	-500	-1,278	-	-	-	-	-	-	-	-	-	-
Equity attributable to shareholders of BMW AG	89,596	87,125	-	-	-	-	-	-	-	-	-	-
Non-controlling interests	3,327	4,163	-	-	-	-	-	-	-	-	-	-
Equity	92,923	91,288	61,971	67,234	-	-	16,573	17,737	56,031	48,894	-41,652	-42,577
Pension provisions	427	339	326	233	7	9	17	20	77	77	-	-
Other provisions	7,797	8,445	7,559	8,206	80	83	158	156	-	-	-	-
Deferred tax	2,797	2,765	2,601	2,786	-	-	2,603	3,447	226	315	-2,633	-3,783
Financial liabilities	52,880	53,469	2,726	2,730	2	2	18,003	16,343	32,249	34,515	-100	-121
Other liabilities	7,065	6,199	8,041	6,840	808	721	36,848	39,654	485	1,185	-39,117	-42,201
Non-current provisions and liabilities	70,966	71,217	21,253	20,795	897	815	57,629	59,620	33,037	36,092	-41,850	-46,105
Other provisions	9,240	7,316	8,547	6,668	128	123	558	519	7	6	-	-
Current tax	1,401	1,224	1,045	886	-	-	141	123	215	215	-	-
Financial liabilities	42,130	40,727	1,680	1,646	-	-	25,392	25,718	15,065	13,366	-7	-3
Trade payables	15,547	14,120	13,906	12,763	566	494	1,071	852	4	11	-	-
Other liabilities	18,683	21,034	35,226	37,032	226	239	49,028	44,844	13,768	20,215	-79,565	-81,296
Current provisions and liabilities	87,001	84,421	60,404	58,995	920	856	76,190	72,056	29,059	33,813	-79,572	-81,299
Total equity and liabilities	250,890	246,926	143,628	147,024	1,817	1,671	150,392	149,413	118,127	118,799	-163,074	-169,981

Source: <https://www.bmwgroup.com/en/report/2023/financial-statements/balance-sheet/index.html>

Appendix 5 *Income Statement for Group and Segments at 31 December 2023*

INCOME STATEMENT FOR GROUP AND SEGMENTS AT 31 DECEMBER 2023

in € million	Group		Automotive (unaudited supplementary information)		Motorcycles (unaudited supplementary information)		Financial Services (unaudited supplementary information)		Other Entities (unaudited supplementary information)		Eliminations (unaudited supplementary information)	
	2023	2022	2023	2022	2023	2022	2023	2022	2023	2022	2023	2022
Revenues	155,498	142,610	132,277	123,602	3,214	3,176	36,227	35,122	11	8	-16,231	-19,298
Cost of sales	-125,809	-118,042	-109,920	-104,324	-2,656	-2,628	-31,548	-30,437	-	-	18,315	19,347
Gross profit	29,689	24,568	22,357	19,278	558	548	4,679	4,685	11	8	2,084	49
Selling and administrative expenses	-11,025	-10,616	-9,195	-8,801	-303	-296	-1,559	-1,543	-34	-33	66	57
Other operating income	1,045	1,377	967	1,230	6	6	63	121	13	14	-4	6
Other operating expenses	-1,227	-1,330	-1,148	-1,072	-2	-1	-128	-100	-3	-192	54	35
Profit/loss before financial result	18,482	13,999	12,981	10,635	259	257	3,055	3,163	-13	-203	2,200	147
Result from equity accounted investments	-159	-100	-159	-100	-	-	-	-	-	-	-	-
Interest and similar income	701	422	1,389	739	7	5	5	6	3,403	1,543	-4,103	-1,871
Interest and similar expenses	-656	251	-1,502	-57	-8	7	-11	-6	-2,372	-1,539	3,237	1,846
Other financial result	-1,272	8,937	-67	7,701	-	-	-87	42	-1,118	1,194	-	-
Financial result	-1,386	9,510	-339	8,283	-1	12	-93	42	-87	1,198	-866	-25
Profit/loss before tax	17,096	23,509	12,642	18,918	258	269	2,962	3,205	-100	995	1,334	122
Income taxes	-4,931	-4,927	-3,685	-3,951	-75	-57	-861	-673	29	-209	-339	-37
Net profit/loss	12,165	18,582	8,957	14,967	183	212	2,101	2,532	-71	786	995	85
Attributable to non-controlling interests	875	641	857	601	-	-	17	40	1	-	-	-
Attributable to shareholders of the BMW AG	11,290	17,941	8,100	14,366	183	212	2,084	2,492	-72	786	995	85
Basic earnings per share of common stock in €	17.67	27.31										
Basic earnings per share of preferred stock in €	17.69	27.33										
Dilutive effects	-	-										
Diluted earnings per share of common stock in €	17.67	27.31										
Diluted earnings per share of preferred stock in €	17.69	27.33										

Source: <https://www.bmwgroup.com/en/report/2021/financial-statements/income-statement/index.html>

Appendix 6 *BMW Group Comparative financial metrics, end of year 2021*

BMW GROUP

Comparative financial metrics, end of year 2021

Company	Revenue (US\$ billions)	P/E ²	P/B ³	Dividend Yield ⁴	FCF Yield ⁵	ROE ⁶	Earnings Margin ⁷	Asset Turnover ⁸	Leverage (A/E) ⁹
BMW	113	4,71	0,79	6,55	15,55	18,24	11,20	0,50	3,27
Mercedes-Benz	136	6,79	0,99	7,40	11,44	16,32	8,25	0,49	4,03
Volkswagen ¹	255	5,99	0,62	4,26	18,11	11,22	6,17	0,49	3,73
Tesla	54	215,67	36,16	0,00	0,44	20,43	10,49	0,94	2,07

Capital IQ <https://www.capitaliq.com/CIQDotNet/login-okta.aspx>, accessed August 2022

¹ Volkswagen brands also include SKODA, SEAT, CUPRA, Audi, Lamborghini, Bentley, Porsche and Ducati.

² P/E = stock prices as of the end of 2021 / earnings per share

³ P/B = stock price as of the end of 2021 / common equities as of the end of 2021

⁴ Dividend yield = dividends per share / stock price as of the end of 2021

⁵ FCF yield = free cash flow per share / stock price as of the end of 2021

⁶ ROE = Income from continued operations / average

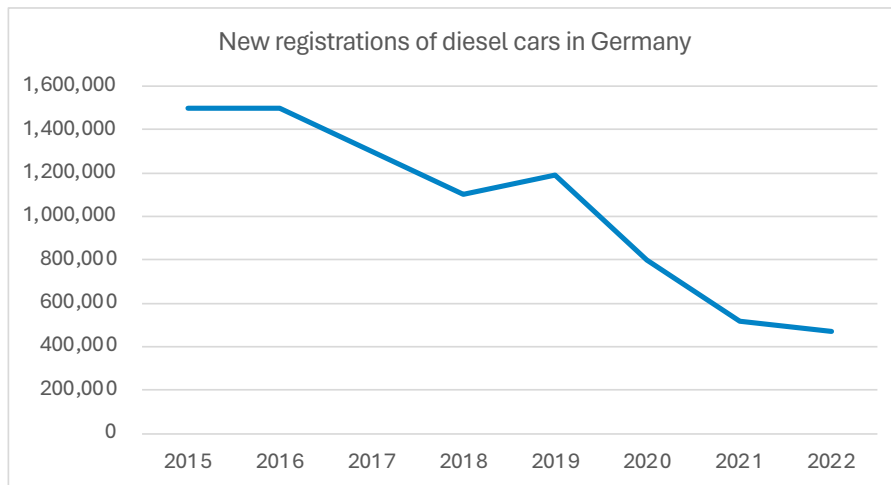
⁷ Earnings margin = Income from continued operations / revenue

⁸ Asset turnover = Revenue / average assets

⁹ Leverage = Average assets / average equities

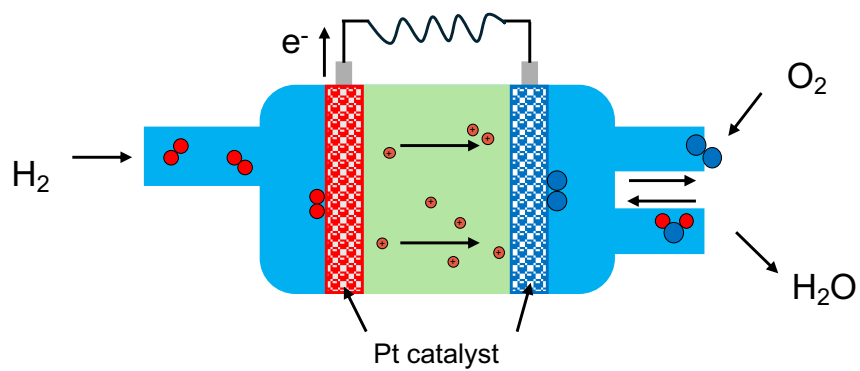
Source (adapted): S&P Global Market Intelligence, 2022

Appendix 7 *New registration of diesel cars in Germany*



Source (adapted): Statista, 2024

Appendix 8 *Construction of a fuel cell*



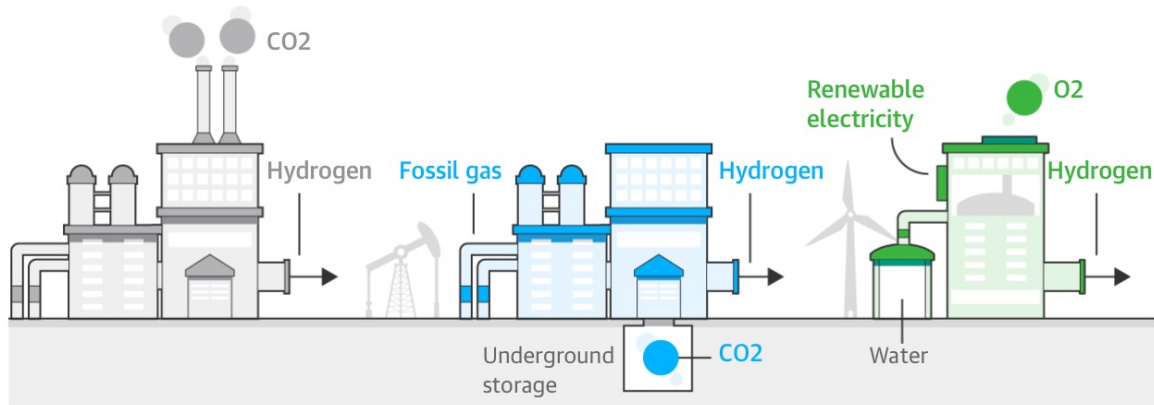
Source (adapted): Crabtree & Dresselhaus, 2008

Appendix 9 *How gray, blue and green hydrogen are made*

Gray hydrogen, which still accounts for almost all hydrogen production today, is derived from fossil fuels. To produce it, natural gas is usually split into hydrogen (H) and carbon dioxide (CO₂) under the influence of heat. The CO₂ is then released into the atmosphere, which is harmful to the climate.

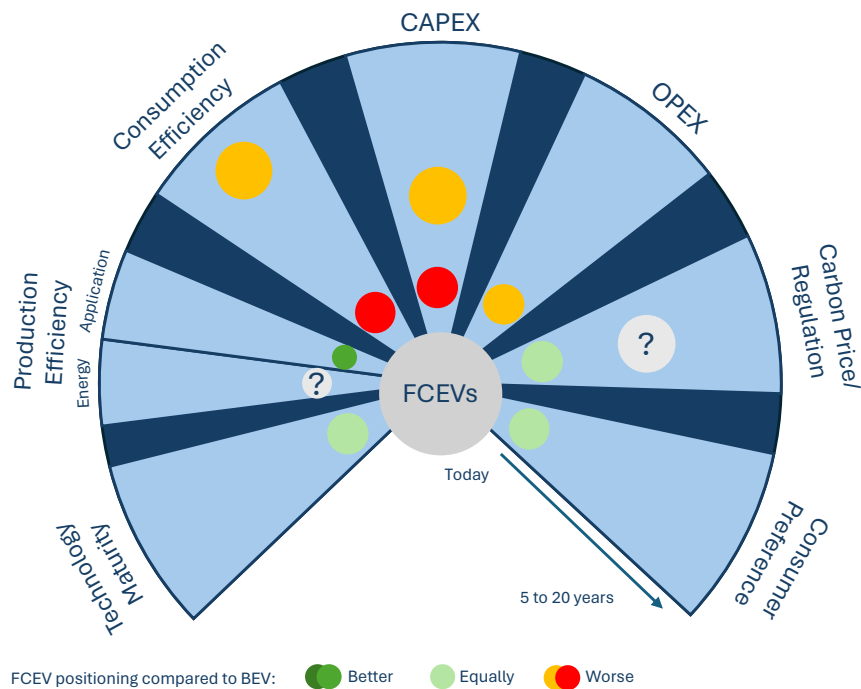
Blue hydrogen is also produced from fossil fuels, but the CO₂ is captured and stored rather than released, making this method low in CO₂.

Green hydrogen is produced by electrolysis of water. To be truly “green”, the electricity for electrolysis must come exclusively from CO₂-free sources.



Source (adapted): Crabtree & Dresselhaus, 2008; Vahlenkamp et al., 2021; Jolly, 2024

Appendix 10 *Assessment Model with a FCEV*



Source (adapted): von Bechtolsheim et al., 2020

Appendix 11 Energy costs fuel cell vehicles (FCEVs)













Energy costs for fuel cell vehicles (FCEVs) Passenger cars

	FCEV	BEV	Diesel	Gasoline
Energy costs per year (15,000 km mileage)	1,995 €	774 €	1,269 €	1,594 €
Costs per 100 kilometers	13.30 €	5.16 €	8.46 €	10.63 €




*as of March 2024

Source (adapted): <https://alternativ-mobil.info/alternative-antriebe/brennstoffzellenfahrzeuge-fcev#:~:text=Brennstoffzellen%20arbeiten%20komplett%20emissionsfrei.,fossilen%20Energietr%C3%A4gern%20wie%20Erdgas%20hergestellt.https://www.bmw.de/Redaktion/DE/Artikel/Energie/2021-08-pkw-energiekostenvergleich.html>

Appendix 12 Performance Assessment FCEVs vs. BEVs

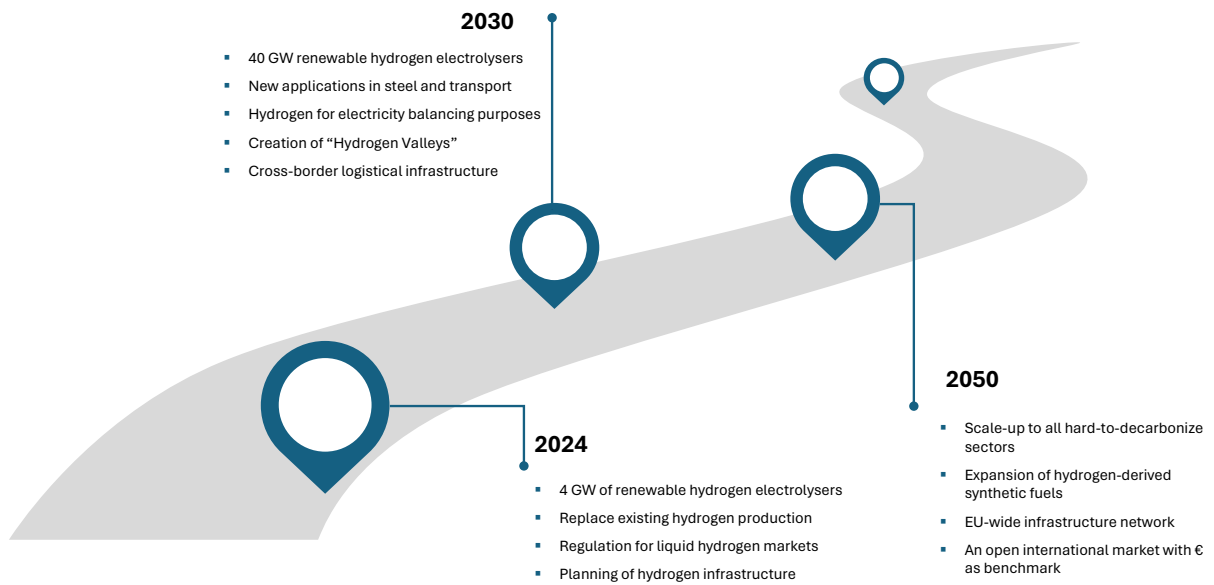
KPI	FCEV	BEV	
 GHG Emissions (CO ₂ /km)*	2.4 kg CO ₂ per 100 km	1.35 CO ₂ per 100 km	
 Reach	500 to 800 kilometers	350 kilometers	
 Charging/Fueling Infrastructure	254 hydrogen fueling stations	374,000 public charging stations	
 Charging/Fueling Time	3 to 5 minutes	approx. 20 min to reach 80% of battery capacity (fast charging station)	
 Acquisition Costs	> 60,000 €	> 20,000 €	
 Driving Dynamics	< 6 seconds from 0 to 100 km/h Top speed > 180 km/h (BMW iX5 Hydrogen)	5.6 seconds from 0 to 100 km/h Top speed = 180 km/h (BMW iX1)	

* in a renewable energy scenario

   Green: FCEVs superior to BEVs
 Yellow: FCEVs equally to BEVs
 Red: FCEVs worse than BEVs

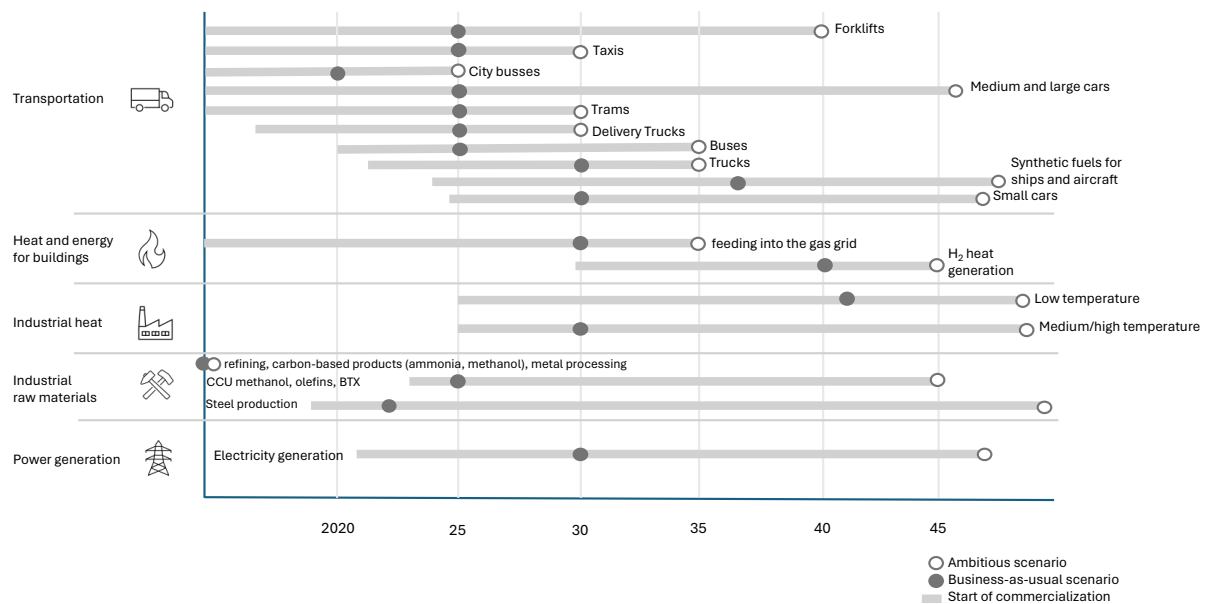
Source (adapted): https://www.fcneonerc.rwth-aachen.de/global/show_document.asp?id=aaaaaaaaabrsfja

Appendix 13 Hydrogen Strategy- 3 Phases



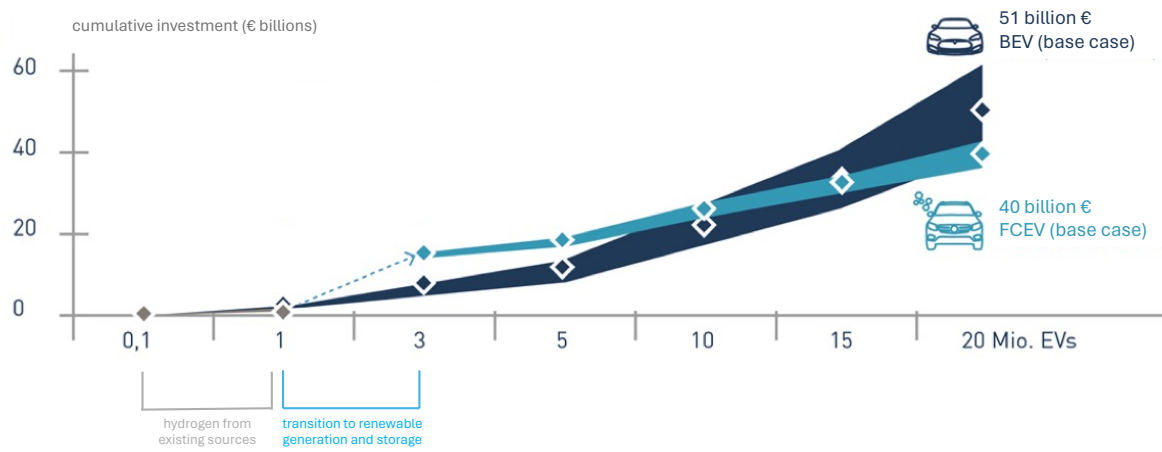
Source (adapted): Weinberger, 2020

Appendix 14 Hydrogen will establish itself in Europe in phases



Source (adapted): Vahlenkamp et.al., 2021

Appendix 15 Comparison of the cumulative investment of supply infrastructures



Source: Robinius et. al., 2018

Appendix X1

Our interviewee is Alexander Matter, a Hydrogen Consulting Manager who works for a management consulting firm based in Northwest Germany that offers a wide range of consulting services. The company focuses on shaping the digital future of its clients by advising on all phases of strategy and organization development, planning and management of IT, energy, transportation, finance and government projects, including security. For compliance reasons we are unable to disclose the name of the company.

<https://www.linkedin.com/in/matter-alexander/>

First of all, thank you for your time and the opportunity to validate our research with an expert opinion and to get further input for our master thesis. Where do you see the greatest advantages of hydrogen propulsion over battery electric vehicles, or how does hydrogen differ from other alternative propulsion systems?

Fuel cell electric vehicles (FCEVs) also require a battery, but a much smaller one that minimizes the disadvantages of heavy battery weight. Hydrogen also has an advantage over BEVs over long distances. Compared to internal combustion engines (ICE), there are no local emissions, so even with 100% renewable generation, there are no emissions (of course, there are still emissions in a lifecycle assessment). However, hydrogen still has a negative reputation among the population due to its history (Hindenburg as a classic example).

How can hydrogen compete with other alternative propulsion technologies, especially in terms of infrastructure and refueling times?

Compared to the refueling infrastructure of BEVs, H₂ does not require a power connection. This means that remote locations would be possible for the first time. In addition, the refueling method and type is much more similar to that of a traditional ICE. Unfortunately, the technical approval aspects of H₂ refueling stations are not trivial (BimSchG¹⁵).

How do you see the role of hydrogen as an energy source in future mobility?

Hopefully not for e-fuels. As mentioned above for heavy-duty transportation and/or long-distance mobility, but not in inner-city traffic. Even for buses, I tend to see the

¹⁵ The German Federal Emission Control Act (BImSchG) is part of environmental law and aims to protect humans, animals, and plants, as well as the soil, water, atmosphere, cultural assets, and other properties from harmful environmental impacts.

advantage for BEVs. So H2 should certainly be part of mobility, but not the sole solution.

How do you see the current and future cost ratio of hydrogen compared to other alternative drive systems?

This depends on whether externalities are taken into account, i.e. if you include the CO2 costs and the environmental costs, "Green H2" should do quite well. However, since gasoline/diesel is still heavily subsidized in Germany, the cost ratio is currently not given. Also "Gray H2"¹⁶ cannot compete at the gas station in Germany (as far as I know).

In your opinion, what technological or economic breakthroughs would be necessary to establish hydrogen as the main source of energy in the automotive sector?

Fuel cells would have to be more powerful to eliminate the need for a battery. Alternatively, internal combustion engines running on H2 would have to be efficient and emission-free. Otherwise, I see it as difficult. Economically, there would either have to be an equivalent subsidy, or conventional fuels would have to be quantified with real costs.

How do you assess the current market development for hydrogen vehicles in Germany and Europe? In your opinion, which European countries are pioneers in the use of hydrogen technology in the transport sector and why?

I first dealt with H2 in vehicles in my bachelor's thesis in 2018. Even back then, it was said that it would start now. We are still waiting for the actual launch. I think the development of hydrogen vehicles in Germany is very weak. BMW already has some history in this area and, as a pioneer in Germany, should therefore have the biggest head start. I don't have an overview of countries in Europe that use a lot of H2 in transportation. As far as I know, these tend to be marginal events compared to BEVs.

What are the most important trends and developments in the field of hydrogen energy that car manufacturers should take into account when designing their strategy?

Note: Hydrogen energy is a misleading term. Hydrogen can be converted into heat and electricity, as it contains chemical energy. Hydrogen energy as such does not exist.

The production and marketing of electrolyzers for H2 production is in my opinion a major shortcoming. Further efficiency improvements are needed to reduce the

¹⁶ Gray hydrogen refers to hydrogen created from fossil fuels, mainly natural gas, in which the carbon dioxide emissions produced during the production process are discharged into the atmosphere rather than absorbed or reused.

production price of (green) H2. In addition, skilled personnel must be trained to operate these plants. The whole issue of RED II¹⁷ and GHG quotas ¹⁸is crucial for the competitiveness of H2 vehicles. Recent developments (see Karlsruhe decision and corruption in the Ministry of Transport) are likely to hinder the development of H2 in transport.

How do you assess the current state of competition and cooperation between the main players in the hydrogen sector, including car manufacturers?

The market is big enough for everyone, as the supply is small, and the demand is potentially very high. In my experience, cooperation and exchange are very good, as it is a very young market with enormous potential. It is important to remember that hydrogen is already a widely used resource (in chemistry, industry, etc.) and that the transport sector is not the only consumer.

In which industries, apart from the automotive industry, do you see the greatest potential for hydrogen today and in the future?

Steel industry and high-temperature processes that currently run on natural gas (e.g. brickyards) and cannot be electrified.

Why do you think that Oliver Zipse, the CEO of BMW, is the only German car manufacturer that is focusing on hydrogen in the passenger car sector?

Perhaps it knows more than we do - BMW has a history with hydrogen that other automakers do not. To completely ignore this advantage would be foolish. I think if H2 gets more support, BMW will have a foot in the door.

Thank you very much for this deep insight, your time and the detailed answers.

¹⁷ RED II, the revised Renewable Energy Directive 2018/2001/EU, sets an overall EU renewable energy consumption target of 32% by 2030 to promote clean energy and reduce dependence on fossil fuels.

¹⁸ The GHG quota is intended to create incentives to reduce CO2 emissions in transport.

Appendix X2

Our interviewee is Andreas Riedel, CEO of RA.CE, a company specializing in engineering and consulting for automotive racing projects. RA.CE acts as a technical contact for the driver in motor racing and takes responsibility for the optimal use of the vehicle. They also offer support in the implementation of large and complex racing projects and projects in the energy sector.

<https://race-consulting.com>

First of all, thank you for your time and the opportunity to validate our research with an expert opinion and get further input for our master's thesis.

Our first question is a little more general: In your opinion, what are the biggest advantages of hydrogen drives over battery-powered electric vehicles and how does hydrogen differ from other alternative drives?

A major advantage of hydrogen drives, especially hydrogen engines, is their weight. Compared to hybrid or purely electric vehicles, which often have a considerable weight, the use of hydrogen as a fuel opens up the possibility of weight reduction. This aspect is of particular importance, as every additional kilogram that needs to be accelerated requires additional energy, which is contrary to the goals of energy efficiency.

Furthermore, hydrogen-powered vehicles have an extended range compared to the purely electric vehicles that are currently available. This is particularly relevant for applications where long distances are involved.

Another significant advantage is the shorter refueling time compared to charging large batteries. The rapid refueling of hydrogen enables efficient use of the vehicle without time-consuming charging times, which makes it especially convenient to use.

How can hydrogen compete with other alternative drive technologies, especially in terms of infrastructure and refueling times?

In my opinion, hydrogen already outperforms electric mobility in terms of range. However, the availability of hydrogen poses a greater challenge compared to the supply of electricity. Various barriers can be overcome through clever strategies and the use of synergies, for example by processing gases in biogas plants to produce CO₂, from which hydrogen can be produced by electrolysis.

To the best of my current knowledge, the refueling times of hydrogen vehicles are already shorter than the charging times of electric vehicles.

As soon as the development of hydrogen infrastructure is pushed forward to the same extent as for electric vehicles, refueling times will also be further reduced.

How do you see the role of hydrogen as an energy source in future mobility?

I think that different energy sources will coexist in different areas of mobility in the future. Electric vehicles and drives could primarily be used in urban areas, while hydrogen could increasingly be used alongside fossil or synthetic fuels in long-distance and heavy-duty transportation.

How do you assess the public interest and acceptance of hydrogen vehicles?

Ultimately, both marketing and political decisions will be crucial in determining whether hydrogen is accepted as an energy source. Advertising and political marketing messages have helped to promote electric mobility as extremely environmentally friendly, but often ignore the fact that the environmental damage, although different, can be just as significant as that caused by the use of fossil fuels.

What are the most important trends and developments in the field of hydrogen energy that car manufacturers should take into account when designing their strategy?

I currently find the hydrogen engine itself the most exciting. It has similar characteristics to the current combustion engines, including the soundscape. This is a decisive advantage over electrically powered vehicles.

The "hydrogen paste" could also be interesting, after appropriate research and solving the remaining problems (availability, recycling...)

How do you assess the current state of competition and cooperation between the main players in the hydrogen sector, including car manufacturers?

Difficult to assess from my perspective. We hear that Bosch is working on a hydrogen engine or has one ready. Since all car manufacturers (in Germany) are working with Bosch, this should also be accessible to all. We hear similar things from BMW, but here the competitive behavior of the car manufacturers will probably stand in the way. In terms of global competitiveness, a hydrogen alliance would be highly desirable.

What are the biggest technical challenges in integrating hydrogen drive systems into vehicles?

The storage and sealing of the "fuel system".

What technological or economic breakthroughs do you think would be necessary to establish hydrogen as the main energy source in the automotive sector?

The biggest challenge is probably the infrastructure, worldwide. As mentioned above, this is much easier with electricity.

What opportunities do you see for BMW and the automotive industry through the use of hydrogen as the fuel of the future?

Germany has missed out on the hype surrounding e-mobility. Being a pioneer in a technology that, in my opinion, offers more opportunities than risks, is a good way and a chance to establish a positive image in the market and win over a large share of buyers.

How do you see the current and future cost ratio of hydrogen compared to other alternative drives?

Difficult to assess. In the end, it depends on the quantity that is produced and the strategies behind it. With more research and more customers, the costs should fall.

Thank you very much for this insight, your time and the detailed answers, we appreciate this very much.

Appendix X3

Our interviewee is an expert in the hydrogen sector and worked many years as a head of research in an energy institute.

The interviewee requested anonymity.

What are the biggest advantages of hydrogen fuel cell vehicles (FCEVs) compared to battery electric vehicles (BEVs) from your perspective, and how does hydrogen differ from other alternative drivetrains?

Compared to battery electric drivetrains, the main advantage is that I'm not bound to an electrical grid infrastructure. In other words, there's no need to lay power cables at petrol stations, charging stations, etc., which are not only very expensive but also entail a considerable amount of effort. With hydrogen, we can potentially rely on existing gas pipelines. Of course, new pipelines may need to be laid for hydrogen refueling stations, or the hydrogen can be transported by truck, but at least there are transport advantages because we don't have the issue of congested lines. This ties directly to the second advantage, which is storability. Especially with electricity, we face the drawback of having to balance input and output; the amount of electricity supplied must equal the amount withdrawn from the grid, which can cause significant problems, particularly in the mobility sector when everyone wants to charge their car in the evening. This means strategies for coordinated charging are necessary, and while efforts are underway, they are not quite there yet. However, with hydrogen, storage is relatively simple. We can create large underground tanks at refueling stations to store hydrogen, whether liquid or under pressure, and then dispense it into cars as needed. There's also refueling time; I'm not very familiar with the exact duration, but it's likely to be much less than that of electric vehicles, including those at fast-charging stations.

And particularly in comparison with traditional internal combustion engines, let's say those with e-fuels like synthetic gasoline or diesel, the advantage is a higher efficiency over e-fuels. If we were to categorize efficiencies - the amount of electricity that goes in at the start and what ultimately translates to kinetic energy on the road - electromobility is the best, approaching 90%, followed by hydrogen, and then e-fuels, which have a significantly lower efficiency because the electricity has to be converted to hydrogen, then to synthetic gasoline, for example. Then, in the car's combustion engine, there are substantial efficiency losses. As a result, more green electricity must be produced at the

start of the value chain, meaning more solar or wind farms need to be built compared to hydrogen or even more so with electromobility.

I find it fascinating that you mentioned infrastructure because we've always seen it as an obstacle since the infrastructure largely does not yet exist. But from your perspective, as you've presented it, we've actually never seen it that way, very interesting.

Yes, well, I'm not a mobility expert either; I'm generally more familiar with the whole market perspective of hydrogen. But for refueling stations, you can consider two strategies: either lay a hydrogen pipeline and try to supply the station completely via the pipeline, similar to the electrical grid. Alternatively, like today's diesel and gasoline, you could have a truck deliver the pressurized hydrogen to the station's tank. At least there's an infrastructure that we could build upon. Clearly, the pumps would have to be entirely rebuilt, but, for example, there's no need to tear up the entire road to lay cables to rest stops on highways. So, I see the effort involved in electromobility transport as significantly higher.

Our next question is: How can hydrogen compete with other alternative drivetrain technologies, especially in terms of infrastructure and refueling times?

Well, when I read the question, I had to think about it for a while because to compete, I see some hurdles. There are hydrogen refueling stations, but they're still scarce and need to be more widely deployed and standardized to reduce costs. So, economic viability is still the main issue.

How do you assess public interest and acceptance of hydrogen vehicles?

My sense is that acceptance is relatively high, maybe even higher than for electromobility. There have always been waves where hydrogen was touted as the new energy carrier for the transport sector. In the current cycle, we're counting on success, and the discussion is much more about industry and the energy sector, with mobility turning towards ships and trucks.

Hydrogen in the transport sector was always a topic in the '70s, '80s, '90s, and so many associate hydrogen, especially with fuel cell vehicles. I've always felt that acceptance is relatively high, with many saying, "why do everything with batteries and not with hydrogen, which is so much simpler with refueling and doesn't require hauling heavy batteries around?"

However, then come the issues I mentioned, efficiency and high costs. But my impression is that acceptance is relatively high, although we must be cautious. A few

years ago, a refueling station in Oslo exploded, and it shows that there can be risks since it's significantly more explosive than natural gas.

And it must also be ensured that the technology is truly safe and perceived as safe, so that we don't eventually run into acceptance problems. After that incident, all hydrogen stocks plummeted, but that was quite a setback, so to speak.

What technological or economic breakthroughs do you think are necessary to truly establish hydrogen as a main energy source in the automotive sector?

Well, I believe we really need to look at the entire value chain, starting from the top, to clarify we are talking about green hydrogen. One could also consider blue or gray hydrogen, but let's say we want green hydrogen, which is also the strategy at least in Germany. We start with renewable energy sources, such as wind, solar, or hydropower. A lot more needs to happen there; we need to expand capacities significantly. Currently, green electricity just about meets the targets in the electricity sector, and to produce hydrogen, we need to expand or import more. And then costs need to come down as well. First, the electricity itself needs to be cheaper. Then in the next step, we have electrolysis, the production of hydrogen from green electricity. Here, we currently see prices that are much too high, often exceeding what you would pay for gasoline at the pump. We expect costs to decrease through learning effects, but that first needs to be achieved, which requires incentivization. This is done by providing state funding for the initial, expensive projects, so that costs can be gradually reduced. And then downstream, there are still some technical questions to be clarified, such as what is actually more cost-effective? Do we lay a pipeline to the filling station, or do we handle everything by truck? Which storage technology do we then use?

In the field of fuel cell vehicles, I am not so well informed, but there are likely things that can be optimized here too. One point in transportation is quite interesting if one were to choose the strategy of connecting to a hydrogen pipeline. The technical effort and corresponding costs would then be higher, and the purity of hydrogen from the pipeline is usually too low for use in watercraft. Watercraft require the highest purity grade so that their fuel cells do not clog, so to speak, and this cannot be guaranteed with a pipeline. That means costs would increase again because you need processing or purification plants.

So, along the entire value chain, the technologies are more or less present, but they all need to be scaled up more strongly. So that costs come down, and we move towards competitiveness. Exactly, but that also needs to be accompanied by political measures,

such as CO2 pricing, incentives, and quotas, because I simply don't think all this will happen on its own.

How do you view the interest and willingness of investors to invest specifically in hydrogen technology in the automotive sector?

Yes, in general, there is an increasing interest and investment activity, although I believe everyone is still quite cautious. Currently, projects also need to be relatively well-secured, both in terms of usage duration and production time. Production means all components, so all contracts need to be concluded, and especially a buyer for the hydrogen must be found who pays the appropriate price to make the projects worthwhile. These can quickly become very high million-dollar investments.

The same applies on the customer side, especially when we talk about industry, that guarantees are in place that green hydrogen can be used competitively. If a steel mill says, "I'm using green hydrogen instead of the blast furnace route" investors often want to see, for example, a contract for difference concluded between the steel manufacturer and the state, which compensates for the additional costs of the green hydrogen at least to a large extent, so that one doesn't invest and two years later the plant shuts down and must be written off because hydrogen is just too expensive. So the risk is still very high, and therefore investment readiness is associated with high security guarantees.

How this is divided among the various sectors, I can't say much about. My estimation is that the interest is currently very high in the industry and among all renewable energy producers, hydrogen producers, and also hydrogen pipelines.

Downstream, at the consumers' end, I perceive that it is more about industry and less about the transport sector. My assessment would be that there is relatively little interest in individual transport because currently, battery electric vehicles have almost won the race there, and then more so in heavy-duty transport, such as hydrogen trucks, where investors might be more likely to go in.

But actually, I have no figures on this, nor have I read anything.

We have only read a lot about how often new technologies establish themselves in phases, and experts expect, as you already said, that it will first establish itself in the industry, then in heavy-duty transport, and perhaps lastly in the automotive sector.

Yes, although one must of course say that it could also turn out differently if it were to happen in such phases. It could then be too late for hydrogen, as everything might have already switched to electromobility, and then there's a lock-in, and no one starts talking about hydrogen anymore.

If a critical mass is reached in mobility, and network effects come into play, then hydrogen might no longer be an option, perhaps only for niche applications like taxis, but individual traffic will mainly run on electromobility.

How would you assess the role of the EU in promoting hydrogen technologies, specifically through political initiatives and financial resources?

The EU is the most decisive body on this subject, as usually, it is EU laws that are then transposed into national legislation. And in recent years, we have seen very high activity.

Firstly, through quota requirements for the use of renewable fuels, and specifically the "Fuels of non-Biological origin". These are, in essence, fuels that are meant to be climate-neutral but are not of biological origin, so not in biodiesel or E10, for example. That means no bioethanol. Instead, it could be hydrogen or synthetic fuels or something similar generated from electricity used in the transport sector. The EU has set binding targets, which is currently seen as a very strong incentive to get hydrogen into the mobility sector. However, not necessarily into pure hydrogen cars but even so that current oil refiners who incorporate green hydrogen in their production processes can get credit for it. The Red III is currently in progress, where targets for the transport sector and industry are being discussed, and goals will also be set for these sectors for the use of these alternative fuels, mainly hydrogen cells, which, as said, is a very strong incentive. Then, of course, there's everything to do with funding, i.e., directly subsidizing projects that want to produce or use hydrogen. These are mostly direct CAPEX subsidies, where the EU and also the national governments are very active. How this is broken down sector-specifically, i.e., how big the funding pot is for mobility and how big for industry, I can't say. Overall, I still think it's a bit too slow. I mean, the EU has very ambitious targets, aiming to deploy 20 million tons of green hydrogen across all sectors by 2030, and to get there, I think there's still a lot of projects and financing opportunities missing because everything is just too expensive at the moment.

What specific opportunities do you see for BMW now, and also for the automotive industry, through the use of hydrogen as a radical fuel for the future?

Ultimately, it's about getting the entire industry ready for the future; I think the topic of combustion engines is essentially over. There are always a few voices that say we should talk about e-fuels, but I believe that will be at most a niche application, and clearly, hydrogen is a huge opportunity as an alternative to battery electric vehicles to make the

industry climate-neutral. We have the technology and the know-how and can adapt it according to government strategies.

Of course, there's also the associated risk; I believe it's the same for battery electric vehicles as for fuel cell vehicles, that the vehicles simply consist of significantly fewer moving parts.

That means the value creation that occurs in a vehicle will probably be significantly lower, but with hydrogen vehicles, you don't have the problem of being so strongly dependent on the battery, which is mostly manufactured in Asia, in Korea, Japan, etc. With hydrogen, we might have the opportunity to produce more locally and retain the know-how here. After all, a fuel cell vehicle is also an electric car; they have a small battery, but it doesn't have to be nearly as large as in purely battery-driven vehicles.

What are the biggest challenges for scaling hydrogen mobility, in your view?

I think, as I said before, we have to look at each component of the value chain; they are at different stages, but all in all, it needs to be scaled up even more strongly.

How would you assess the current state of competition and collaboration among the key players in the hydrogen sector, including possibly the automobile manufacturers?

Overall, there is currently a high willingness to cooperate among the actors in the hydrogen market.

There are now many initiatives where companies, sometimes even competitors, come together, at least in initiatives, to really shape the market ramp-up together, i.e., develop solutions, approach politics, and pragmatically implement laws. And I also found it very interesting how cross-actor collaboration works across the entire value chain, both vertically and horizontally. That companies that are competitors still work together because they say, "I can't do this alone. We all need to drive this forward together". I find that very remarkable at the moment. In the automotive sector, I actually know too little. As far as I know, at least in the truck sector, I think Daimler Trucks has formed a joint venture with Volvo Trucks¹⁹ .and want to jointly develop fuel cell trucks, so you can see that a lot is happening in the automotive sector. In the car sector, I'm actually out of my depth; I wouldn't know if there are any cooperation or initiatives there, I'm not sure.

¹⁹ Daimler Truck AG and Volvo Group have formed a fuel cell joint venture, with Volvo Group buying a 50% stake in Daimler Truck Fuel Cell GmbH & Co. KG for about €600 million. They aim to make the joint venture a leading global manufacturer of fuel cells, contributing to climate-neutral transport by 2050. The company will be rebranded as cellcentric GmbH & Co. KG.

Would any particular example come to mind immediately?

Yes, for instance, there is the "Get H2" initiative, which is primarily in Northwestern Germany, and I believe even cross-border to some extent.

Then there is "Hydrogen Europe", which is a large Europe-wide consortium of companies.

There is also "Herkules", which is mainly pipeline-driven, where producers and potential consumers join forces. Then there's a major initiative called "AquaVentus", which aims to produce hydrogen offshore in the North Sea and then transport and distribute it.

And then there are many regional things, "Rhein Ruhr EV"; there is also "H-Cologne", which is from where I come, Cologne.

That was super interesting! Thank you for your time (...).

Appendix X4

Our interviewee is a PhD student at Fraunhofer ICT. His research focuses on battery research, safety testing and hydrogen.

The Fraunhofer-Gesellschaft, based in Germany, is the world's leading organization for application-oriented research. It plays a central role in the innovation process with its focus on future-oriented key technologies and the application of the results in business and industry.

The interviewee requested anonymity.

First of all, thank you for your time and the opportunity to validate our research with an expert opinion and get further input for our master's thesis.

Our first question is a little more general: In your opinion, what are the main advantages of hydrogen propulsion over battery electric vehicles and how does hydrogen differ from other alternative propulsion systems?

I think we should differentiate further: Drive types for passenger cars and for freight transportation (such as trains, ships, or trucks).

Advantages for cars: Further ranges. Faster refueling times, but the filling station has to "regenerate" for some time afterwards. A future problem for the necessary expansion of the infrastructure.

Advantages for ships, trains and trucks: Fuel cells are not so suitable for short bursts of energy, but they can provide constant power, which is more likely to be needed in trucks, trains and ships. Hydrogen trucks have a longer range than their purely battery-powered counterparts and are much lighter, which is important for load ability.

Part of the disadvantages of FCEVs include efficiency. The conversion of energy into hydrogen and back into electricity involves more energy losses than the direct use of electricity in batteries:

Efficiency of BEVs: approx. 73% vs. Efficiency of FCEVs: approx. 22%

Furthermore, FCEVs require frequent maintenance to ensure safety. It can be assumed that the running costs for FCEVs are higher.

Okay, moving on to the next question, thanks for all the information. You may have already answered it in part, but to get back to the point: "How can hydrogen compete with other alternative propulsion technologies, especially in terms of infrastructure and refueling times?"

In Germany, we should first supply industry with hydrogen for processes such as steel production and chemicals. This is why hydrogen pipelines are being planned and,

indirectly, the hydrogen filling station infrastructure is being driven forward, but this will take some time. In addition, we do not have enough hydrogen and will always have to import hydrogen/energy for industry. It therefore makes sense to charge the cars with electricity during power peaks. Electrolysers are also not designed for short-term loads such as power peaks.

Thank you, important point. But what do you think are the biggest challenges for scaling up hydrogen mobility in terms of FCEVs?

For me, scaling only makes sense for heavy-duty transportation. Unfortunately, I'm not familiar with the current state of research.

However, planning security is an enormously important component and unfortunately tends to be an obstacle in Germany (especially for SMEs). Germany cannot afford a back-and-forth policy. The national hydrogen strategy 2.0 is an important and good building block. The question remains as to whether it can be relied upon.

But what opportunities do you see for BMW and the automotive industry in using hydrogen as the fuel of the future?

For heavy-duty transportation only.

How do you see the current and future cost of hydrogen, especially FCEVs, compared to other alternative propulsion systems?

The plan for 2020 and 2021 was to create demand with subsidized gray hydrogen until green hydrogen production becomes economical. Unfortunately, I can't comment on the current situation.

Coming back to the question of where you see hydrogen in future mobility: Is it really only for heavy-duty transportation?

Yes.

Okay, thank you. If we now take a look at opportunities and challenges of this topic: What are the key opportunities and potential disruptors that could shape the future of the hydrogen sector on a global scale?

War and protectionism will make a global connection with hydrogen-producing countries and hydrogen-consuming countries difficult or even impossible.

Taking a strategic position on the side of producers now offers great opportunities.

Research into batteries and fuel and electrolysis cells will pay off in the future. As will the strategic procurement of the relevant raw materials.

Well, in which industrial sectors do you see the greatest potential for hydrogen today and in the future, apart from the transport sector?

In the steel industry for direct reduction, in the chemical industry (e.g. ammonia production), refineries, heating (e.g. direct feed-in (>10% into the natural gas grid)).

One final question: What technological or economic breakthroughs do you think would be necessary to establish hydrogen as the main energy source in the automotive sector?

We would need an almost unlimited clean energy source that can afford to produce the comparatively energy-intensive hydrogen.

Thank you very much for this deep insight, your time and the detailed answers.

Appendix X5

Our interviewee is part of a leading strategic management consulting firm that specializes in overcoming complex challenges and achieving ambitious goals for clients in a variety of industries. In the specific area of hydrogen technologies, our interviewee works to enable companies and organizations to recognize and exploit the potential of this sustainable energy source. This includes advising on market developments and supporting the development of efficient value chains to drive the energy transition.

The interviewee requested anonymity.

First of all, thank you for your time and the opportunity to validate our research with an expert opinion and get further input for our master's thesis.

Our first question is a little more general: In your opinion, what are the main advantages of hydrogen propulsion over battery electric vehicles and how does hydrogen differ from other alternative propulsion systems?

Is the question just about cars or also about trucks?

Actually, it is more about motorized passenger transportation, i.e. cars.

Okay, thank you. As you probably know, there has been an intense political debate in recent years about the preferred technology for decarbonizing the transport sector, particularly in light of the influential EU regulation on CO₂ fleet limits²⁰. Three main technologies have been at the centre of the debate: battery electric vehicles, hydrogen propulsion technologies and power-to-liquid (PTL) e-fuels, i.e. synthetic hydrogen-based fuels. However, political decisions have resulted in PTL e-fuels not being favored in the context of CO₂ fleet limits. These limits evaluate vehicles according to their direct emissions, with the aim of promoting vehicles that have no or very low direct CO₂ emissions. This favors battery and hydrogen vehicles in particular, as PTL e-fuels release CO₂ during combustion in the engine, even if they are potentially produced from renewable energy sources and can be CO₂ neutral over their life cycle.

A key factor when comparing technologies is efficiency, or how efficiently the energy consumed is converted into propulsion energy. Battery electric vehicles perform best in this comparison because they use electrical energy directly for propulsion.

²⁰ If a manufacturer's fleet's average CO₂ emissions exceed its specific emissions target in a given year, the company is required to pay an excess emissions premium of €95 per g/km of excess emissions for each new vehicle registered that year.

Hydrogen technologies, on the other hand, require electricity to produce hydrogen, a process that involves significant energy losses. In addition, fuel cells are less efficient in vehicle operation than electric motors. As a result, many automakers are increasingly focusing on electric mobility.

Along with Toyota and Hyundai, BMW is one of the few automakers to push the development of hydrogen technologies. In my opinion, the focus on hydrogen and fuel cell technologies shows how important the energy efficiency argument is for the automotive industry.

In addition to efficiency, there are other important factors to consider. These include the availability of energy sources and their energy efficiency, as well as how well renewable electricity can be stored and transported. This discussion illustrates the complexity of the decision-making process, because while renewable energy is a clean solution, its storage and distribution can be challenging.

The potential benefits of hydrogen are particularly evident where the refueling infrastructure is unique and not in close proximity to renewable energy sources. Hydrogen is easier to transport and store than electricity. Despite progress, battery-powered vehicles still have some catching up to do in terms of charging times. A Tesla, for example, can charge up to 80 percent of its battery capacity in about half an hour, which is quite efficient compared to other electric vehicles that may take longer. Refueling hydrogen vehicles is similar to the conventional gas station refueling process and only takes about 3-4 minutes, which is a significant time advantage.

Another critical factor is range. Hydrogen can still offer advantages here, even though battery development is progressing rapidly and the differences in range are becoming more and more equal. The question is how long hydrogen can maintain its range advantage.

A further important aspect is the infrastructure for charging and refueling, which is of crucial importance for the acceptance and diffusion of the technologies. In Germany, the charging infrastructure for electric vehicles is relatively well developed and growing, while there are only about 100 hydrogen refueling stations, fewer than for electric vehicles. Internationally, the situation is difficult for both technologies. The ability to easily refuel electric vehicles, and even more so hydrogen vehicles, abroad is often limited. This is increasingly important for long-distance travel, such as vacations to Italy or Spain, where refueling and recharging options are critical.

Okay, moving on to the next question, thanks for all the information. You may have already answered it in part, but to get back to the point: "How can hydrogen compete with other alternative propulsion technologies, especially in terms of infrastructure and refueling times?"

In terms of infrastructure, hydrogen currently lags far behind electromobility and will probably take a few years to catch up, similar to the early days of electromobility. A big advantage of hydrogen is the fast-refueling process, which is much shorter than charging batteries.

Personally, however, I am skeptical about the use of hydrogen in road traffic. Especially for a car manufacturer like BMW, which is swimming against the tide in this respect, it seems risky. Although a change in external conditions could give BMW a considerable head start, the current political and funding focus is clearly on electromobility and the expansion of the corresponding charging infrastructure.

The development of a hydrogen infrastructure in addition to the already developed infrastructure for electric vehicles represents an immense challenge and financial burden from an economic point of view. The development of three infrastructures - for gasoline/diesel, electricity and hydrogen - appears to be too costly in the long run.

Nevertheless, it is important to emphasize that BMW's decision to invest in hydrogen technology is a sign of a free market in which companies can pursue different strategies. However, I personally see a clear advantage for electromobility, mainly due to the efficiency argument.

Renewable resources such as sun and wind are available to us almost indefinitely. However, we are limited in the production of the wind turbines and solar panels that harness these resources, which means that these valuable commodities are becoming scarce. This is where the efficiency argument comes in, which favors electric mobility over hydrogen propulsion. In addition, it is expected that electric mobility will continue to catch up in areas such as range and charging time, which will reduce the current advantages of hydrogen vehicles.

But would you actually say that hydrogen will play a bigger role for trucks in the future, or do you think that it will actually reach its limits there as well, that people will simply continue to rely on electric mobility and then of course continue to rely on normal combustion engines in some way?

It is difficult to predict the future precisely. But I can give my opinion on what I think is likely. I still see potential for hydrogen in the lorry sector, mainly because battery technology, especially for long-distance and heavy-duty transport, still needs to be

developed further in order to deliver the required performance. However, the problem of refueling infrastructure is not just a problem for cars, but also for trucks travelling across Europe, and is therefore a challenge for the entire continent.

But there are some projects involving hydrogen in the truck sector. And it can also be an advantage that there are some logistics companies behind them that are pushing this further. I know that DHL is doing a lot and, as far as I know, so is Amazon.

These companies have the financial means and the motivation to invest in such technologies, also in order to achieve their climate targets. A vehicle like the BMW X5 with a hydrogen drive may be expensive, but such costs are more affordable for companies that have committed to improving their carbon footprint than for private car owners. There is a completely different financial power behind it.

Yes, that's definitely an important point, thank you. What technological or economic breakthroughs do you think would be necessary to establish hydrogen as the main energy source in the automotive sector?

The development of the hydrogen economy in the EU is currently lagging far behind the targets. By 2030, we want to import 10 million tons of renewable hydrogen and produce a similar amount ourselves through electrolysis. However, we are still a long way from achieving these targets, as the production of green hydrogen has practically not yet started and is only available in minimal quantities. To achieve these targets, hydrogen production would have to be increased almost 20 times per year. In addition, the expansion of the necessary wind and solar power plants, of which we would need tens of thousands, is an enormous challenge.

The situation is worsened by the loss of subsidies and the abolition of the climate fund. Added to this are rising material costs, which make expansion even more difficult. Should we nevertheless succeed in producing or importing the targeted quantities of hydrogen, we face the problem that these quantities will still not be sufficient to decarbonize all industrial processes that are urgently dependent on hydrogen, such as steel production and other industries that are difficult to decarbonize.

Politically, it is argued, and this seems sensible, that the available hydrogen should initially be used in areas where there are no alternatives to decarbonization. In steel production, for example, there is only a choice between the traditional, CO₂-intensive process using coal or switching to hydrogen. This is why politicians are focusing on prioritizing the use of hydrogen in these sectors, while electromobility is seen as a viable alternative for the passenger car sector.

I don't think we need to change much technologically. The existing problems are not of a technical nature; both fuel cells and the production of green hydrogen work well in principle. The challenge lies in the fact that it is currently not economically viable for companies to produce or utilize hydrogen. One solution could be massive state subsidies to boost hydrogen production. In addition, long-term purchase agreements are necessary, which can be concluded primarily by large companies, as only these are in a position to purchase significant quantities.

Coming back to subsidies and the diversity of technologies: On the one hand, there is the Green Deal, which is driving the movement towards greater sustainability. On the other hand, you mentioned that there is a lack of specific funding to avoid focusing exclusively on electromobility. Do you see a problem with focusing on electromobility to the exclusion of other possible alternatives?

Of course, automakers are free to develop hydrogen vehicles if they believe this is the right strategy. But developing a fuel cell and a vehicle based on it is only part of the challenge. It is crucial that these vehicles are successfully brought to market and sold. The CO₂ fleet regulation also plays a key role here, with significant penalties for manufacturers who fail to meet their CO₂ targets. It is therefore not enough to develop a hydrogen car; success will ultimately be measured by how many of these vehicles are actually sold and launched.

The Toyota Mirai, for example, is being driven by many taxis, and also by Uber. Of course, it may still have some advantages for their specific use case, but these are all cost-driven and finance-driven companies. So, I think they will be looking at this very closely. They will have taken a close look at what it costs them to buy and operate the hydrogen car and what it costs them to operate the electric car. But that's exactly how you would compare it privately, of course there are some emotional factors involved, some people say they would never buy an electric car, but in the end, it will always be a matter of weighing the options. And if the infrastructure for electric mobility is going to be massively expanded, the ranges are going to get better and better, etc., then I can't imagine that the decision will still be in favor of the hydrogen car.

Our next question, which is related to this topic, is What are the key trends and developments in hydrogen energy that automakers should consider when formulating a hydrogen strategy? In particular, we are interested in what BMW should consider when formulating its hydrogen strategy.

As I mentioned earlier, the availability of hydrogen is absolutely critical, and it is de facto non-existent at the moment. Another important issue is price. This is particularly important when we are talking about green hydrogen, because it is still very expensive. In addition to the cost of production, there is the cost of distribution and the cost of operating the filling stations.

A fuel cell car can drive about 100 kilometers (km) on 1 kilogram (kg) of hydrogen. Even with the existing hydrogen refueling stations, gray (fossil) hydrogen currently costs between 10 and 15 € at the filling station. If we assume a production cost of 2 €/kg for fossil hydrogen, this means a price premium of about 12 €/kg for transportation, storage, filling station operation, margin, etc.

If renewable (green) hydrogen is produced for 8 €/kg, which is already optimistic for Germany, green hydrogen would cost about 20 €/kg at the filling station. This can then be compared with the 6 liters of diesel a combustion engine needs per 100 km at a price of 1.80 €/liter = 10.80 €. So even fossil hydrogen is already slightly more expensive than diesel, and when it becomes green hydrogen, it will be significantly more expensive again.

Absolutely, but do you have a plausible explanation as to why BMW continues to focus on hydrogen and do a lot of R&D despite the adversity and lack of infrastructure? Mainly because they seem to be one of the few automakers that are focusing so heavily on it, especially in Europe. There is also Daimler, but they have dedicated themselves to hydrogen in the truck sector, while VW is fully focused on electromobility.

Difficult, but good question! I also wonder what BMW's motives might be. The decision to invest in the development of a new technology, in this case hydrogen, can only be made if a relatively certain return on investment is expected. In other words, they have to assume that they can reach significant customer groups now and, in the future, although I'm thinking more of commercial customers such as fleet operators or taxi companies and less of private individuals.

But the question is whether these corporate customers could just as easily switch to electromobility if they are willing to pay more for alternative drive technologies. But what incentives are there for companies to focus specifically on green hydrogen instead of switching to electromobility straight away, where development and infrastructure are miles ahead?

Another strategic point could be to invest in hydrogen in order to later transfer the technology to other areas such as lorries, although I have to object here too that BMW does not have a lorry business.

Another consideration could be marketing in order to position itself as a sustainable company. But that could also be achieved with electromobility. But perhaps BMW also recognizes the major challenges in electromobility, e.g. in terms of materials for battery production, and thinks that hydrogen could be a good alternative in the future.

However, it is difficult to answer conclusively why BMW is currently one of the only companies pushing the issue of hydrogen.

Thank you for your comments. In summary, you do not currently see hydrogen as the most convincing solution in the passenger car sector. But apart from the automotive industry, where do you see the greatest potential for hydrogen now and in the future?

Certainly, in industrial processes that require very high temperatures, such as steel production, as these temperatures cannot be reached efficiently with electricity. We are talking here about processes that require temperatures of over 800 degrees, sometimes even over 1000 degrees Celsius. In such cases, the use of electricity is either extremely inefficient or technically impossible. For example, steel production, in which steel is made from iron ore, requires these high temperatures. The same applies to the production of certain basic chemicals, which are then used in other products such as plastics or pharmaceuticals. There is currently no practicable alternative to hydrogen for these processes, especially when it comes to green, i.e. environmentally friendly, variants.

However, transport and storage solutions for hydrogen, which I refer to as 'carriers', play a central role in these processes. These carriers must be able to transport the hydrogen efficiently to the place of use. Legislation is also already beginning not only to promote the use of hydrogen, but in some cases even to require it. A major obstacle, however, is the high-cost sensitivity of such industrial processes. Even small increases in the price of electricity or gas can have a significant impact. When switching to hydrogen, a possible multiplication of costs is to be expected. Despite the urgent need for hydrogen, the willingness to bear these additional costs is limited. This problem is exacerbated by international competition from companies outside the EU that continue to rely on fossil fuels and by the enormous quantities of materials required for projects such as steel bridges. Ultimately, these costs must be sustainable and affordable.

It is also important to emphasize that the efficiency and environmental impact of hydrogen is highly dependent on the production method. Green hydrogen produced by electrolysis using electricity from renewable energy sources is crucial for reducing CO2 emissions in these processes. The biggest challenges currently are the cost and scaling up the production of green hydrogen to meet industrial demand and enable widespread application. This emphasizes the potential of hydrogen as a key component for more sustainable industrial production and the need to find solutions to the current production and supply challenges.

I also see potential for hydrogen in shipping and aviation, as these sectors are difficult to electrify. Large container ships and passenger aircraft could rely on hydrogen as an energy source. However, it's important to note that for these applications, the focus may shift to the use of synthetic fuels (PTL fuels) derived from hydrogen, rather than the direct use of hydrogen.

This makes sense and emphasizes the complexity involved in the transition to a hydrogen economy. Thank you very much for this deep insight, your time and the detailed answers.

It shows how important it is not only to scale the production of green hydrogen, but also to develop the infrastructure for its transport and storage. It gives us a lot to think about and shows that there are many other aspects besides production that need to be considered in order to really utilize hydrogen efficiently.

Appendix X6

Our interviewee Nikolas Beneke works for BHH Consulting, a provider of consulting services to energy and infrastructure companies.

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So first, I would like to thank you for taking your time for this expert interview and for the contribution to our work project. Let's start with the first question: What are the biggest advantages of hydrogen drives compared to battery electric vehicles, and how do they differ?

The first point, which you probably know, is refueling time, followed by infrastructure requirements, depending on how public transport and fleets are designed.

Today it can be positive that no electricity infrastructure needs to be built, especially for applications in remote areas where it's not so easy to lay cables for electricity, then there's also the issue of lower space requirements.

In our projects, it's often not only the vehicle-specific advantages of hydrogen that should play a role. For instance, we have companies in the public transportation sector that say they don't have enough space to install many charging stations.

For us, a hydrogen infrastructure or fuel cell vehicles would actually be better suited because we can refuel elsewhere.

I think that's important for heavy traffic on long distances. That's a very interesting application area for hydrogen drives or fuel cells where advantages could play out.

Moreover, we've heard from many logistics companies that say they have very long distances that batteries can't yet handle, but that's still a very open point for me because we're also seeing efficiency improvements in batteries.

I find it very difficult to say that fuel cells will sweep through, I can't really assess that.

I can only say from practice that many logistics companies who need to drive long distances find fuel cells very, very interesting because battery vehicles from their perspective are not there yet.

If I may interject, if that's okay, would you say that hydrogen will remain more of a niche product in the transport sector, or do you think it will eventually catch up with batteries or even surpass them in terms of electric mobility potential?

Well, currently, even batteries haven't really achieved a high penetration rate.

There aren't so many battery vehicles in operation on the roads yet.

Because of that, I find it difficult to make any statements since I don't have any quantitative indicators to say whether fuel cells will achieve a very high penetration rate or not. So, I really can't say, and I would also claim that there is almost no one who can say that.

So, one must also look at the hydrogen infrastructure as well as the battery charging infrastructure that needs to be built.

For example, if we look at cross-country traffic on long hauls, it's pointless if someone has an extensively developed network of hydrogen fueling stations in Germany, or a charging network, and then outside of Germany, it's not the same.

How the infrastructure will be built beyond Germany, there is a regulatory directive from the EU .I don't know if you're familiar with it.

About the infrastructure development regarding charging and hydrogen, so that will definitely at least bring some structure and also guidelines for the member states.

The issue of performance under various conditions, like topography, cold - those are the points that come to my mind where my feeling is that batteries still have difficulties and fuel cells might have advantages.

But we have to say that we are more on the hydrogen consulting side so I don't have an assessment of how battery performance will improve, whether that in two years will no longer be an issue, and whether the outside temperature will no longer affect the range. These are just points I know from practice and are currently relevant topics. For instance, the Wuppertal public transport system has purchased many fuel cell buses because they say, with Wuppertal's hilly terrain, it's better performance-wise.

How can hydrogen compete with other alternative drive technologies, especially in terms of infrastructure and refueling times?

Yes, I was just thinking completely...Independent of infrastructures, also daytime, I believe the economic efficiency of production is important.

I believe you are also aware that hydrogen is ultimately a conversion technology, which means there are efficiency losses, so that hydrogen is theoretically always quite expensive. It could be that through imports, for example, hydrogen might be available more cheaply, but there is a big question mark as to whether imported hydrogen will really be cheaper than domestically produced hydrogen. Nevertheless, these conversion losses exist either way. I believe that is simply a topic that, that is important to have in mind.

Economic efficiency of production, electricity availability, electricity prices, and such things. Or when talking about biomass hydrogen, the availability of biomass is the goal, ideally to produce hydrogen from biomass, from waste, while simultaneously aiming to produce less waste, so that naturally reduces the potential there, so economic efficiency of production is very important and hydrogen availability is closely linked to it.

If there are many actors willing to buy hydrogen, availability will certainly increase faster. Then the expansion of the fueling station network, I think that's very relevant.

The AFIR²¹ directive I've already mentioned, I think it plays a role and can contribute to this now taking off, although the requirements for hydrogen compared to the construction of charging stations are relatively low.

So, for example, there were once requirements for liquid hydrogen fueling stations in this directive, which have been removed. If you look at Daimler, which aims to bring liquid hydrogen to the roads, that probably didn't please them that this topic was removed. And then the reliability of the refueling infrastructure.

We perceive from practice is hydrogen fueling stations that are in operation are often not in operation because it is indeed a challenging technology because you have this interplay of compressors and pressure tanks, as the hydrogen is compressed to 350 - 700 bar in the vehicles, so there must also be corresponding storage, compressors, and this is a technology that is still somewhat prone to failure. The vulnerability of the charging infrastructure, I'm not so familiar with that, but it's a topic, and I think it needs to be improved, or rather, we need to collect experience values, so that it gets a really reliable technology.

Which are the biggest challenges for scaling hydrogen mobility from your perspective?

From your point of view, basically all the points that stand under the question "How can hydrogen compete with other alternative drive technologies, especially in terms of infrastructure and refueling times?", then vehicle availability. You probably know the situation; you can't order many models yet.

In the passenger car sector, there are two or three; in the bus sector, there are a few more, for example from Solaris. Although there the reliability can sometimes be difficult, that's not due to the fuel cell but rather to the vehicles themselves.

²¹ With the Alternative Fuels Infrastructure Regulation (AFIR), the European Commission has created the basis for a nationwide public charging infrastructure to support the transition to zero-emission vehicles and achieve the EU's climate neutrality target by 2050.

There's Hyundai; there will probably soon be others, but those are logistics companies that can say "yes, I'm going to buy a brand vehicle now, I don't know if that's going so well right now", so I think a lot needs to be done there, and that's also what the logistics companies tell us. To add more challenges the expansion of infrastructure is to mention, but also the distribution we'll come back to shortly. In the transportation sector, probably won't work with pipelines, but rather with trailers. That's naturally a bottleneck because there aren't so many actors who can do that ad hoc, those are gas manufacturers or gas.

Maybe, if I may interject again, you mean mainly green hydrogen then, right?

Exactly, you're right about that. Generally, hydrogen is already available through steam reforming, from methane. Methane, but the goal is decarbonization, and that's where the question comes up a bit, what is now?

Green hydrogen, I don't know if you're familiar with the topic, but it's not as simple as saying we'll take renewable energy or electricity from wind turbines, make hydrogen out of it, and that's green. There are some regulatory nuances, and they play a very strong role here in economic viability.

And there is the so-called THG Quota²² mechanism, which means that companies that put diesel and petrol fuels on the market are obliged by the EU and therefore also by Germany to reduce their emissions from gas.

They can do this by incorporating emission-free fuels into their fuel mix, and hydrogen can be one of those options. So, in addition to selling petrol and diesel, they would also sell hydrogen and thereby reduce their emissions.

Now, as I just mentioned, it's not as simple as taking electricity from the grid or from solar power plants and assuming that when you convert it to hydrogen through electrolysis, it automatically becomes green. There are additional regulatory requirements from the EU or from Germany that need to be met if you want these additional revenues from the THG quota trade I just spoke about.

Therefore, this is relevant for the economic viability of production. If you want these additional revenues, you have to comply with these regulations.

But these regulations are not minor; that means, it's a complex interplay of different factors that need to be aligned to meet this requirement here.

²² The greenhouse gas reduction quota is a market-based climate protection instrument that has been legally standardized in Germany since 2015 and aims to introduce more renewable energies into the transport sector and thus reduce climate-damaging greenhouse gas emissions.

What opportunities do you see for BMW and the automotive industry through the use of hydrogen as the fuel of the future?

That's difficult for me to estimate because it really is a global issue; we're not just active in Germany but all around the world, with China being an important market, I believe. So, the question is a bit about how the markets develop? In China, there is a movement towards hydrogen.

Also, the US has plans for hydrogen, though I'm not sure if they lie in the transportation sector. I think they are focusing more on the industrial use of hydrogen, like Germany, at the moment. So, it's hard to assess the chances. It depends on how the global market develops.

Sorry, to ask quite bluntly, would you say that it is extremely negligent of BMW because obviously their R&D investments are probably much higher in batteries or electric mobility than in hydrogen? For example, Audi still maintains a small area where they research fuel cells, yet they position themselves publicly clearly towards electric mobility, while BMW still says they see both electric mobility and hydrogen fuel cell technology as leading, and this will be the path to a transformation to sustainable mobility. Is this more about image polishing, or what?

It's hard to judge; I don't know if that's the way to go.

I believe it's not just for the image; they do have a trial vehicle, don't they? Haven't they even released this X5 or X3?

Yes, exactly. They have the pilot fleet.

So, I don't believe it's just for image purposes. I also cannot objectively say whether their strategy is wrong or right. No one can really say at the moment, I personally would say betting on both technologies for now is not wrong because where the trend will go is simply unknown.

Let's move on to our next question: How do you see the current and future cost ratio of hydrogen compared to other alternative drive systems?

The domestic production of hydrogen, particularly through electrolysis, presents us with major challenges. It should be noted that the conversion of electricity into hydrogen is associated with losses that have a significant impact on costs. In contrast to the direct use of electricity in batteries, where the main costs lie in expanding the infrastructure for transporting electricity, hydrogen as a potential storage medium offers the possibility of cushioning the volatility of electricity generation.

In the case of e-fuels, i.e. fuels produced from hydrogen, further conversion losses must be taken into account. The advantage, however, is that the existing infrastructure - such as transport routes and filling stations - only needs to be adapted slightly.

For the transportation of hydrogen, we see the need for transport by road tanker in the medium term, as the role of pipelines in the transport sector is still unclear, especially in comparison to the industrial sector, where consumption is significantly higher. Depending on the location, however, synergy effects could play a role.

Another important point is the import of hydrogen. The National Hydrogen Strategy assumes that 50-70% of hydrogen demand will have to be imported. However, this does not automatically mean that prices will be low. Many factors play a role here, from international market dynamics to transportation costs.

Overall, there is no one-size-fits-all answer to the question of the best strategy for alternative drive systems. Each approach has specific factors that need to be considered in order to develop a comprehensive and effective energy strategy.

What role do you think hydrogen will play in future mobility?

In the road transport sector, particularly for buses and heavy commercial vehicles, it is already clear that fuel cell technology is very suitable for certain applications. Many bus operators and logistics companies recognize the potential, especially in these classes, even if the degree of penetration is difficult to predict.

In air transport, the focus is primarily on the use of liquid hydrogen (LH2). We see relevant potential for LH2 for short to medium distances of up to 1,000 km, although there is direct competition here with battery drives and sustainable aviation fuels (SAF). For long-haul routes, the use of LH2 requires considerable design adjustments to aircraft but represents an interesting alternative to SAF that is associated with further conversion losses without the need to change the existing infrastructure.

The major aircraft manufacturers are pursuing different strategies: Airbus is investing heavily in liquid hydrogen technology, while Boeing is focusing more on SAF. This shows the diversity of approaches and challenges facing the industry.

In shipping, on the other hand, fuels such as methanol and ammonia, whose starting product is hydrogen, are of greater importance. These options are more suitable as they are easier to handle and integrate into existing drive systems.

The first fuel cell trains are already in use in the field of rail transport technology, e.g. in Lower Saxony. These developments show that sustainable drive solutions are also

gaining a foothold here and represent a viable alternative to conventional diesel-powered rail transport.

In summary, it can be said that the choice of technology depends heavily on the specific application requirements and framework conditions. The energy industry must remain flexible and continuously evaluate developments in the various areas in order to implement the most efficient solutions in each case.

Thank you for the insight. How do you assess the role of the European Union in promoting hydrogen technologies through funding and policy initiatives?

Several factors are crucial for a successful ramp-up of the hydrogen industry. Firstly, specific funding programs such as the establishment of 'Hydrogen Valleys' are of central importance. These concentrated initiatives create an ecosystem in which the production, distribution and use of hydrogen can be optimized to drive synergies and innovation. Another crucial aspect is the sovereignty of the individual states over their funding programs. This includes the application of the General Block Exemption Regulation (GBER), which allows member states to approve certain types of state aid without prior examination by the European Commission. Equally important is the notification of specific aid that requires special approval by the Commission to ensure that such aid does not distort competition and contributes to economic development. Finally, the regulatory environment plays a crucial role. The framework conditions under which the hydrogen industry can operate are largely determined by regulatory requirements. These requirements must support both economic and environmental objectives and help to encourage investment in hydrogen technology while ensuring fair competition.

What are the key opportunities and potential disruptors that could shape the future of the hydrogen sector on a global scale?

The opportunities arising from the use of hydrogen are particularly important for the decarbonization of industry. Especially in areas that are difficult to decarbonize, such as material applications and high-temperature heat generation, hydrogen offers great potential as an alternative. The fact that leading economies such as Europe, the US, Australia and China are looking to increase their use of hydrogen underlines the global interest and strategic importance of this technology. These regions have recognized that hydrogen can play a key role in the transition to a low-carbon economy.

However, this potential also comes with significant risks. One critical issue is the lack of a mature transportation infrastructure for hydrogen and its derivatives such as

ammonia and methanol. The development and scaling of such infrastructures are crucial to fully realize the benefits of hydrogen. This challenge is exacerbated by the current reversal of globalization, as it leads to a renationalization of supply chains and potentially to higher costs and greater complexity.

Apart from the transport sector, in which industrial sectors do you see the greatest potential for hydrogen today and in the future?

In industry, especially in sectors such as steel production, refineries and ammonia production, hydrogen plays a crucial role in decarbonization and achieving climate policy goals. Support measures such as climate protection contracts and special support programs are helping industry to reduce its CO₂ emissions.

At the same time, the role of hydrogen in the energy industry, particularly in gas-fired power plants, is another key aspect of the German government's energy strategy. The conversion of conventional gas-fired power plants to hydrogen is part of a comprehensive power plant strategy to ensure security of supply and achieve climate targets at the same time.

This brings us to our final question: What technological or economic breakthroughs do you think would be necessary to establish hydrogen as the main energy source in the automotive sector?

Whether hydrogen can serve as the main energy source for road transportation is an open question. This uncertainty stems in part from the fact that the economic viability of hydrogen is heavily dependent on various factors such as support from government programs, the scaling of production technologies and the development of infrastructure. A crucial aspect for the economic viability of hydrogen in this sector is the greenhouse gas quota mechanism (GHG quota mechanism). This mechanism enables market participants to trade emission reduction certificates, thereby creating a financial incentive to invest in clean technologies. The availability of hydrogen will therefore not only be a question of technological feasibility, but also of economic incentives.

The current funding landscape and political support play a crucial role in the development and introduction of hydrogen technologies in the transport sector. Despite the potential benefits for decarbonization and air pollution control, further progress in production efficiency and infrastructure investment is needed to establish hydrogen as a sustainable mainstream energy carrier in road transport.

Thank you very much for your interesting insights!

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**Towards Circularity: Life Cycle Assessment of Fuel Cells and
their Sustainable Value Creation**

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Introduction

The European Union (EU) aims to significantly minimize greenhouse gas (GHG) emissions, with a target of 80-95% below 1990 levels by 2050 to meet international climate commitments such as the Paris Agreement. This is critical because transportation accounts for 20% of the EU's carbon emissions. To combat this, European governments have introduced incentives such as subsidies and tax breaks to promote Zero-Emission Vehicles (ZEVs), including Battery Electric Vehicles (BEVs) and Fuel Cell Electric Vehicles (FCEVs) (Ahmed et al., 2023).

BEVs, which run entirely on stored electricity, have attracted considerable interest for their zero emissions during operation. However, the true environmental impact of these vehicles is significantly influenced by the energy sources used to generate the electricity. BEVs can only achieve their full emissions reduction potential with renewable electricity. Moreover, the sourcing of the raw materials needed to make the batteries raises concerns about the sustainability and ethics of the supply (Nature, 2021).

In contrast, FCEVs, which produce electricity through the chemical reaction of hydrogen in fuel cells (FC), produce no direct GHG emissions during operation. However, indirect emissions may occur depending on how the hydrogen is produced. If hydrogen is obtained by electrolyzing water with electricity from renewable sources, the process can be virtually emission-free. But when hydrogen is derived from fossil fuels, the indirect emissions are substantial. Furthermore, the use of platinum as a catalyst in fuel cell membrane technology is associated with significant environmental problems, including high CO₂ emissions and intensive land and water use, leading to habitat destruction and pollution (Ahmed et al., 2023; Wittstock et al., 2016).

Thus, despite improvements over (traditional) Internal Combustion Engine Vehicles (ICEVs) in many environmental dimensions, the life cycle impacts of ZEVs, including the manufacturing of the vehicles and their components, the generation of electricity, and the

disposal/recycling of batteries and fuel cells at the end of their life, raise new environmental issues. Effective manufacturing, recycling, and materials recovery strategies are therefore critical to reducing these impacts and supporting the sustainability of the transition to ZEVs (Syré et al., 2024). The purpose of this report is therefore to analyze the life cycle assessment of FCEVs and their impact on sustainable value creation.

The comprehensive literature review examines the Life Cycle Assessment (LCA) literature of FCEVs and analyzes whether there is a path towards a Circular Economy (CE). First, the theories of LCA and CE are explained. This is followed by the findings of the relevant theories related to the LCA of FCEVs derived from the research results. In a subsequent discussion, the results of the literature review are evaluated with regard to possible improvements. Finally, the research findings are summarized and recommendations for future research priorities are given.

Theoretical Foundation

In order to assess the potential of LCA in the evaluation of FCEVs, a thorough knowledge of the basic principles of both LCA and CE is required. The concept of CE fundamentally changes the traditional linear economic model by emphasizing the reuse of resources to maintain or increase their utility over time (Spreafico, 2022). Originally defined by Pearce and Turner (1990), CE promotes the recycling of waste into resources through technological or natural loop-back mechanisms. This model not only aims to conserve resource quantities but also seeks to enhance the value of products, components, and materials throughout their extended life cycle (Pearce & Turner, 1990). Furthermore, it focuses on preventing waste, minimizing pollution and regenerating natural systems (EMF, 2013; UNEP, 2011). In addition, CE prioritizes waste prevention, pollution reduction, and the regeneration of natural systems, thereby promoting sustainable consumption and production patterns that are critical to achieving the Sustainable Development Goals (UNIDO, 2017).

The growing interest in CE highlights the need for robust methodologies that can accurately measure environmental and social impacts. The current literature presents various metrics for assessing product circularity, but these metrics often suffer from inconsistencies (Moraga et al., 2019).

To address this, ISO Technical Committee TC323 was established to develop standardized guidelines that integrate LCA and eco-design principles to ensure that CE strategies are both effective and measurable (Peña et al., 2021). This ensures that CE practices not only aim to achieve significant environmental benefits, but also focus on resource efficiency and product life extension to reduce the need for resource-intensive recycling (Peña et al., 2021). LCA complements CE by applying a standardized scientific framework to assess the ecological and socio-economic effects of products throughout their life cycle (ISO 14.040-14.044, 2010). This methodology is a critical part of CE because it provides detailed insight into the environmental performance of recycling processes and product reuse strategies, which is fundamental to making informed decisions (Peña et al., 2021) (*see Appendix 1*). By identifying and comparing the most effective CE strategies, LCA contributes to optimizing environmental outcomes and improving overall sustainability (Haupt & Zschokke, 2017).

Life Cycle Sustainability Assessment (LCSA) broadens the scope of LCA to include not only ecological, but also social and economic dimensions. While LCA primarily assesses environmental impacts, LCSA enables a thorough evaluation throughout the full life span, considering all sustainability impacts (Finkbeiner et al., 2010; Kloepffer, 2008). A comparison between LCA and LCSA is provided in *Appendix 2*. As a result, LCA and LCSA aid in the evaluation and comparison of viable CE strategies, thereby facilitating improvements in the environmental effectiveness of societal consumption and production practices (Chinnakali, 2023; Peña et al., 2021).

Integrating LCA into CE enables stakeholders to systematically assess and manage the effects of products from production to disposal, promoting a more sustainable economic model in line with global sustainability goals (Haupt & Zschokke, 2017).

Methodology: Qualitative Comprehensive Literature Review

A literature review was performed to assess the integration of LCA in FCEVs and its influence on sustainable value creation. The choice of a literature review can be reasoned by the fact that a deductive or “top-down” research approach often lacks the depth provided by exploratory techniques. Woo et al. (2017) argue that inductive research offers more prospects for a comprehensive analysis, addressing the problem of “insufficient theory” in deductive research. To provide a meaningful assessment given the lack of methodological techniques in this area, this report conducts a comprehensive inductive investigation (Bryman & Burgess, 1994).

The literature review was conducted as follows: A preliminary literary analysis was carried out to establish the research area and research questions. Relevant academic papers were identified using the keywords listed in *Appendix 3*. These keywords were used to guide a detailed literature search to determine the opportunities and challenges associated with LCA of FCEVs. The search was conducted on several platforms, including Scopus, Google Scholar, Science Direct and EBSCO. The following criteria were selected for all search engines and platforms: The language of the search should include literature in English or German, and the keywords should appear in the abstract of the paper. Given the ongoing transformation of the automotive sector around FCEVs, and to ensure that no FCEV LCA use cases were overlooked, the search focused on the period from 2015 to the present. In addition, literary analysis has been complemented by studies of exceptional research and practical importance (websites, conference papers). The method of selection is shown in the PRISMA flowchart in *Appendix 4*.

To assess the results of the literature review, it is important to categorize the dimensions of the life cycle of an FCEV. These include the **production phase**, the **use phase**, and the **end-of-life (EOL)/recycling phase** (*see Appendix 5*). Consequently, the literature overview incorporates numerous factors related to the dimensions, including their impact on the environment and costs, resource consumption, and economic competitiveness with other propulsion technologies.

Findings

Several studies have evaluated the environmental impact of FCEVs in the **production phase**. A comparison of the global warming potential (GWP) of the manufacturing phase of a FC system from these studies is presented in *Appendix 6*. However, a common indication in all studies is the high environmental footprint of manufacturing the hydrogen fuel tank and the FC stacks, which require platinum for catalyst production (Evangelisti et al., 2017; Miotti et al., 2017; Syré et al., 2024; Usai et al., 2021). The study by Usai et al. (2021) even highlights that the production of the tank and catalysts is responsible for more than 53% of the GWP impact of a FC system (*Appendix 7 provides an overview of the components of a FC*)¹. The fabrication of the hydrogen tank is primarily influenced by the energy needed to produce the carbon fibers and therefore contributes the most to the GWP. The catalyst, which is mainly composed of platinum, also contributes significantly to the environmental footprint. This is attributed to the energy-intensive platinum mining process, which results in high CO₂ emissions, habitat destruction, and excessive water consumption (Usai et al., 2021). Furthermore, emissions from platinum mining are also responsible for soil acidification, human toxicity and particulate matter emissions. As a result of these factors, platinum is on the EU's list of critical metals. Furthermore, the components such as carbon fibers and platinum not only lead to an increase in environmental pollution, but also to an increase in production costs (Miotti et al., 2017; Usai

¹ For the sake of simplicity and space, only the H₂ tank and the FC stack are evaluated in detail during the use phase, as they have the highest environmental impact.

et al., 2021). Compared to other drive technologies, these factors significantly impair the competitiveness of FCEVs (Miotti et al., 2017). Given the limited annual supply and unfavorable mining conditions, platinum prices are anticipated to stay high, creating a significant barrier to FCEV adoption by increasing production costs (Wittstock et al., 2016). Both BEVs and FCEVs have high emissions in the manufacturing phase. However, studies indicate that FCEVs appear to be more polluting than the production phase of BEVs because of their reliance on materials including platinum for fuel cells and carbon fiber-reinforced plastic for hydrogen tanks (Simons & Bauer, 2015; Evangelisti et al., 2017; Usai et al., 2021). A direct comparison of emissions from the production of FCEVs (measured in kg CO₂eq/kW) and BEVs (measured in kg CO₂eq/kWh) is difficult because the units of measurement (kW vs. kWh)² and the underlying system efficiencies and usage profiles are different (*Appendices 6 and 8*). In addition, the environmental impact is strongly influenced on the materials used and the efficiency of the production processes. Although both FCEVs and BEVs have zero to low direct tailpipe emissions, studies show that the environmental benefits of their use are somewhat offset by the higher emissions from their production (Syré et al., 2024). This underscores the importance of moving large manufacturing plants from high-carbon economies that rely heavily on fossil fuels to low-carbon economies that use cleaner energy sources. This shift is critical to maximizing the overall environmental benefits of electric vehicles (Evangelisti et al., 2017; Simons & Bauer, 2015).

However, there are significant barriers to large-scale market penetration of FCEV technology, including a lack of infrastructure, such as refueling stations, and high costs for both industry and consumers (Staffell et al., 2019). Despite these challenges, several original equipment manufacturers (OEMs), such as BMW, are investing in the development of this technology.

² Kilowatt (kW) is a unit of power that describes how quickly energy is converted. Kilowatt-hour (kWh) is a unit of energy that describes how much energy is stored or consumed in a given period of time. For FCEVs, efficiency and capacity are often considered in terms of the power (kW) of the fuel cell that directly generates the electrical energy. BEVs store electrical energy in batteries, so storage capacity (kWh) is an important factor.

Thus, mass production of FCEV systems could drive down production costs, similar to battery packs for BEVs once they have been introduced on a large scale (Usai et al., 2021).

Appendix 9 provides a well-to-wheel analysis³ to demonstrate a comparative energy efficiency analysis of FCEVs and BEVs in the **use phase**. It provides information on which technologies are potentially more environmentally friendly because they lose less energy along the entire path from source to wheel. During the use phase of BEVs, emissions are mainly produced during electricity generation. If the electricity comes from renewable sources, BEVs are emission-free, resulting in significant reductions in air pollution and greenhouse gas emissions. BEVs have higher overall efficiency ($\approx 73\%$) than FCEVs ($\approx 22\%$) and ICEVs ($\approx 20-40\%$) because the electrical energy from the grid is converted directly into mechanical energy in the electric motor (-5%). However, over time, the performance and range of BEVs may be affected by battery degradation, requiring the battery to be replaced or refurbished (Onorino, 2023).

The efficiency of FCEVs is highly dependent on the hydrogen source⁴. Provided that hydrogen used is derived by electrolysis from renewable energy sources, FCEVs emit only water vapor during operation. However, the overall energy efficiency of FCEVs is significantly lower than that of BEVs due to energy losses during hydrogen production and conversion of hydrogen to electrical energy in the vehicle (Electrolysis: 30%, Transport, storage & distribution: 26% and H₂ electricity conversion: 50%) (Onorino, 2023).

In addition, FCEVs require about threefold the electricity per mile compared to BEVs when hydrogen is generated through electrolysis, resulting in a significant demand for electricity from renewable sources (Miotti et al., 2017). Furthermore, if the hydrogen is produced by steam reforming of methane (gray hydrogen), the environmental benefits are offset and the vehicle shows no significant improvement in greenhouse gas emissions compared to conventional

³ A well-to-wheel analysis can be used to examine the overall footprint of vehicle operation. This includes not only the emissions generated directly by the vehicle, but also the emissions generated during the production and distribution of the fuel (electricity or hydrogen).

⁴ Notably, the example in *Appendix 9* assumes the use of 100% renewable energy.

technologies (Miotti et al., 2017). The comparative CO₂ footprint per 100 km further illustrates the environmental impact. In a 2030 renewable energy scenario where 80% of electricity comes from renewable sources, BEVs produce about 1.35 kg of CO₂ per 100 km. In contrast, even with green hydrogen, FCEVs emit about 2.4 kg of CO₂ per 100 km (Specht et al., 2022).

End-of-life management is also an essential part of the LCA of FCEVs. The EU's Directive 2000/53/EC requires manufacturers to ensure the recycling and handling of end-of-life vehicles (ELVs). This directive promotes the reuse and recycling of vehicle components, including fuel cell systems, which must be carefully dismantled to avoid safety risks and to ensure the recovery of valuable resources, including platinum (Wittstock et al., 2016).

Future projections suggest that while FCEVs can potentially match the environmental performance of BEVs, this will depend on significant progress in reducing environmentally harmful materials such as platinum and carbon fibers, as well as improved recycling technologies. These improvements must be accompanied by a reduction in production costs to make FCEVs a viable alternative for the mass market (Miotti et al., 2017). A superficial description of the EOL process for FCEVs compared to BEVs is shown in *Appendix 10*.

Recycling, especially of platinum, plays a critical role in reducing environmental impacts. Industrial catalysts achieve recycling rates of nearly 90%, yet the recycling rates for platinum from automotive exhaust catalysts are significantly lower, ranging from only 50%-60%. As a result, the automotive sector is already the largest net consumer of platinum, even without considering the growth in vehicle sales. FCEVs, which contain more than ten times the amount of platinum as ICEVs, could significantly exacerbate the already noticeable temporal and structural shortages in the global platinum market if widely adopted (Bosch, 2023).

Increasing recycling rates and reducing the amount of platinum in catalytic converters could significantly reduce the environmental footprint of FCEVs (Wittstock et al., 2016). These steps are crucial for reducing not only GHG levels, but also costs. For FCEVs to achieve cost parity

with ICEVs and BEVs, significant progress is needed in reducing fuel cell system costs (Miotti et al., 2017). On the other hand, the recycling of carbon fibers is a challenge, indicating the need to minimize the amount of material used and increase production efficiency. Since recycling carbon fibers into a comparable quality material has proven to be infeasible, efforts must concentrate on reducing the amount of carbon fibers used in the hydrogen tank (Miotti et al., 2017). For example, future FCEVs could be equipped with recycled carbon fibers, which studies have shown to have a lower impact on production (Meng et al., 2017). However, recycled carbon fibers currently do not have the desired strength for high-pressure hydrogen storage, making their future use uncertain (Usai et al., 2021).

Discussion

The literature review used a “cradle-to-grave” approach to assess the impact on the environment at each phase of the FCEV life cycle, from resource extraction and manufacturing to use and final disposal. The results show that the extraction of primary platinum is a major environmental impact. The most significant advances in reducing this impact include reducing the amount of platinum in catalysts. In addition, the adoption of cleaner energy sources and the use of secondary platinum sources are critical steps forward. These measures suggest that, in addition to technological improvements, a shift to cleaner production processes is essential for sustainable development.

German automotive supplier Bosch exemplifies progress in this area with its innovative approach to recycling fuel cell stacks. By repurchasing and recycling these components at the end of their life cycle, Bosch not only facilitates the recovery of valuable materials such as platinum, but also demonstrates the significant environmental benefits of circular economy practices. Specifically, recycling platinum can reduce more than 95% of the carbon emissions associated with its primary extraction. As a result, Bosch's practices increase economic efficiency and significantly reduce the carbon emissions associated with platinum mining

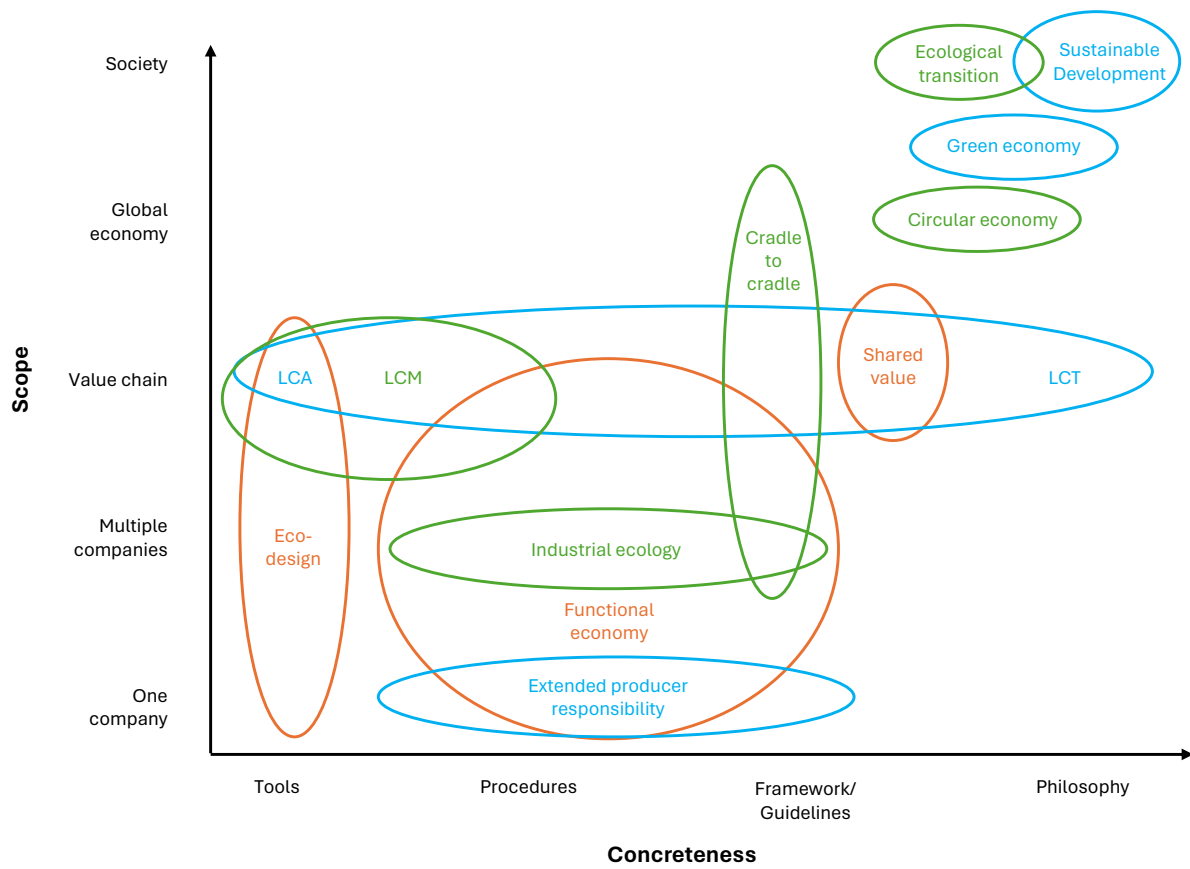
(Bosch, 2023). BMW, a proponent of FCEV technology, operates Germany's largest recycling center, setting a standard for resource management in the automotive industry. The center uses advanced technologies to improve vehicle recycling and reduce environmental impact. By promoting closed-loop recycling, BMW not only minimizes waste but also reduces CO₂ emissions. Further improvements could include extending material recovery processes to platinum and other critical resources, further strengthening BMW's commitment to sustainable automotive technologies (BMW, 2024).

Conclusion and Directions for Future Research

Although still in development, FCEV technology holds great promise for reducing the ecological footprint of the transportation sector. The commercial viability of fuel cells is still low, and with only a few vehicles currently using the technology, accurate impact assessments are difficult and based on incomplete data. However, their current deployment is hampered by high production costs and environmental impacts, as well as an underdeveloped refueling infrastructure compared to BEVs. Despite these challenges, cleaner hydrogen production methods and sustainable manufacturing practices could significantly reduce the life cycle impacts of FCEVs, making them a viable option for future transportation needs.

Future research should focus on optimizing component design to standardize and reduce variability in the LCA of FCEVs. Investigating the scalability of using secondary platinum and recycled carbon fiber could provide insight into more sustainable production methods. In addition, expanding the hydrogen refueling infrastructure and improving the efficiency of hydrogen production are critical areas for further research. Research should also explore policy frameworks and incentives that could accelerate the adoption of FCEVs and support the transition to a decarbonized transportation sector.

Appendix 1 *Scope versus concreteness mapping*



Source (adapted): CIRAIIG, 2015 “A comparison of different CE concepts and tools makes it clear that LCA is a tool, while CE is seen as a philosophy that encompasses society and the global economy.”

Appendix 2 *Comparison between LCA and LCSA*

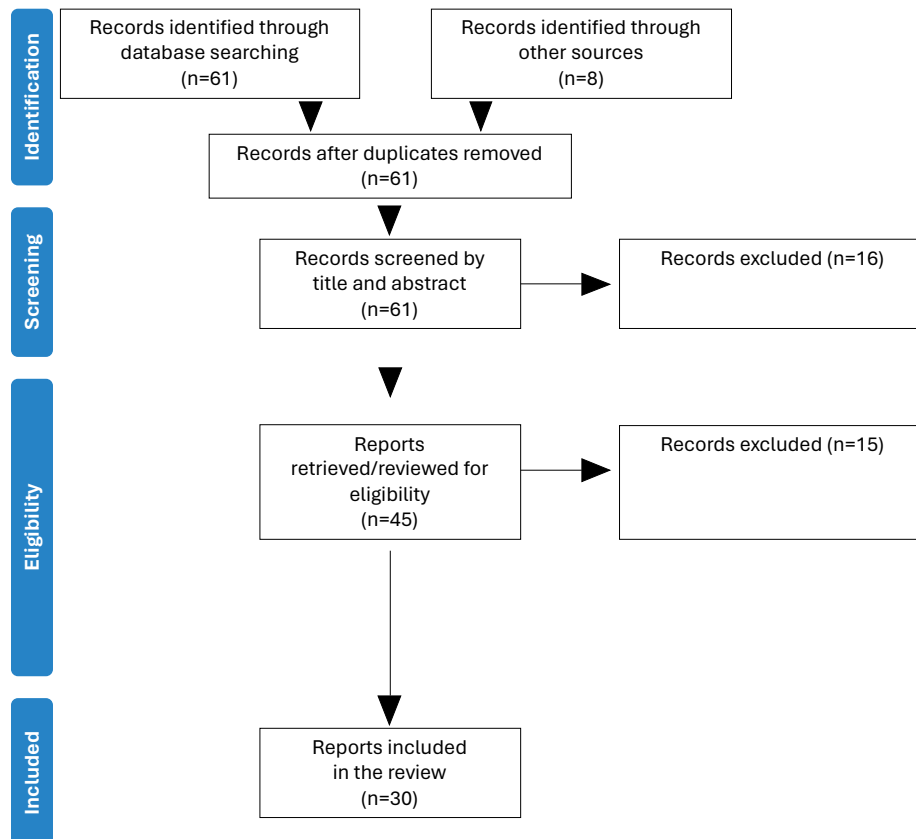
Aspect	LCA	LCSA
Dimension	Assesses environmental impacts from extracting raw materials to disposing or recycling.	In addition to environmental impacts, it also evaluates social impacts (e.g., labor conditions, human rights) and economic impacts, such as production costs or market value.
Application	Identifies areas for environmental improvement, optimizes design, and enables informed, sustainable decisions by quantifying resource use, energy consumption, emissions, and waste generation.	Supports sustainable decision making by considering broader implications and trade-offs.

Source (adapted): Chinnakali, 2023

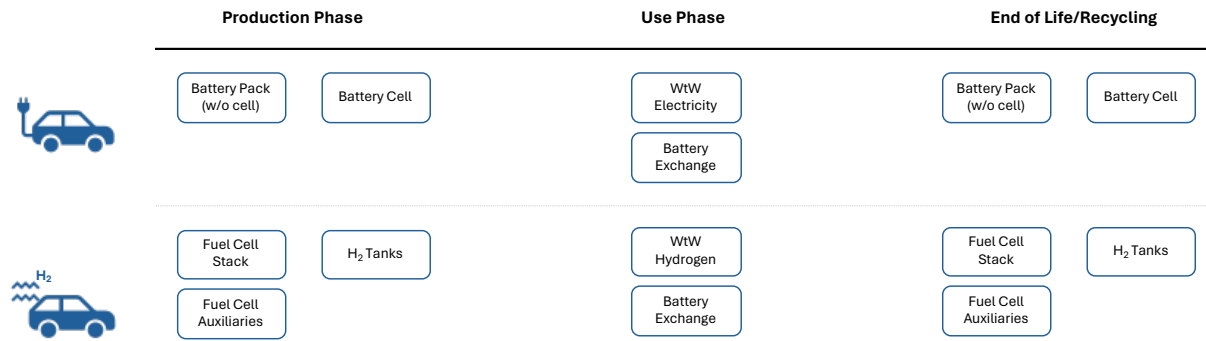
Appendix 3 *Keyword search*

Life Cycle Assessment*	Recycling*	Fuel Cell Vehicle*
Circular Economy*	Re-use*	Automotive Sector*
Assessment*		

Appendix 4 *PRISMA flow diagram on strategic paper selection*



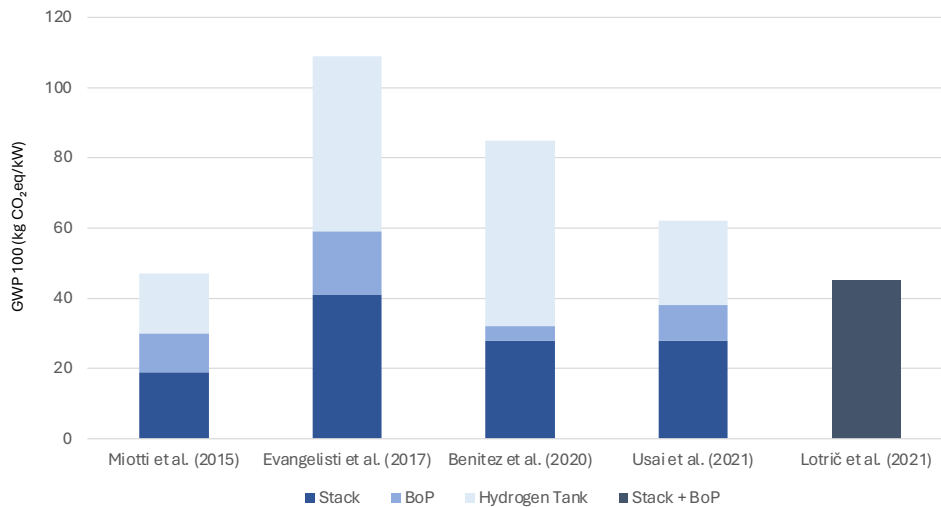
Appendix 5 *Dimensions of LCA approach*



* WtW = Well-to-Wheel Analysis

Source (adapted): Syré et al., 2024 “Comparison between BEV and FECV”

Appendix 6 *Study comparison of the GWP of the production phase for a fuel cell system*



Source (adapted): Syré et al., 2024 “Several studies have examined the environmental impact of fuel cell systems with different power outputs. While Miotti et al. (2015), Evangelisti et al. (2017) and Usai et al. (2021) focused on an 80 kW system, Benitez et al. (2020) and Lotrič et al. (2021) analyzed 100 kW and 5 kW systems, respectively. Miotti et al. (2015) examined modern fuel cell technologies and considered future scenarios with alternative materials. Usai et al. (2021) extended this investigation to include current data on fuel cell components. Benitez et al. (2020) modified the approach of Miotti et al. (2015) by focusing on the hydrogen tank. Evangelisti et al. (2017) evaluated a comparable system but relied on different data on the production of the components. Lotrič et al. (2021) looked at fuel cells and hydrogen in general and did not focus specifically on automotive applications. They analyzed a 5 kW system but excluded the hydrogen tank and focused on end-of-life strategies for the products.

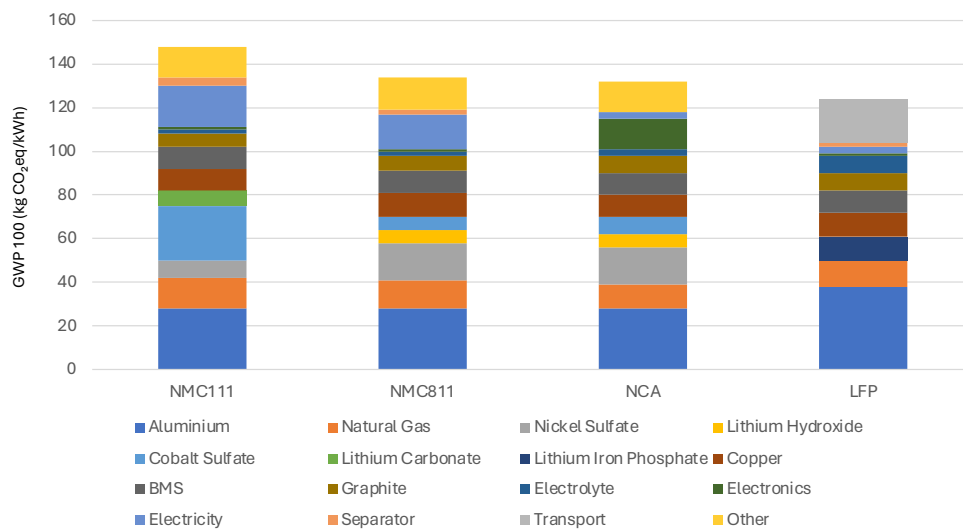
As a result, the calculated total global warming potential (GWP) per kW of the fuel cells varies, primarily due to differences in platinum content and hydrogen tank size in the studies considered. As the studies were published over a period of five years, some variation in the results is to be expected as the available data on the technology evolves over time.”

Appendix 7 *Main components and sub-components included in a fuel cell*

Primary component	Sub-components	
Fuel cell stack	<ul style="list-style-type: none"> • Membrane • Bipolar plates • Catalyst ink • End plates • Current collectors 	<ul style="list-style-type: none"> • Gaskets • Membrane electrode assembly • Stack compression bands • Stack housing • Coolant
H ₂ tanks	<ul style="list-style-type: none"> • Tanks (carbon fiber and resin) 	<ul style="list-style-type: none"> • Tank auxiliaries (boss, foam, glass fiber)
Fuel cell auxiliaries	<ul style="list-style-type: none"> • Air management • Water management • Heat management 	<ul style="list-style-type: none"> • Fuel management • Electronics (controller, sensors, wiring)

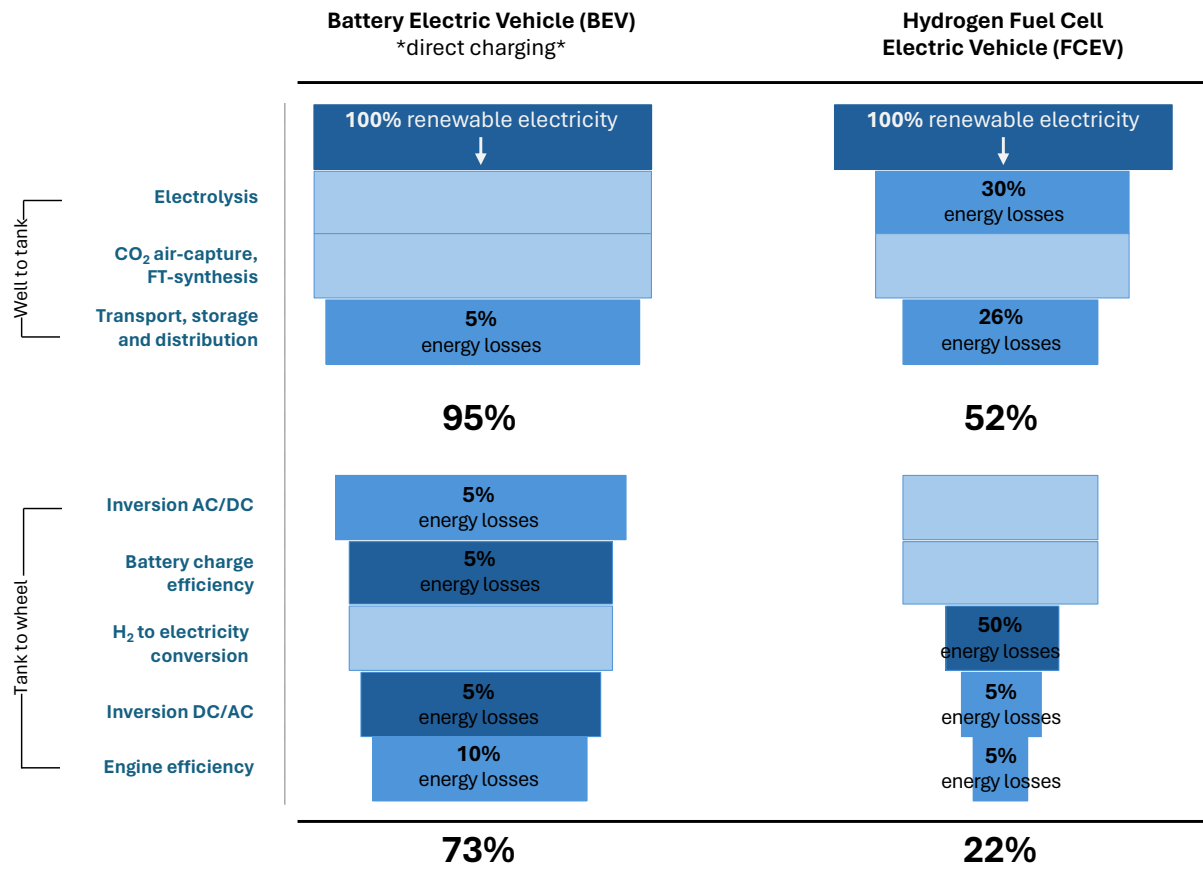
Source (adapted): Syré et al., 2024

Appendix 8 *Battery pack materials and processes for different cell chemistries - Production*



Source (adapted): Syré et al., 2024 “The production of batteries for BEVs also requires significant amounts of energy, especially for high energy density batteries.”

Appendix 9 Energy efficiency of BEVs and FCEVs



Source (adapted): Onorino, 2023

Appendix 10 Comparison of FCEV and BEV end-of-life management

Aspect	FCEV	BEV
Environmental Impact	Focuses on the safe removal and recycling of fuel cells, especially platinum, to minimize losses. Handling hydrogen and high-voltage components also poses specific safety risks.	Pyrometallurgy involves crushing and burning, which is energy intensive and produces waste and emissions. Hydrometallurgy produces acidic waste and metal-rich solutions, as well as hazardous residues.
Methods	Manual dismantling focused on recovering platinum from fuel cells. Cryogenic milling proposed to prevent platinum losses. Alternative methods, such as hydrometallurgical processing, are being developed to safely manage fluorine compounds.	Pyrometallurgy (burning and melting) and hydrometallurgy (acid leaching), often used in combination to recover various metals from batteries.
Challenges	<ul style="list-style-type: none"> • Ensure safe disassembly due to high voltage components • Limited facilities equipped for specialized disassembly • Loss of platinum during disassembly 	<ul style="list-style-type: none"> • Ensure safe disassembly due to high voltage components • Toxic emissions and residues; energy-intensive processes increase GHG emissions • Transportation, a critical but under-researched aspect of recycling, has a significant impact on costs and contributes to GHG emission
Innovations & Research	Research into improved handling and recovery methods, including less hazardous alternatives to manage fluorine emissions during the recycling process.	Ongoing research is aimed at improving efficiency and reducing environmental impact, including better management of transportation and refining processes.

Source (adapted): Wittstock et al., 2016; Mayyas et al., 2019; Slattery et al., 2021; Tawonezvi et al., 2023

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