8

The Power of Technological Innovation

Driving Sustainable Mobility

Jörg Franke, Peter Wasserscheid, Thorsten Ihne, Peter Lamp, Jürgen Guldner, and Oliver Zipse

8.1 Introduction

The rapid decarbonization needed to meet the 1.5 °C target will require disruptive technological change. In general, there are strong interactions between technological innovation and increased sustainability. So, technological progress can be a key to increased sustainability. In parallel, a stronger focus on sustainability goals requires technological innovation. In this context, technological progress presents both opportunities and risks for many market participants. Emerging technologies are always associated with uncertainties from various sources, which means that their potential, likelihood of occurrence, and the timing are often unclear for a long time (Kapoor & Klueter, 2021). As a result, all relevant stakeholders in business, society, and politics are faced with major challenges.

This is especially true for the mobility transition that is currently taking place in almost all relevant markets in the context of climate change and environmental protection. On the Road to Net Zero, this chapter on *The Power of Technological Innovation* addresses the management of uncertainty associated with emerging technologies in the mobility sector. At the heart

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O. Zipse et al. (eds.), *Road to Net Zero*, https://doi.org/10.1007/978-3-031-42224-9_8

of this technological transformation is the drive system and its interaction with the associated energy ecosystem. This chapter thus complements the previous chapters on *Creating Sustainable Products* (Chap. 5), *Transforming Value Chains for Sustainability* (Chap. 6), and *Sustainability in Manufacturing* (Chap. 7) by broadening the perspective to include external factors such as infrastructure and energy systems. These aspects and technology are inextricably linked and can only be evaluated together in terms of carbon emissions and ecological footprint. In parallel, the economic balance must also be considered holistically, as this aspect is critical to the success of the transformation. Forecasts vary widely, ranging from scenarios in which fossil fuels continue to play a significant role globally, to scenarios dominated by e-mobility (Zapf et al., 2021).

The purpose of this chapter is to discuss these corresponding factors in more detail. First, Sect. 8.2 presents the advantages and disadvantages of alternative drive systems. This is followed by an explanation of the motivation for the current technological transformation. Section 8.3 presents the expert conversation by Prof. Oliver Zipse, Chairman of the Board of Management of Bayerische Motoren Werke (BMW) AG, Dr. Peter Lamp, General Manager Battery Cell Technology at BMW, and Prof. Dr.-Ing. Jörg Franke, Institute for Factory Automation and Production Systems at FAU Erlangen-Nürnberg, on the future of drive technology from a business perspective. In Sect. 8.4, Prof. Oliver Zipse, Dr. Jürgen Guldner, General Program Manager Hydrogen Technology at BMW, and Prof. Dr. Peter Wasserscheid, Director of the Helmholtz Institute Erlangen-Nürnberg for Renewable Energy and Chair of Chemical Engineering I (Reaction Engineering) at FAU Erlangen-Nürnberg, engage in an expert conversation on the future opportunities of hydrogen as an alternative energy carrier for the automotive industry. Finally, Sect. 8.5 identifies future directions for research and practice to advance the market viability of alternative drivetrains. The focus is set on the energy ecosystem as an enabler for future drive technologies. The chapter concludes in Sect. 8.6 with a brief summary and a link to the concluding chapter (Chap. 9), *The Road to Net Zero and Beyond*.

8.2 An Overview on Alternative Drive Systems

The European automotive industry is undergoing dynamic change (see Fig. 8.1). In the face of the climate catastrophe, emission limits are becoming increasingly stringent, fuel prices are rising, and individual mobility is being

Fig. 8.1 Overview of the competitive environment in the automotive industry

hampered by regulations, competing mobility concepts, and conflicting customer interests. While Western private passenger car markets tend to shrink, new competitors are emerging, especially from China (Kaul et al., 2019). Most importantly, new technologies are arising that are shaking up the automotive market, which has been fairly stable for decades. Autonomous driving promises completely new business models for passenger and freight mobility, software will increasingly dominate over mechanical functions, and, finally, the internal combustion engine (ICE) will eventually be replaced by electric drive systems.

The ICE was the foundation for the triumphant advance of individual mobility in the twentieth century: robust and reliable gasoline and diesel engines powered, at their peak, almost 100 million annually newly produced passenger cars and trucks, as well as tens of millions of motorcycles worldwide (European Environment Agency, 2019; Umweltbundesamt, 2022; Wang, 2021). The enormously high energy density of fossil fuels allowed enormous ranges of up to 1000 km without stopping for refueling, while the persistently unrivaled low energy cost of oil and its seemingly unlimited availability provided the general public with continent-wide freedom of movement.

Over time, ICE-based drivetrains have evolved into highly complex engineering marvels, improving their energy efficiency and significantly reducing their impact on air pollution and climate change. However, ICE-based road transport is still responsible for about approximately 20% of carbon dioxide (CO_2) emissions, contributes to air pollution especially in large cities, burns the precious natural resource of fossil fuels, and perpetuates dependence on

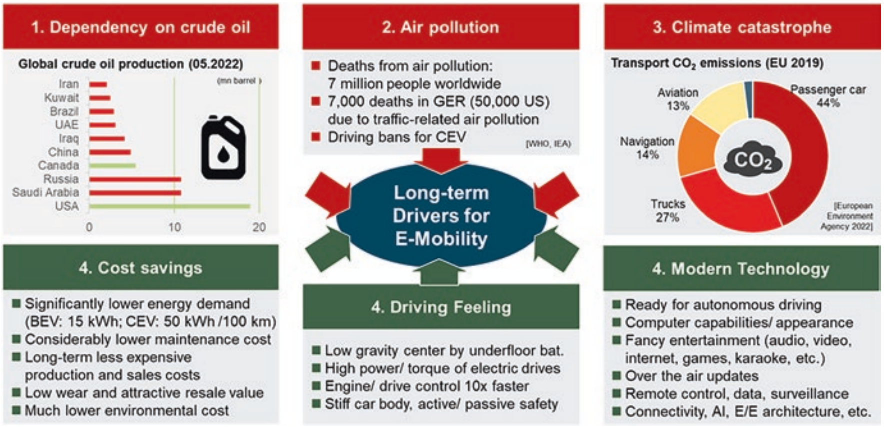

Fig. 8.2 Push and pull factors underpinning the success of electromobility (own illustration based on International Energy Agency (2022, 2023) and Reitz et al. (2020))

politically unstable or unreliable countries (see Fig. 8.2) (International Energy Agency, 2022, 2023; Reitz et al., 2020).

In this context, political regulations, such as the tightening of European emission limits (Euro 7) and the goal of climate neutrality by 2050 (European Green Deal), are increasingly weighing on the market environment. As ICEs have approached the asymptotic branch of their S-curve, where further improvements require disproportionate effort, and have little impact, many automotive manufacturers (OEMs) have already announced to stop the development of new ICEs.

The electric motor is a comparable old propulsion technology. It is completely emission-free, has an unsurpassed efficiency (~95%; the ICE is barely above 30% efficiency), and therefore causes only about a tenth of the losses of internal combustion engines. It can use renewable energies directly and without great effort, and it does not waste valuable fossil resources. The unrivaled characteristics of electric motors offer a much wider speed range with consistently high torque, thereby eliminating the need for complex shifting transmissions (with up to ten gears) and providing a highly dynamic driving experience. The control dynamics of electric drives, which are an order of magnitude faster, allow the vehicle to be steered longitudinally and laterally over wide ranges without braking, and kinetic energy can also be recuperated in the process (e.g., the BMW iX xDrive50 has a 208 kW maximum recuperation power) (Schwarzer, 2019). In addition, the power density of electric motors is significantly higher, their running smoothness is unparalleled due to the rotating drive, and their wear is negligible due to the contactless power transmission (Parizet et al., 2016; Specht, 2020). Based on the technical, ecological, and economic advantages summarized in Fig. 8.2, it is highly likely that at least the majority of land vehicles will be powered by electric drives at some point in the future.

Electric motors are compatible with a wide range of different drive configurations: As a result, electromobility takes many forms, from battery electric vehicles to hybrid concepts and fuel cell applications. Battery electric vehicles (BEV) are increasingly gaining market share. BEVs incorporate a high-voltage battery, enabling electrification of auxiliary units, brake energy recuperation, and plug-in recharging at a wall outlet or charging stations. The major remaining weakness of BEVs is their comparatively short range (currently about 400 to 700 km), as electrochemical batteries allow only about 5% of the gravimetric energy density of gasoline storage systems (0.5 versus 11.4 kWh/kg) (Sartbaeva et al., 2008; van Basshuysen & Schäfer, 2017). From a technical perspective, this disadvantage is exacerbated by the still considerable charging times (around 30 min), since even an electrical charging power of 250 kW corresponds to only about 1% of the power transfer during refueling. With the current state of technology (SoT), these immense differences can only be partially compensated for by the significantly higher efficiency of electric vehicles, which is a factor of three to four for a typical driving profile (e.g., for a WLTP[1] cycle: the BMW i4 eDrive40 Gran Coupé [250 kW]: 16.8 kWh versus BMW M440d xDrive Coupé [250 kW]: 5.7 l_{Diesel}/100 km, 55.9 kWh/100 km).

Battery technology is currently undergoing continuous development to address the range issue. Lithium-ion batteries are currently the automotive standard due to their robustness, high cycle stability, and a high energy density. Significant increases in energy density are currently being achieved, while costs are falling. While the price per kilowatt hour averaged 600 euros/kWh in 2010, it is expected to be approximately 83 euros/kWh in 2025. In addition to specific energy density and costs, other aspects such as shorter charging times, longer lifetimes, improved temperature performance, and higher reliability are also in focus. Environmental compatibility and the supply of critical raw materials are also important aspects. Battery reuse and recycling are already being implemented, and the corresponding capacities are currently being greatly expanded (Blois, 2022). In parallel, alternative battery technologies are being researched such as solid-state batteries, which allow significantly

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[1] Worldwide Harmonized Light Vehicles Test Procedure (WLTP): Standardized test cycle determined on test rigs under defined laboratory conditions and based on empirically determined real driving data from Asia, Europe, and the United States. The WLTP cycle has been valid in the European Union (EU) since September 2017 (Verband der Automobilindustrie e.V. 2018).

higher specific energy densities. BMW is also involved in the all-solid-state-battery (ASSB) technology.

Because of the range issue, hybrids are still relevant today. Hybrid vehicles have at least two different energy converters and two different energy storage systems, so they include both an ICE and an electric motor, as well as a fuel tank and a battery. Hybrid powertrains can be classified according to the degree of hybridization and the energy flow. Development has started on micro-hybrid electric vehicles (MCHEVs), which enable a start–stop strategy, and mild-hybrid electric vehicles (MHEVs), in which an electric machine supports the ICE for load-point shifting. From an environmental and climate protection perspective, these measures are no longer sufficient. To eliminate local emissions and provide at least temporary zero-emission driving, the degree of hybridization must allow for full electric driving. Full-hybrid electric vehicles (FHEVs) allow all-electric driving over shorter distances, while providing good efficiencies through load-point shifting and recuperation. However, the electric range and performance are limited. Plug-in hybrid electric vehicles (PHEVs) compensate for the disadvantages by allowing the traction battery to be recharged externally. Figure 8.3 provides an overview of the functionalities of different hybridization strategies.

Regardless of the degree of hybridization, the architectures differ. The serial hybrid uses the ICE as a generator and is driven only by electric motors. This means that the ICE is constantly operating at an optimal operating point. Range extenders are a special form of serial hybrids in which a normally

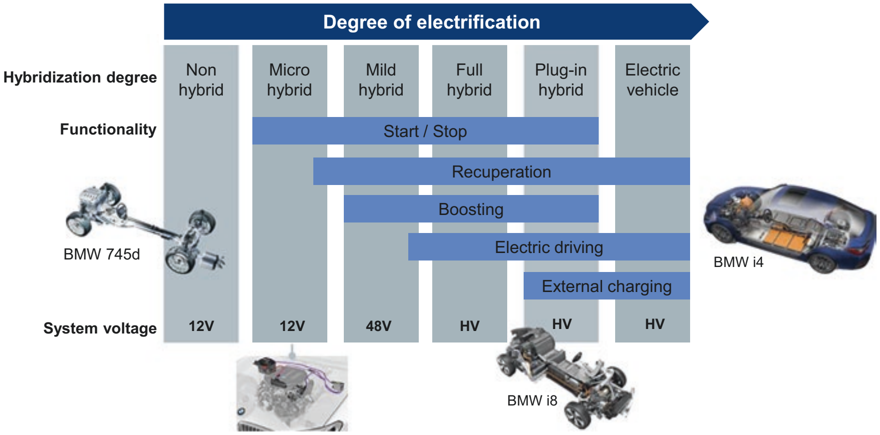


Fig. 8.3 Functionalities of different hybridization strategies (own illustration based on Doppelbauer (2020) and Tschöke et al. (2019))

switched off ICE charges the battery of otherwise all-electric vehicles when needed. The parallel hybrid has a switchable mechanical connection between the ICE and the drive axle, so that either drive can be used for propulsion. These can be dimensioned smaller, accordingly. Mixed forms of serial and parallel hybrids are also available. These power-split hybrids use the power of the ICE for both propulsion and battery charging, resulting in high efficiency over the entire load profile. Although hybrids, in general, have the potential to reduce both fuel consumption and emissions, their medium-term future on the European market seems questionable. The main drawbacks are high system complexity, higher purchase and operating costs, increased vehicle weight, and limited installation space. At the same time, they do not permit completely emission-free operation.

Electric traction drives in automotive engineering exhibit a variety of designs and mounting positions. Regarding the installation position, completely new configurations are possible, such as wheel hub motors. All-wheel-drive systems and torque vectoring are comparatively easy to implement using multiple motors. Functional integration can also be intensified. The spectrum ranges from a partial integration of motor and transmission to fully integrated systems including electric motor, gearbox, and power electronics. The functional unit can even be supplemented with axle components to form a ready-to-install e-axis. This variance in available systems is visualized in Fig. 8.4.

Just as with internal combustion engines, different types of electric motors are relevant for automotive applications. Current commercial use focuses on induction motors, permanently excited synchronous motors, and externally excited synchronous motors. Induction motors have a simple design and are easy-to-manufacture. In automotive applications, squirrel-cage rotors are relevant, in which the stator field induces a magnetic field in integrated aluminum or copper bars in the rotor. As a result, the rotor follows the rotating

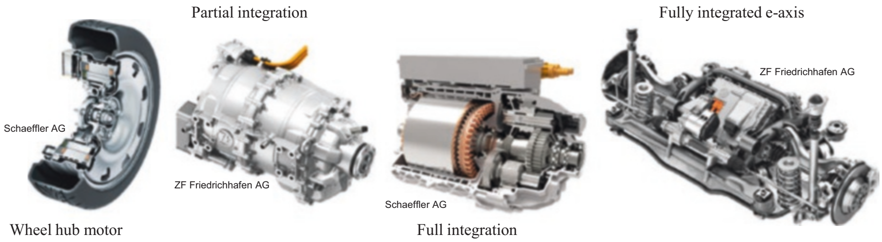


Fig. 8.4 Overview of various forms of function integration of electric motors (illustration based on Schaeffler Technologies AG (2014, 2023) and ZF Friedrichshafen AG (2017; 2023))

magnetic field in the stator with a delay. Disadvantages of this motor type are lower efficiency and the reduced volumetric and gravimetric power density.

Permanently excited synchronous motors, also called permanent magnet synchronous motors, offer the best efficiency and gravimetric torque density, as well as favorable reliability and packaging characteristics. The main reason for these characteristics is the absence of excitation windings in the rotor and the associated losses. However, the use of rare earth permanent magnets has significant drawbacks in terms of cost, environmental footprint, and supply chain risks. In this context, the establishment of recycling processes for rare earth permanent magnets is an important task for the future. The permanent excited synchronous motor has been used in the BMW i3, for example.

Externally excited synchronous motors are based on a similar operating principle, but they use copper windings at the rotor instead of magnets for excitation. This results in slightly lower efficiency and higher packaging requirements, but the flexible adaptation of the rotor magnetic field allows good operating behavior. According to the current state of the art, the power supply to the rotor is often realized via slip rings, which are subject to wear. As a result, slip rings can have negative effects on lifetime and efficiency. In its current fifth-generation drives, BMW uses an optimized system based on slip rings in which harmful dust contamination is retained by improved sealing. An alternative is offered by inductive transmitters, which are currently gaining interest in the market (Fig. 8.5).

In addition to the types mentioned, the switched reluctance machine and the axial flux motor also show potential for use as traction motors. The switched reluctance machine is currently the subject of increased research activity as an alternative to the permanently excited synchronous motor. It offers high efficiency without the use of rare earth elements, but the control of the motor is more complex. Axial flow machines are also of research interest because they offer high power density in combination with a small packaging impact. Although permanent magnets are used, their quantity is reduced. Apart from these new motor types, there are trends toward higher operating voltages (800–1000 V), higher motor speeds, and optimized cooling concepts. Another challenge is the electrification of the medium- and heavy-duty segments.

As an alternative to diesel, gasoline, or batteries, hydrogen (H_2) has a calorific value of 33 kWh/kg and can be used as an energy storage medium. The hydrogen can then be used by fuel cells or even internal combustion engines without producing CO_2 emissions. While hydrogen combustion is expected to play a greater role in heavy-duty and off-highway applications, fuel cell electric vehicles (FCEVs) could be a complementary technology for

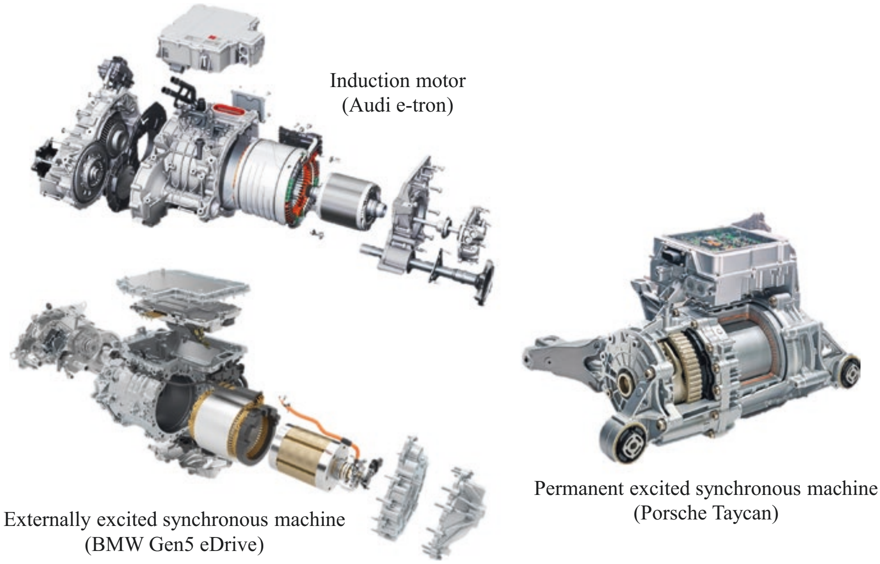


Fig. 8.5 Series drivetrains based on different types of electric motors (illustration based on AUDI AG (2019), Dr. Ing. h.c. F. Porsche AG (2021), and BMW AG (2020))

zero-emission long-distance individual mobility. These vehicles include conventional electric drives in addition to the fuel cell stacks and storage systems. Range is less of an issue, since hydrogen can be fueled in 3–4 min. Hence, hydrogen vehicles combine "the best of both worlds": They offer all the advantages of electric driving, such as instantaneous acceleration and a smooth, silent, and emission-free ride, combined with the convenience of the fast refueling associated with combustion engine vehicles. Together with its partner Toyota, BMW has many years of experience in the development of FCEVs and has recently launched its second generation of fuel cell systems in the BMW iX5 Hydrogen pilot fleet (see Fig. 8.6).

A perceived drawback is the efficiency of the hydrogen energy chain because of the conversion steps involved (see Fig. 8.7). First, hydrogen is generated from electricity by electrolysis, made transportable either in compressed form (e.g., for transport in retrofitted natural gas pipelines), or cooled down until liquefaction, or in form of a liquid organic hydrogen carrier (LOHC), and finally converted back to electricity by means of a fuel cell in the vehicle.

However, in addition to pure efficiency, overall system aspects must be considered. The comparison in Fig. 8.7 only takes into account the use phase. When considering the whole life cycle, starting with the mining of raw materials, the production of components and systems, the assembly of vehicles,

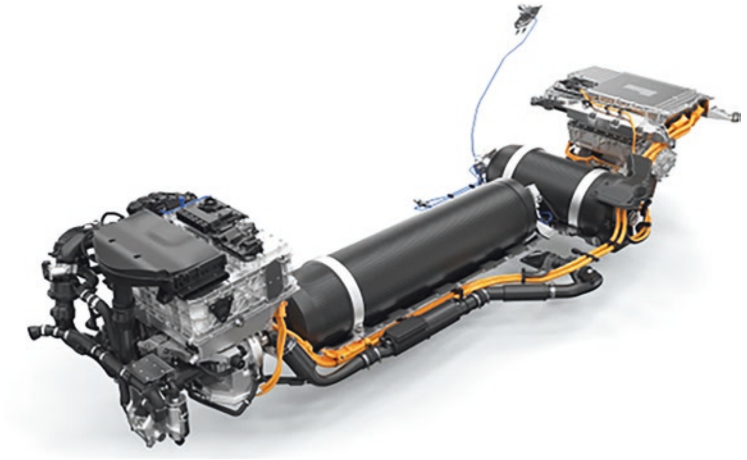
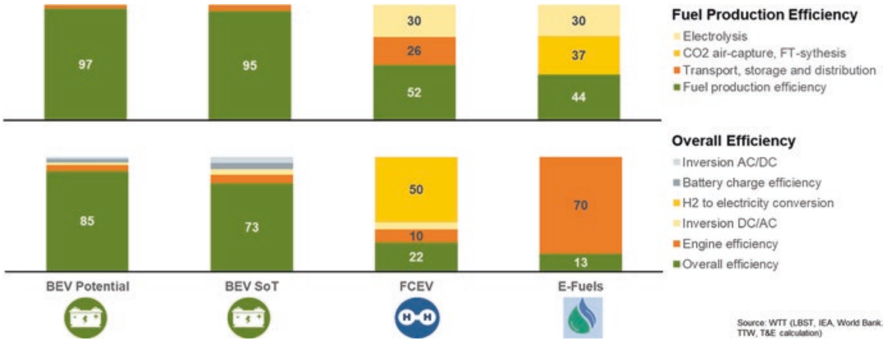


Fig. 8.6 Powertrain of the BMW iX5 Hydrogen with fuel cell stack, electric motor, and two high-pressure hydrogen tanks (BMW AG 2022)



Source: WTT (LBST, IEA, World Bank; TTW, T&E calculation)

Fig. 8.7 The efficiency of different powertrain options (*BEV* Battery Electric Vehicle, *SoT* State of Technology, *FCEV* Fuel Cell Electric Vehicle) (own illustration based on European Federation for Transport and Environment (2017))

and finally the recycling after the usage, the difference between BEVs and FCEVs is much smaller. In the case of energy generated entirely from renewable sources, conversion losses have no significant effect on the ecological balance.

Also, from an economic and overall energy system point of view, the location and timing of the production of renewable energy must be considered. Self-sufficiency regarding emission-free energy will not be possible in many developed countries, so that they will continue to be dependent on energy imports. Here, hydrogen as a regeneratively produced, chemical energy carrier can make a significant contribution to decarbonization. For example, ideal regions for the production of solar or wind energy are often far away from main industrial areas, requiring hydrogen as an energy carrier for the transport of energy, as electric powerlines have their limitations, especially for long distances. Since the yield of energy production in these regions can be much higher, the conversion losses are mostly compensated by the lower yield of local production of renewable energy in industrial areas (e.g., in Central Europe). In addition, the production of renewable energy depends on the weather conditions, which leads to times of energy surplus when the energy demand is low. In these surplus situations, instead of turning off the production of solar or wind power, the production of hydrogen results in a higher overall system efficiency and also provides additional revenue for the operators of the solar and wind parks.

For the existing fleet of combustion vehicles, synthetic fuels based on renewable electricity can be considered another solution. These so-called e-fuels are produced by reacting hydrogen from electrolysis with carbon dioxide taken from the atmosphere or emission sources. Combustion of e-fuels in conventional ICEs cannot match the superior technical properties of electric drives, and at the same time, they lose a large amount of energy. Therefore, the cost of providing them is extremely high (see Fig. 8.7). While aviation relies on e-fuels to reduce its carbon footprint, these fuels are not currently expected to be relevant for road vehicles in the long term. Exceptions include niche applications, such as racing or vintage cars. For example, Formula 1 will use e-fuels in its hybrid cars beginning in 2026 (Barretto, 2022).

The difficult-to-understand technical characteristics and potentials, the complex factors influencing the performance data, the costs, and, in particular, the environmental compatibility are very difficult to compare objectively among drivetrain choices, even by proven experts (Weigelt, 2022). As a result, despite the clear predominance of electric drivetrains, traditional customers still seem to feel daunted when faced with the necessary change in attitude, and they continue to cling to familiar ICE cars, as reflected in the number of registrations and the fact that governments have to set targets for the number of electric vehicle registrations (Association des Constructeurs Européens d'Automobiles, 2022; Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz [BMUV] 2021; Bundesministerium für Wirtschaft und Klimaschutz [BMWK] 2023). Therefore, one of the major challenges is to increase customer acceptance by demonstrating technological reliability.

Mobility must always be considered holistically. In addition to the vehicle and its drivetrain, this includes the infrastructure and the established energy ecosystem, which vary greatly from country to country. These aspects also have a major impact on the overall efficiency and the ecological footprint of the various drive concepts. In the case of electromobility, for example, these are technological disruptions in cell chemistry, the charging infrastructure, and the closing of material cycles for battery raw materials. For hydrogen and synthetic fuels, these include the production and eco-efficient transportation of green hydrogen or synthetic fuels. Unfortunately, this situation challenges incumbent car manufacturers to manage the uncertainties surrounding emerging technologies, while new entrants seize the opportunity to focus on new technologies.

After this brief introduction and comparison of alternative drivetrains, the following two dialogues between experts from research and practice will address the current challenges and opportunities for the future of the drivetrain and the potential of hydrogen in the automotive context.

8.3 Expert Conversation on the Future of Mobility

What is the History of Electric Vehicles at BMW and Where Do You Stand Today?

Franke: It is a real honor and a great pleasure for me to talk with you about the future of mobility. The future of mobility, especially automotive mobility, for me is summed up in the four letters C, A, S, E, which stand for connected, autonomous, shared—I personally would redefine it as sustainable—and, of course, electric driving. This was the mantra when BMW decided, 10 years ago, to design and produce a fully electric car, the BMW i3. I drive an i3 as well.

Zipse: Do you? I hope you enjoy driving it.

Franke: It is still an excellent car, even though it is about 10 years old. It is fully purpose-designed for electric driving, although it started with a small range extender to overcome the range anxiety. This range extender has disappeared, and now BMW has changed its strategy a bit. As far as I can see from the outside, BMW's strategy now is to offer all drivetrain alternatives in every model series. However, fully purpose-designed electric cars would potentially outperform BMW models in terms of better integration, cable harness, compartment design, maybe even efficiency and costs. How will BMW overcome these potential disadvantages?

Zipse: Thank you very much for that really strategic question. What you call CASE, we call ACES, but it means the same thing: autonomous, connected, electric, and shared. In terms of electric cars, which is what we are talking about here, we have not changed our strategy. We have evolved it into the future. We built the first electric car in 2008: an all-electric Mini. It was not for public use, but there was an electric Mini in existence. There was also an electric 2-Series, you know. We experimented with that, and then, we finally made the decision, "Let's build an electric car." At the time, we called it the Megacity Vehicle. It later evolved into the i3. We also said, more or less, this can be an experimental field for car body design, as we had to reduce the weight to increase the range of the car. The i3 became a carbon car because of the lightweight constraints. It is still the only high-volume carbon car in the world to this very day. There is no other manufacturer that has built a car like this.

Franke: What has happened since then?

Zipse: Back then, we were working with the third generation of our battery technology. Now we are in our fifth generation. Back then, we knew—and in the automotive industry you have to look years ahead—that electromobility was coming. Up until then, there was no mandatory use of electric mobility. There was not enough infrastructure, and there was no customer commitment to buy these cars. But because we saw that this was going to happen because of the carbon regulation that was coming, first in the United States and then in Europe, and then also in China, we made a bold move, a very early move. We changed our strategy at that time, not afterward; that is the misconception. We took the change that was coming very seriously. Then, we waited a year and a half, until about 2014, to see how the i3 was doing. We saw competitors coming up and making plans. So, we said, "OK, let's get serious now!" Then, after the i3 experience, we took a very consequent step of electrifying our main architectures. These are not conversion products, but are built on flexible architectures. This took 4 to 5 years, while the outside world had the impression that we had stopped doing electrification, which is not true at all. We prepared for the point in time when electromobility really would take off. That time is now: The iX3 was our first fully electric car after the i3; the iX is the second car. There was a test in Auto Motor Sport the other day, and they tested six fully electric vehicles—purpose-designed vehicles. Other than the iX3, there were vehicles from our German friends, Japanese manufacturers, and so on. They were all there. The iX3, which is built on a flexible architecture, not on a purpose-built architecture, came out on top by a wide margin. First prize! It is the best system overall, and people are buying it.

Franke: So what are the benefits of working with flexible architectures?

Zipse: People do not buy ACES or CASE; they buy cars. People always buy a system, and there is this misconception that you can say, "Well, I built the best battery, and people buy the car because it has the best battery." Even the first i3 with a range extender did not have enough range. So, customers always buy complete cars. There is a misconception that you can only build electric cars on singular, dedicated architectures. That is a mistake. We are now at the point where between now and 2030, electric mobility is going to take off on a large scale, and in a company like ours, you build up entirely new architectures every 10 years, including on the digital side. Now, we have made the decision that, in 2025, the volume for battery-only vehicles in the market will be high enough to develop a dedicated architecture and also to renew not only the electric drivetrain, but also the digital architecture. This is the point where we replace our current architecture with a new architecture. It is not that dedicated electric architectures are better than others. The logic is a different one. And we are ramping up massively. By the end of 2023, we will have launched 12 battery-only vehicles. The next 7 Series will come with four drivetrains. It is the same principle with the iX3, which has won all the tests. We love the next 7 Series. It will be a hit; we are preparing to ramp up quickly, and the volume is there. That was the reason for this decision. It was a transformation of our strategy, not a change of direction.

Franke: Not only the technical tests prove your concept, but also the financial success tells us that your strategy is right. How many cars per year do you need to sell to dedicate a single-purpose-design platform?

Zipse: Usually, we build 6–8 cars on one architecture, for a production volume of about 1 million cars. But, of course, the customer does not see that this is one architecture. You know, the cars built on one platform come in completely different shapes. Nobody would assume that the 4-Series convertible and an X5 are based on the same architecture. But they are.

What Is the Strategy for the Electric Drivetrain?

Franke: Let us take a closer look at the electric drivetrain. As a production engineer, I am impressed by how BMW designs and builds not only combustion engines, but also electric motors. But as a production engineer who focuses on the production of electric motors, I also know that the drivetrain is made up of not only electric motors, but also batteries and power electronics, and of course, it is integrated in a charging network. How will BMW differentiate itself in the future in the other modules of the drivetrain?

Lamp: It is exactly as you say. It is not the single component, but the full drivetrain that makes the difference. That is where we have our experience. As Mr. Zipse mentioned, in the fifth generation, we tried to optimize the whole system between the electric motor, the charging unit, and the battery pack. As you said, the e-motor, in particular, is not only one of the most efficient e-motors, but we have more than doubled the power density of the e-motor between the i3 and what we now see here in the iX. More importantly, in the iX, we are focusing on electrically excited synchronous motors that are free of rare earth metals. This is essential for sustainability. We are very pleased with that. We have gone one step further, by fully integrating the motor, the gearbox, and the power electronics in one housing, which reduces the cost and makes it more compact for integration into different platforms, such as a multi-purpose or a special-purpose platform.

Franke: How do you reconcile this integration with the diversity of your products?

Lamp: The key is that the set of components is built to be scalable across the different models. We can go from about 90 kilowatts up to almost 400 kilowatts with the same concept of the e-motor. The same goes for the other components. The battery is the most significant in terms of cost—80% of the drivetrain costs is related to the battery. Here, we have the same thing: a very simple building block. We design or define the cells in such a way that we can build very standardized modules that are then assembled into different battery packs.

Franke: Even the battery cells?

Lamp: We specify the cells ourselves. So, we have never built—or, let us say, bought—cells off the shelf. Even when we built the i3, which was one of the first large automotive battery cells, Samsung was producing at that time, and we had the opportunity to build up our competence to be on an equal footing with the cell manufacturers. So we worked together to find the best solution for our standardized building block for a battery. We have different module sizes, but the basic way we build it this is the same. We can make different numbers of cells with the same equipment.

Franke: In my professional career in business and industry, I have learned that it is all about core competencies. It is not only the design or the definition of the product, the module, and the parts, but also the production and even the production technology and the tools. The other competitors produce and design their battery cells; they use silicon carbide power electronics, for example. What modules will BMW produce in the future to claim this as a core competence and differentiate itself from its competitors?

Zipse: You should try to build up a core competence if you are likely to have a monopoly or an oligopoly in the market: Then, customers are very dependent on you, as they cannot choose. Or it would be an option if it differentiates you from your competitors, or if your development speed can be significantly faster than in the outside industry. If you can answer yes to these questions, you can build batteries from scratch yourself. But this is not the case. The battery is a rapidly evolving technology.

Franke: Can you elaborate on what these different aspects mean for the battery?

Zipse: First of all, there is no monopoly out there, not even an oligopoly out there. There are a lot of competitors: Europeans, Koreans, Japanese, and Chinese. There is a big worldwide industrial network that is emerging. So, right now, we have four major battery suppliers. We are not dependent on anyone, and we do not have the need to build the batteries ourselves, because with four suppliers, our demand is in good hands. You must have the right contracts, of course. That is a negotiation skill.

The second thing is the speed of development. You increase your development speed when you have more than one supplier. In 2019, we built our own research and development (R&D) center here, where we developed our own competencies. There are more than 2000 parameters in the cell. The right combination determines the performance of the cell. Now comes the interesting part. What happens with a lithium-ion cell? First, you try to optimize the cathode by increasing its performance. You increase the nickel (Ni) content, you increase the manganese content, and you increase all the ingredients of the cathode. But what happens if you increase the energy density on the cathode? You have to change the anode as well. You go away from graphite to silicon–graphite or something like that. Once you have that, the third step is the performance of your electrolyte, and then, the fourth step, which we may do in this decade, is to go from a liquid electrolyte to a solid electrolyte.

Franke: And that rapid pace of development requires flexibility on the supplier side.

Zipse: Exactly. This is a rapid development path from the cathode to the anode and then to electrolyte. It may happen that you need other suppliers along the way. Nevertheless, we are very careful not to invest a lot of time in one technology. In 2021, you might have had the latest state-of-the-art technology and have been well advised to use it, but in 2026, you might need a different technology. There is a big difference between a fluid electrolyte and a solid electrolyte.

Why are we investing? Because there are many competitors out there, and they are extremely competent. We can build up partnerships, as for our business model. It is much better to use the market than to invest in developing specific technologies ourselves. We invest wherever we have an integration task, where all the technologies come together in the car. We refer to this as HEAT, which stands for the German acronym "Hochintegrierte Elektrische AntriebsTechnik" (meaning Highly Integrated Electric Drivetrain), a combination of the electric drivetrain and the clutch end zone.

Franke: I see the arguments with the battery in a similar way to the semiconductor market 30 years ago. In Europe, we thought that we had to build our own semiconductor production capacity. Now, nobody is talking about that. We even have an oligopoly here with a few processor manufacturers worldwide. Taiwan Semiconductor Manufacturing Company (TSMC) makes 80% of the processors. But we are okay with that. So why did you decide to design the electric motor yourself, but not the power electronics? Why don't you get into the production of power electronics, given how important it is for efficiency and dynamics and that it is integrated into the electric motor?

Zipse: Let us take a look at our internal combustion engines. We produce only 5% of the work content of combustion engines ourselves, even though we are called the Bayerische Motoren Werke: 95% is produced by suppliers. We do not make pistons, we do not build turbochargers, nothing. There is a thriving market out there. We are the system integrators, and we believe that we still build the best engines in the world, even with very little value-added in-house content.

The assumption that in-house production gives you a higher competence is simply wrong. Our experience is very different. You build up your own competence when you operate in a monopoly situation. Take press shops, for example. Building those up is very difficult, a super high investment: One costs 100 million euros. There are not many market players out there who build press shops. It is not high-tech, but you have a very clear oligopoly situation—and you are completely dependent on press shops. It is a simple technology, and it makes sense to invest in ourselves.

That is the situation we have. Of course, in our purchasing department, we always look at the market situation. If we cannot increase our speed and we do not have a shortage of supplies out there, we rather tend to buy.

Franke: And when will you bring your first silicon carbide power electronics to market? This can save 20% of the energy, as competitors have already successfully demonstrated.

Zipse: Launches always depend on the introduction of a new architecture. We live in a 7-year cycle, so some OEM will always be earlier than another. We will integrate them into our next architecture. It is a normal process that a competitor may start earlier because their architecture will be new. I am not afraid of that.

What Does the Future of Mobility Look Like?

Franke: I see. Let us move on to the next topic. We are going to start a new course called "Future of Mobility." You call it ACES. The competition is extremely strong in autonomous driving technologies: sophisticated sensors like stereo cameras, radar, lidar, and ultrasonic sensors. In our department, we buy powerful control hardware from Nvidia or Mobileye, using graphical or neural processing units on artificial intelligence (AI)-based software trained on millions of miles driven and giant data infrastructure. The major competitors, like Google, Waymo, and Apple—or even Tesla in the United States or Huawei in China—control several of these key technologies: sensors, AI, data infrastructure, and so on. How will BMW maintain its technological leadership in this area over the long term?

Zipse: I would add connectivity to that list. We want to be the technology leader, not only in electric drivetrains, but also in assisted driving. That will come in stages. But, in addition to technology, there are two important factors that we have to bring into this equation. It is not only the availability of technology, it is not only competence, and it is not only the technological capability. For these, we are already there: We have Level 5 cars driving out there in our test centers. But two other factors are critical. First, what do the legislators do? Do they allow you to sell a car with autonomous driving capabilities? And what are the specific requirements in Germany for them? For example: You can have Level 3, but only up to 60 km/h. Second, you have to ask yourself—and that is the final part of the equation—Is this a business case? Because between Level 2 and Level 3, there is a price tag of more than 10.000 euros, which is a lot of money even for premium customers. You have to check all three boxes: technological competence, legislation, and a valid business model.

Franke: So you are not afraid of Google or Apple?

Zipse: The companies you mentioned are not building cars. They build technology. Inside the automotive sector, they are not making any money. So the question is: When do you, as a car producer, make specific investments without looking at the contribution margin? It is quite simple: When we bring a car to the market, the cost has to be lower than the price needed to make a positive contribution margin. None of these companies think about contribution margins. What will happen, at least for the next 10 years? We will be at the forefront of assisted driving that goes to a Level 2+ with driver supervision in Germany—which is hands-free, by the way.

People think that only Level 3 is hands-free, but this is not true. You, as the driver, are monitored to see if you are still looking forward, and if you are not, the car will ask you to take over control. Level 3 is completely hands-free, but that is highly restricted around the world. To offer Level 3, you need radar, lidar, and optical sensors like a camera—we are absolutely sure of that. You cannot do Level 3 with cameras alone. But a lidar sensor in a car is very expensive.

Franke: Well, the new Apple iPhone 12 has already has a lidar. Very cheap. I know.

Zipse: This is a matter of progress. We are watching very closely what happens here and at what point of time we see a business model. We are fully aware that there is another race going on, but that is actually happening in a different part of our industry. That race is Level 5. That is an entirely different thing, but it will start in the transportation industry, not in the normal passenger car industry. We will see Level 5 trucks very quickly, possibly in China and the United States. However, those will only drive on highways. They will never enter a city, never enter a normal traffic jam, and never have to turn corners; there are no drivers in there; they just go from point A to point B, like a train. You will see that fairly quickly. In the rest of the industry, you will see people movers, driving at low speed, and so on. Robo-taxis may move people through cities, but this again will be a question of a business case—will the investment in the technology work on a large scale?

Franke: So what does this mean for BMW?

Zipse: The question is: Are you going to participate? We do not build vans today, but it is an important market segment. We are looking very closely at the point at which vans could contribute to our business model. But again, this is not so much a question of technological competence, because in this area, everybody needs partners. Nobody can do it alone. Do you have a business model where you can convince customers to pay a specific price for a specific competence in the car? You will see BMWs with Level 3 on the streets as soon as we are allowed to do so.

What Is the Role of Connectivity?

Franke: I have to touch on at least one last question. We talked about electromobility and autonomous driving, but I think connectivity toward the customer and toward infrastructure is also very important. Modern cars are already connected to the Internet through mobile communications technology, telephone, web conferencing, updated maps with up-to-the-minute congestion information, music, video, entertainment services, and Netflix—you name it. Everything is available in the car.

Equally important is the constant connection of electric cars to the smart energy grid. Dynamic inductive power transfer technology, which means recharging the car while driving it and promises infinite range. Connectivity supports autonomous and convoy driving, stabilizes the electricity grid, and offers new services for individual mobility, such as tolls without pay stations, navigation, fast Internet communication, and so on and so forth. This technology is never discussed. We all talk about batteries and hydrogen, but no one talks about inductive power transfer while the car is moving. How can BMW take advantage of this promising technology?

Zipse: The second letter in the acronym ACES stands for Connected. We talk about that. This car behind us (points to an iX model) is one of the first series vehicle with full 5G capability. Let us go back to autonomous driving: Real 5G is necessary to put the intelligence of autonomous driving outside the car, which is ultimately much cheaper. If you put all the AI, all the components and sensors inside the car, the car becomes too expensive. This is what the Chinese are doing: They invest much more in infrastructure and connectivity than Europe or the United States. The first question they ask is: What is the latency time of the car? Because that determines whether you can do autonomous driving with the infrastructure around you. It is your latency time: A few milliseconds are critical. There are different approaches, but it all comes down to connectivity.

Franke: You just mentioned the connectivity of information. I am talking about connectivity of energy. Why do you not charge your car while you are driving down the highway at 200 km/h? Why do you not use an inductive power transfer (IPT) technology? The technology is there. We have test tracks all around the world. Even 10 years ago, I rode in a bus with 60 kilowatts of power at a speed of 60 km/h. We can easily upscale that to 200 kilowatts and 200 km/h. It is a question of decision, perhaps a political decision, but also a decision by a major car manufacturer who could say to the state or the city of Dubai: We will sell you a million electric cars, and we will prepare the infrastructure with IPT, inductive power transfer. Could this be a new business model for BMW?

Zipse: Good question. Of course, this is a chicken-and-egg problem.

Franke: If you look at it as a project business, which is completely new for BMW, then it is not a chicken-and-egg problem. It would be a project. You install the technology in Dubai all over the city, and you only sell BMWs that are compatible with this project.

Zipse: We would not do anything that we could not scale. We are a global player. We have 140 markets. The only way to be efficient in this industry is to scale.

Franke: Well, you can do it in Dubai, you can do it in London, you can do it in Shanghai, and then you scale it up elsewhere.

Zipse: If we saw the scaling, we would do it. But right now, it is not only about scaling; it is something else. On the A5 highway between Darmstadt and Frankfurt, there is a 10 km stretch for truck catenary charging. I drive there sometimes, and we keep a close eye on it, because it is an excellent solution for trucks.

Franke: But not for passenger cars?

Zipse: Even for trucks, it is not being scaled up in Europe or in Germany. That would be something where we would say, we will put it on the R&D side; we will see what happens. But we would not make a solitary, heavy investment just from BMW to scale that up. Because we do not see that. What could happen before that, especially in China, is that there are completely green cities that are built from scratch. They could be based on a fully integrated solution. In those scenarios, we would offer ourselves as a technology partner. But there are not many cities of a certain size that are built from scratch.

Franke: Thank you very much, Mr. Zipse and Mr. Lamp, for sharing your insights with me. It has been a pleasure for me to discuss these new technologies and strategies at BMW. Thank you very much for this discussion.

8.4 Expert Conversation on H_2 as Fuel of the Future

What Is the Importance of the Hydrogen Strategy?

Wasserscheid: I am really excited to be here and to discuss with you the topic of hydrogen as a future fuel. It seems to me that hydrogen is a very dynamic field at the moment. A lot of scientists, companies, and even politicians have recognized that this fully defossilized energy system that we want to have in 2045 can only work if we have storable energy carriers. The time has come: People are developing hydrogen strategies everywhere. There is a Bavarian hydrogen strategy, there is a German hydrogen strategy, there is a European hydrogen strategy, and my first question is: What about a BMW hydrogen strategy?

Zipse: I have been with the company for 30 years, and now, we only have less than three decades until 2050 to become carbon-neutral. That is not very long. It sounds very long, but it is not very long. By then, at the latest, we need to be at least carbon-neutral, better yet, zero emissions. We still think that one of the main paths toward this is—as we discussed before—electromobility. That is the main route. The charging infrastructure is being built. There is a strong consumer demand for electric cars. It will become mainstream—very quickly, we see that coming. The only question is: What if, at some point, you have to be completely emission-free? Electromobility may only be the right answer in certain circumstances. If you do not have access to charging infrastructure, if you do not have access to renewable energy, you need some form of energy storage.

Wasserscheid: So do you agree that energy storage is a relevant topic?

Zipse: We believe that, for automotive market segments, hydrogen is the best answer. I am not just talking about passenger cars, but especially about buses and trucks, marine, aviation, and so on. So, the applications for hydrogen will be much broader than what we see in electric mobility today. With a view to 2050, we see that for BMW—and we can only speak for BMW with a global market share of 3.4%—hydrogen will be an essential ingredient in that mix of propulsion systems, especially because, already today, unlike Germany, we have quite progressive hydrogen-focused countries, such as South Korea (Hyundai) or Japan (Toyota), which have been pushing this technology for almost a decade in serial production. BMW is a global player, and we see this as an important part of our premium brand strategy.

Wasserscheid: In Germany, I am often asked this question: Where will the green hydrogen come from? People say we need 2.5 times more electricity to produce it, but I see it a little differently. My point is that, today, Germany is an energy-importer—and all analyses also show that this will also be the case for future energy systems. Today, 80% of our energy comes from other countries, and it will be similar in the future. The way we will import energy is mainly through hydrogen: hydrogen derivatives, chemically bound hydrogen, ammonia, LOHC, and whatever you want. The point is: If you have hydrogen as a transport vector to Germany, the efficiency discussion is completely different, because it makes no sense to convert the hydrogen into electricity to charge the battery in your car. It is better to use this hydrogen immediately and directly in mobility, of course first in sectors where batteries have problems (e.g., trucks).

Would you say that we have enough electricity in Germany? Because this is not about Germany, is it? Climate change is global. There are places where it is much easier and more economical to generate renewable energy than here in Germany.

Zipse: Right. We have a global perspective on hydrogen. This is important because only about 8% of our worldwide revenue is generated in Germany. So, we have to look beyond the German hydrogen discourse. And if you take a global perspective, you see many use cases where access to electromobility is lacking. From our point of view, the only emission-free possibility for private passenger cars, apart from battery electric vehicles (BEVs), is fuel cell electric vehicles (FCEVs) that run on hydrogen. There will be plenty of cases where people will not have access to charging infrastructure/electricity. So, hydrogen is a perfect complement to our overall strategy. It obviously does not mean that we are undecided. On the contrary, we are determined because we are not in a shrinking scenario. We do not see hydrogen as a shrinking scenario. Because we produce almost 3 million cars per year, we can afford to have three or four different drivetrains, especially because our whole mindset is about architectures and not around platforms. That is the perfect strategy for us. That is the way forward.

What Will a Hydrogen Car Look Like and What Is Its Advantage?

Wasserscheid: It is a disruptive technological change to move from fossil to renewable technologies. If you are going to build your first BMW hydrogen car, what kind of car and what kind of customer are you targeting?

Guldner: We just have completed the development of our second generation of fuel cell technology and integrated it into the X5, one of our bestselling models. A small pilot fleet of BMW iX5 hydrogen vehicles is currently used worldwide for testing and demonstration purposes—very successfully. Then, we will move on to the next development steps, and customer cars will be ready when the markets are ready for them. Different countries move at a different speeds, and we will see when the right point of time comes, probably before the end of this decade.

Wasserscheid: I drive a hydrogen car myself, as a private car, a Hyundai NEXO, and I am really waiting for the BMW. Do not forget me! I am your first customer!

Guldner: We will call you, and you can come for a test-drive soon (laughs).

Wasserscheid: Perfect! And the experience is that this is a nice way of driving, especially for long distances, because even though the network of fueling stations is still quite thin, it is basically enough if you drive long distances. You pass a filling station every 50 km. That is more than enough.

Let us go into the future, into the year 2045, when Germany is supposed to have zero emissions, according to the new climate laws.

What will be the ratio between battery electric and hydrogen electric then? Because my feeling is that batteries are moving fast today because you already have the scale and the mass production effect. In the hydrogen business, the situation is still different. To give an example, if you want to get a cheap fuel cell today, then the best thing is to buy a NEXO or a Mirai, take the fuel cell out, and throw the rest away. The reason is that fuel cell production has yet to be scaled up. What is your outlook for 2045? Let us just assume that, by then, technology development is in the mass market for all technologies, and it is really an established market for both technologies.

Zipse: The question is, which parameter, which vector do you believe in? Do you think that the people are afraid of too long charging times in electromobility—even in the very best case, it will be longer than at a gas station. People might not want to stand in the dark and wait 10 min. They want to refuel quickly and then go. We do not know that. I think the main driver for hydrogen will come from settings in which you have to drive emission-free and you do not have a charging station. That is the main driver. It is not range or anything like that. It is not even the cost. For example, if we say that we want €5 per kilogram of hydrogen, and that would be the point at which it becomes competitive. It is also when countries, through legislation, no longer allow greenhouse gas emissions from cars—and there will be many in 2040. Not all, but a lot. What happens if you cannot charge all these electric cars?—The issue is not the availability of battery electric cars, but the availability of charging stations.

Wasserscheid: What kind of example do you have in mind?

Zipse: What will you do in rural areas? In densely populated areas, like most of Germany, you can provide enough charging interfaces. When you build new houses, you build in charging facilities. You can do that in cities or in the countryside. But in a very scenic, unspoiled environment, where nature is dominant, you cannot tear up all the roads and build a massive amount of charging infrastructure. You will get a massive political problem. What do you do there? But remember, by 2040, we want to drive emission-free. So, either you stop driving cars to those places, which is one option. Or you have a hydrogen car.

Wasserscheid: But the same goes for the city of Munich, right? If you spend half an hour every evening looking for a parking space, it will certainly be more difficult in the future to find a parking space with a charging station. That could be a similar scenario.

Zipse: A similar scenario, yes. I think that is the most dominant parameter: You will not have enough access to charging points. I am not talking about the problem that the build-up of overall charging infrastructure is not moving fast enough. That is also a challenge. But even in societies where the charging infrastructure is developing rapidly, there are simply places where it is too expensive to install charging systems—places you simply cannot or will not access. It would be like trying to bring public charging to the last house in the Black Forest. You are not going to do it.

Guldner: There is also an economic parameter: There are studies that show that a dual infrastructure—both hydrogen fueling stations and electric charging—is cheaper than just putting everything into electricity, because building the electric charging infrastructure has a nonlinear cost vector, because the more you put out there, the more charging stations, the more expensive it gets. But the hydrogen fueling stations always cost the same. From a practical standpoint, the hydrogen fueling stations already exist—they can be easily integrated into existing gas stations. You do not have to discuss who owns the land, who operates it, and so on. All those things are already in place. It makes it a lot easier to get it out there.

Zipse: That is a good point. It is easier to roll out hydrogen gas stations nationwide.

Guldner: And the synergy is with the commercial vehicles, especially trucks, where we have to roll out a hydrogen fueling station network anyway. It is the same hydrogen.

What Is the Technology Strategy Behind Hydrogen?

Wasserscheid: Let me dive a little deeper into the technology strategy. Hydrogen is a brand-new technology; it is disruptive. What is the value chain? And who will be involved with what kind of service and with what kind of product? I guess that this is also a strategic decision for BMW. When and where do we form alliances with other OEMs for fuel cells—I know about your collaboration with Toyota—or do we source in from classical suppliers like

Bosch, Schaeffler, and so on, who fortunately are also quite active in the hydrogen business? I think it is very encouraging that German companies are recognizing that this kind of business fits very well with what they know, maybe different from making batteries. What is the strategic decision for BMW to have a Unique selling proposition in the hydrogen race, but also to have its own product portfolio within this powertrain of the future?

Zipse: We already touched on this point before with the batteries. I think that in-house competence in all areas is overrated. System integration competence is the most important thing you need to have. Then, you have to have a very strong ability to cooperate. If you have strong partners out there—and we do have partners who have been cooperating with us for many years—then you do not need to have all competencies in-house unless you have an extremely unique technology, which is not the case here. I am sure that with all these hydrogen drivers, there will be a thriving supplier market. There will not be just one fuel cell supplier. The important thing to remember is that the integration possibilities—because we already have an electric drivetrain—are quite simple. At the end of the day, a hydrogen car is more or less an electric car. Our car architectures are designed so that BEVs and FCEVs have a high degree of synergy. This is crucial for our electric strategy.

We have a long-standing relationship with Toyota that we are very happy with. Once we decide on a series model, we have to look at who is the best supplier or the best partner. Regarding a make-or-buy decision, it is not always true that the in-house made decision is the optimal choice. It can be right, but most of the time it is not, because you lose a lot of flexibility.

Wasserscheid: This discussion goes even deeper if you think about the whole hydrogen value chain, with green hydrogen production, hydrogen logistics, fuel cells as one way of hydrogen utilization, and the aspect of industrialization and scaling. People sometimes ask me, “Oh, hydrogen has been around for 100 years! Why is it not there yet?” The main problem is this relatively complex value chain: You have to find suppliers and partners—and that is not easy at the beginning. For example, there are different technologies for on-board storage: compressed, cryo-compressed, liquid, and all of that. It is important that the first movers—Toyota and Hyundai are excellent examples—are able and willing to cover parts of that value chain themselves. Otherwise, the technology will not begin to move.

Zipse: Do you see that change happening yet?

Wasserscheid: I am convinced that we will now build this value chain. We see this in the Bavarian Hydrogen Centre. There are companies that do electrolysis, like Siemens Energy; companies that do different kinds of hydrogen logistics, like Hydrogenious LOHC Technologies; and companies that do fuel cells or fuel cell components, like Bosch and Schaeffler. When all these elements come together, the chain will work. What about your willingness as BMW to contribute your part to building these value chains? Is it just to say, "I have to buy this, this, and that, and then I will prepare a car"? Or is it, "I believe in this technology, so I want to be this kind of enabler like Hyundai or Toyota"? We've seen the Toyota cars at the Olympics—they really have a mission on hydrogen. Is the same true for BMW?

Guldner: Of course. We have already mentioned the value chain, and we work closely with Toyota. We also work with a number of suppliers on the components, and then we do the system integration. Look at the fuel cell system itself: We do the integration ourselves because that is our core competence. Also, with the tank system, the storage system, we buy the tank vessels and so on, but we do the system integration. We are working hard to integrate that into our electric vehicle architectures in the future. That is where our particular competence comes in: Taking the components, putting them together into systems, and then having a powertrain that is really BMW-like, that has the BMW driving dynamics—as you might experience when you come back and visit us again for that test-drive (laughs).

Wasserscheid: I would love to do that. And I understand that you need partners to do that kind of system integration. Where else do you need partners?

Guldner: We rely on other players to build the infrastructure. H_2 mobility has done a great job in Germany, building up the first 100 fueling stations. Of course, we need a Europe-wide network, and we see that coming with the European initiatives. Hopefully, in the next 5 to 10 years, there will be gas stations that will sell green hydrogen at a reasonable price for both passenger cars and commercial vehicles because, at the end of the day, it is the same molecule, unlike diesel, where diesel for trucks is different from diesel for passenger cars. This is very exciting to see, and I am sure that there is no need for us to invest in a hydrogen fueling infrastructure, because it is already happening.

What Is the Impact of Hydrogen Technology on Climate Goals?

Wasserscheid: When we talk about defossilization, green products, and a low carbon footprint, we also have to consider the production process for cars. In Spartanburg, I think you were the first company to show that hydrogen mobility can be very helpful in reducing the carbon footprint of your production by using hydrogen-powered forklifts. To what level can you extend that experience? And to what level do you think that competitors and other companies that move goods from Point A to Point B would adopt this kind of technology?

Zipse: Building a highly sophisticated, innovative, and high-performance vehicle is something no company can do alone. That is why we have strong cooperation partners. We are in a constant synergy with regulators, with policymakers, with other industry players, with suppliers, and with external engineering companies. It is always a concerted effort. It is essential that we make it clear that this is part of our strategy for the future and that we are not going in and out with different suppliers every year. Now is the time when our environment is making a big effort, and the recent Important Project of Common European Interest (IPCEI) is just one example of many. We have never had a billion IPCEIs. This is the first time that Europe is doing this. The United States, China, and Korea are doing the same thing at the same time. So, this is a unique opportunity. I am not saying that this is something that will be rolled out quickly across all segments of the car industry, like electromobility. It will find its place in the upper premium segment, where the first buyers are. We have been working on this for more than 20 years. We know that this is a difficult topic. When you only have two choices—700 bars or -250°C—it is a different question (laughter).

Wasserscheid: This is why people are trying to come up with other technical solutions.

Zipse: We know that. But we still think that in our 25 years of R&D with hydrogen, there has never been a better opportunity than now.

Wasserscheid: Absolutely. That is why I said in my initial statement that these are dynamic times: Politicians are convinced—and I think they are right—that this is a significant path forward. It is a strong element of a future defossilized energy system.

Zipse: BMW is strongly committed to hydrogen. Of course, there is the argument that "you are not focused enough," that "you should only focus on one technology to be productive and efficient." We don't think that is the right way. The synergy is not in the drivetrains; it is in the architectures. The choice of the drivetrain is driven by customer needs. The biggest risk of focusing on just one or two technologies is that you end up in a shrinking scenario because customers behave differently around the world. And we strongly believe that if you want to grow in this industry, you have to do that through market mechanisms and technology openness. If there are not enough customers for a certain technology after a period of time, you stop.

But, to give some examples, we see that diesel is not dead—far from it. In Europe alone, one in five customers still buys a diesel car. It is a thriving market. The petrol engine is still there, also the hybrid: We are the world's largest producer of hybrids among all OEMs. This is a flourishing segment for us, despite all the public discussion. Pure electric cars have also grown steadily in recent years. So all four drivetrains are very profitable. The question is: Will hydrogen be the fifth drivetrain, or will it be another technology? It does not matter—as long as you have thought about the possibility and put it into architectures. That is what we have done and what we are doing. So far, that strategy has been absolutely right, because in terms of the overarching strategy, we know that if a company of this size does not grow, it will run into problems. So we have to grow, and the lever is technology openness.

What Are the Limiting Resources of the Hydrogen Business?

Wasserscheid: At the end the day, the customer decides. I think what many people forget is that a car that goes 700 km and takes at least 20 min to charge is a different product than a car that takes just a few minutes to refuel. There will be customers who appreciate that difference and who are willing to pay a premium for it. But let us assume for a moment that the hydrogen business grows, especially in the heavy-duty sector. What do you think about resource constraints? Do you see—also in comparison with other technologies—resource-related limitations?

Guldner: Well. There are two things to this. One is—as we discussed earlier—the efficiency question. We want to look at the entire value chain from the point of view of resources or raw materials: from the manufacture of the vehicle and the production of all the components and assembly, to the use phase, and finally to recycling. The main material used in fuel cells is platinum, and platinum already has a very high recycling rate. In the next few years, there will be a lot of catalysts coming back from all the other vehicles. So the recycling business for platinum is already working very well. That helps in the long run in terms of reducing the amount of raw materials. The battery is a different story. We are putting a lot of effort into making the way we use our raw materials more sustainable. But the battery recycling business requires more effort, and it is just starting to ramp up.

Zipse: All resources are limited. Always. And the car industry is one of the most resource-intensive industries. The two questions are: First, when resources become scarce, do they become more expensive? And second, when does scarcity become an economic argument for survival? That is why we have defined the principle of "secondary material first" as one of the main pillars, at least for the next 10 years. Because humanity is extracting about 100 trillion tons of ores and resources from the planet. Then you ask people, "How long will that continue?" One thing is for sure. Most resources are finite. You can still use them, but they will become more expensive. Palladium, rhodium,… even steel are getting more expensive. So, it makes economic sense to put secondary materials first, at least as a cornerstone of your strategy. I think that is a wise decision.

Wasserscheid: Yes, it helps that platinum is so valuable and people have already developed processes to refine and recycle it. Plus, the quantities that are used in fuel cells and hydrogen release units are small.

That brings me to my last question: There is one resource that may also be limited. And that is brains. Right? (All laugh and nod.) For all that we have discussed, you need people. People with a different mindset. If you are trained as a person with gasoline in your blood, you are quite likely to fail in this electric world. Or maybe not? So the question is: How do you manage the talent pipeline or attract experts in technologies like batteries, hydrogen, and all these electrified mobility technologies? And how does that change the way a company like BMW is going to operate in the future?

Zipse: You hit the nail on the head, because of course brains are a limited resource. But much more important than the limited brain is the mindset. We find a strong source of power in trying to get the right mindset. We did not find such a big difference between the different drivetrains. An electric car is not that different from an internal combustion car. All of the electrics—apart from the battery—are very "mechanical." We move people who work in the internal combustion engine plant to the Dingolfing plant. It is almost the same skill set. And it is not that different. What stays the same is the continuous progress in every technology. Take digitalization, which in principle is not new to us, but every year something new comes along. Putting the right digital solutions into a car and making a profitable business model out of it, that is the most important question. At the end of the day, your product has to be unique, profitable, and attractive. That is not just a question of qualification or whether we have enough digitalization. It is a question of mindset. This is what we are trying to get the whole company to do, that everyone is part of a larger system that pays into a business model. If you have that mindset, you will get enough brains that want to contribute.

Wasserscheid: I think one important way to achieve this is close cooperation and interaction between universities and BMW, as in our very exciting discussion today. Many thanks for that!

8.5 Beyond Technical Functionality: The Energy Ecosystem around Eco-Efficient Drivetrain Solutions

As shown in the previous sections, different technologies compete in the area of individual mobility for different target groups and markets. While some technologies compete directly with each other, others complement each other for different applications and sectors. In this context, technology openness is a key to achieving climate neutrality. In Europe, e-mobility is expected to dominate the mass consumer market in the future. In other areas, such as heavy-duty transportation, it is not yet clear which drive solution will prevail in the long term. All solutions require massive research efforts in various fields to advance the respective technological maturity level.

The associated technological change requires close cooperation between industry (OEMs and suppliers), research, and politics (international and national). At the same time, consumer acceptance must be promoted. The application potential and user acceptance of alternative drivetrains depend to a large extent on the infrastructure and the energy ecosystem. Future practice and research avenues must therefore focus on these two aspects.

In the field of energy ecosystems, three potential future paths for eco-efficient mobile and stationary energy storage are discussed below. Due to the close interaction of new drive technologies with the associated infrastructure, disruptive energy distribution systems in the automotive context are also presented.

8.5.1 Eco-Efficient Storage of Electric Energy on Board an Automobile

The present status and success of battery electric vehicles is closely linked to a specific battery technology—the Li-ion technology. The reason is the outstanding energy and power density of the Li-ion technology compared with other material combinations (see Fig. 8.8).

Several inventions have been necessary to make Li-ion cells work. In 2019, the pioneering work of John B. Goodenough, M. Stanley Whittingham, and Akira Yoshino conducted in the second half of the last century has been

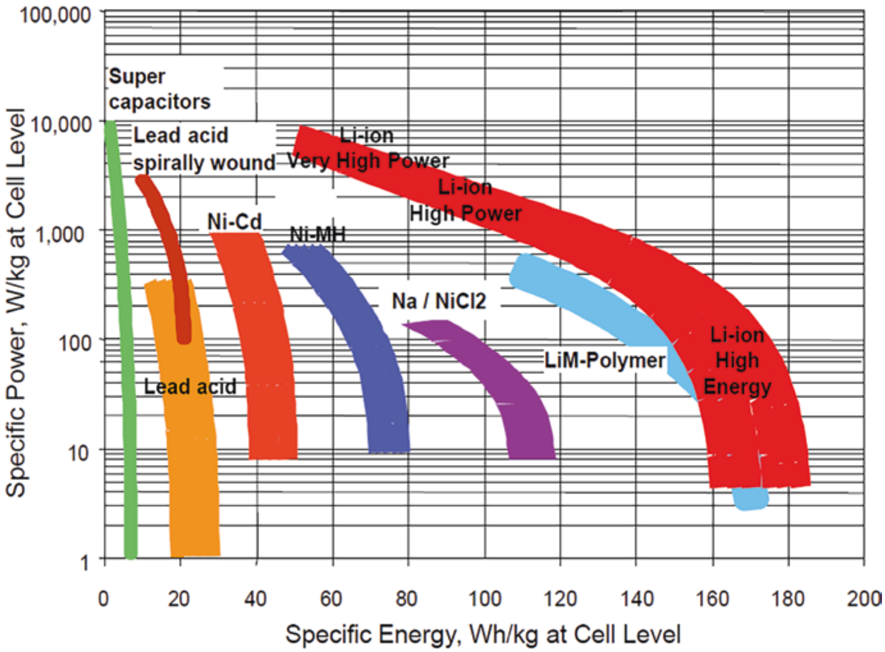


Fig. 8.8 Ragone diagram showing specific energy and power densities of different battery technologies (Note: Status as of 2013 on cell level—today Li-ion expand further to the right; "Ragone plot of various battery technologies with specification at cell level for automotive applications without lithium–sulphur and metal–air batteries." originally published in Budde-Meiwes et al. (2013). Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 227(5), 761–776. https://doi.org/10.1177/0954407013485567; all rights reserved.) (Budde-Meiwes et al., 2013)

honored by the Nobel prize. And it was the need for higher battery capacity for the new consumer electronic devices, like the camcorder, which motivated Sony in the late 1980s to industrialize the Li-ion technology.

The working principle and the subsequent steps to build a Li-ion cell from the incoming materials (powders, solvents, conducting foils, separator, electrolyte, and cell housing) to the final cell is shown in Fig. 8.9. The key materials are the active anode and cathode materials being able to store Li-ions in its inner structure. While graphite is the predominant material for the anode for all applications, the choice of the cathode material (typically a lithium metal oxide) strongly depends on the application and the requirements.

For example, the key performance indicators (KPIs) for automotive applications differ substantially from those of the consumer electronics leading to different solutions. While the lithium–cobalt oxide (LCO) cathode material is used in consumer electronics, LCO is not suitable for automotive

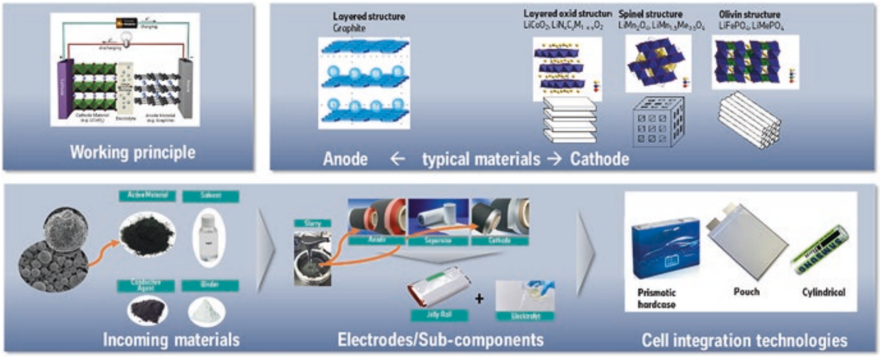


Fig. 8.9 Overview of the working principle of a Li-ion battery cell, the typical set of materials and the typical realization from materials to electrodes and finally to cells (pouch, cylindrical, or prismatic hard case)

applications due to cost and safety reasons. The predominant cathode material in battery cells for electric vehicles today is the lithium–nickel–manganese–cobalt oxide (NMC) chemistry (a layered oxide structure).

Ten years ago, the material composition was the so-called NMC111 (i.e., equal amounts of nickel, cobalt, and manganese [33% of each]). In the future development, the nickel content was continuously increased to 80% in today's so-called NMC811 material (80% Ni, 10% manganese, and 10% cobalt). The benefit is a substantial increase of the specific capacity of the material from about 150 mAh/g (NMC111) to about 210 mAh/g (NMC811). The drawback is that those high-performance materials are thermally less stable, leading to challenges for lifetime and/or safety.

As shown in Fig. 8.9, the active layers of a cell (multiple electrode and separator layers arranged in a stack or jelly roll) can be integrated in different mechanical cell housings. Those are pouch cells, cylindrical cells, and prismatic hard case cells. Each of those has individual weaknesses and strengths, and those are all used in automotive applications.

Pouch cells: The housing consists of a thin composite foil (polymer with an alumina layer in between). The sealing is done by a lamination process. The advantage is its lightweight and high degree of freedom in realizing different form factors (only cell thickness is limited). The disadvantage is the possible diffusion through the laminate seal and the low mechanical robustness.

Cylindrical cell: The housing is mainly steel but could also be alumina. The integration of a cylindrically wound jelly roll gives the best volumetric energy density. Sealing is done by crimping (risk of diffusion but lower than for a pouch) or laser seal. The advantages are the mechanical robustness and constant shape even when pressure builds up inside the cell. The disadvantage is the limitation of the cell size (production process, thermal management, etc.).

Prismatic hard case cell: The housing is a prismatic alumina can. Sealing is done by laser welding. The advantages are the mechanical robustness and long lifetime, and it can be easily used in highly automated production process to manufacture modules and packs.

The battery cell (i.e., the chemistry used) and the mechanical cell concept is responsible for the electric vehicle's core properties of range, driving performance, and charging time. BMW has focused on the prismatic hard case cell as the building block for its battery architecture. The reasons are the mechanical rigidness, the longevity, and the suitability for high-volume and high-quality production of modules and battery packs. BMW has optimized this type of battery over five generations, and it now successfully powers our present fleet of battery electric vehicles (see Fig. 8.10).

In the sixth generation of BMW eDrive technology utilized in the NEUE KLASSE, significant advancements have been made in the cell format and chemistry. The introduction of the new BMW round cell, purpose-built for the electric architecture of NEUE KLASSE models, allows for a remarkable increase in the range of the highest range model, up to 30% (according to WLTP) (BMW Group, 2022; see Fig. 8.11).

Deviating from the fifth-generation prismatic cells, the sixth-generation BMW round cells differ in an increased nickel content on the cathode side. This allows the cobalt content to be reduced. In addition, a notable increase in the silicon content on the anode side contributes to a significant increase in the volumetric energy density of the cell of more than 20% (BMW Group, 2022).

Fig. 8.10 BMW's Gen5 battery cell, module, and pack architecture

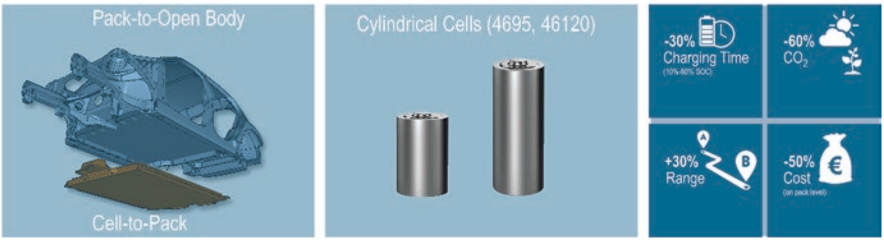


Fig. 8.11 BMW's Gen6 battery cell and pack architecture and the resulting improvements of some relevant KPIs (the reference is the present Gen5 battery pack architecture)

In the NEUE KLASSE, the battery system is critical because, depending on the model, it offers flexible integration into the installation space to save space through a "pack to open body" approach that eliminates the cell module level (BMW Group, 2022; see Fig. 8.11).

Moreover, the NEUE KLASSE's battery, drivetrain, and charging technology will operate at a higher voltage of 800 V. This enhancement optimizes energy supply from direct current high-power charging stations, enabling a much higher charging capacity of up to 500 A. As a result, it will take up to 30% less time to charge the battery from 10% to 80% (BMW Group, 2022; see Fig. 8.11).

The BMW Group places strong emphasis on reducing the carbon footprint and resource consumption throughout the production process, starting from the supply chain. To achieve this, cell manufacturers will use lithium, nickel, and cobalt, incorporating proportions of secondary material, that is, raw materials that already exist in the material loop and are not newly mined. In addition, the BMW Group is committed to using only green electricity from renewable sources for battery cell production. Both of these advances are expected to reduce the carbon footprint associated with producing battery cells by up to 60% compared with the current generation (BMW Group, 2022).

Emphasizing the importance of a circular economy in e-mobility, the BMW Group aims to reuse raw materials. Circular loops significantly diminish the demand for new raw materials, reduce the risk of environmental and social standard violations in the supply chain, and lead to substantially lower CO_2 emissions. The BMW Group's active involvement in all stages of a circular battery economy (see Fig. 8.12) underscores their commitment to this approach. Ultimately, the long-term objective is to adopt fully recyclable battery cells (BMW Group, 2022).

For the new generation of BMW battery cells, the raw materials cobalt and lithium will be sourced from certified mines, ensuring transparency over extraction methods and promoting responsible mining practices. The

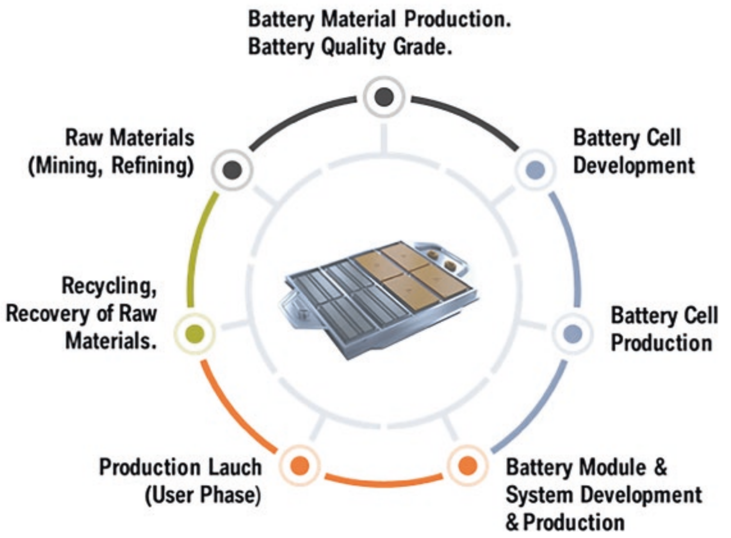


Fig. 8.12 BMW's circular battery value chain

sourcing is carried out either directly through the BMW Group or via the battery cell manufacturer (BMW Group, 2022).

For numerous years, the BMW Group has actively participated in initiatives aimed at establishing standards for responsible raw material extraction and advocating compliance with environmental and social norms through mine certification. This approach not only exemplifies the company's commitment to sustainable business practices but also reduces its dependence on certain resources and suppliers from a technological, geographical, and geopolitical perspective.

For an OEM, the continuous further development of battery systems is mandatory. In the past, the main driver for battery cell development was to increase energy density and hence range of the battery electric vehicle. With the NEUE KLASSE, driving ranges of up to 900 km, depending on the specific vehicle, will be reached. In principle, ranges above 1000 km are technically possible but are, in most cases, neither economical nor ecologically reasonable. It is more important to develop and deliver a product optimized along all relevant KPIs and the needs of the customer. Hence, future battery cell development will diversify and be directed to different areas of the car portfolio (see Fig. 8.13). This will be: a) still the optimization of energy density ("range-optimized"), but equally important, b) the best fit between energy density and cost ("cost-optimized"), and c) the low cost sector for entry models ("low-cost").

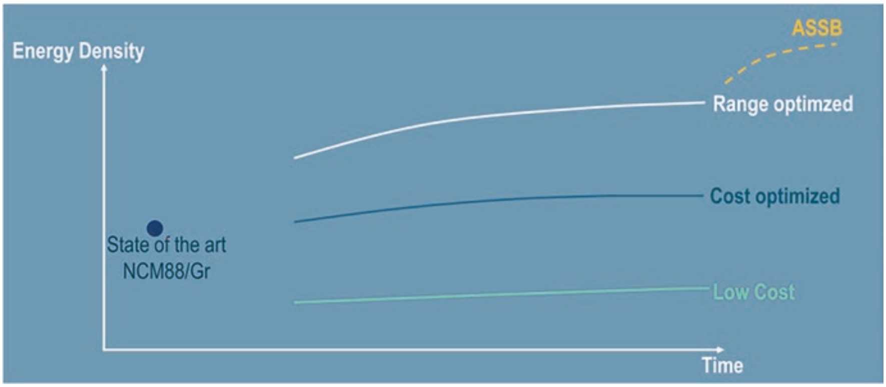


Fig. 8.13 Future diversified development directions for battery cell technology

Since 2008, the BMW Group has been progressively cultivating its expertise in battery cell technology. This expertise has been consolidated at the BMW Group's Battery Cell Competence Centre (BCCC) in Munich since 2019. Encompassing the entire value chain, from R&D to battery cell design and manufacturability, the BCCC serves as a hub for translating cutting-edge battery cell innovations into practical applications swiftly and effectively. To this end, the BMW Group collaborates with a diverse network of approximately 300 partners, including established companies, start-ups, and research institutions. The insights acquired through these collaborations undergo validation at the Cell Manufacturing Competence Centre (CMCC) located near Munich in Parsdorf (BMW Group, 2022).

This competence and continuous effort are needed to ensure that the best possible and most eco-efficient battery technology is offered to the customer.

8.5.2 Eco-Efficient Hydrogen Storage and On-Demand Electrification

Energy from renewable sources enables a climate-friendly supply of electricity, heat, and alternative fuels. However, due to the volatile nature of renewable energy sources, technologies are urgently needed to make renewable energy storable, transportable, and globally tradable to link privileged production sites with centers of consumption. One solution is energy storage in the form of hydrogen, which can be produced by electrolysis of water with renewable energy. If the energy stored this way is needed again, the hydrogen can be used to generate electric energy in a fuel cell, with water vapor as the only additional product. In this way, a CO_2-free energy system can be established.

In the future of defossilized and fully emission-free energy systems, hydrogen technologies will play a very important role. They will provide solutions for applications where battery technologies cannot be used for reasons of cost and practicality. This applies, in particular, to the following areas:

1. Applications where hydrogen is not needed as an energy carrier, but as a "green" reduction equivalent (e.g., the steel industry) or as a reactant for chemical reactions (e.g., for the valorization of CO_2, biomass, or polymer waste).
2. Applications where the amounts of energy stored and transported are exceptionally high and where the number of loading cycles per year is small (typically <20). Examples include the seasonal storage of large amounts of electrical power and the global logistics of low-cost, green energy from global high-yield solar and wind locations for use in industrialized regions with high consumption.
3. Applications in the field of zero-emission, heavy-duty, and long-range vehicles (e.g., for the propulsion of sea ships and river barges, trains, trucks, coaches, and commercial vehicles in the agricultural, forestry, and mining sectors), but also for long-range passenger cars.

One challenge, however, is that elemental hydrogen (H_2) has only a very low energy density at ambient conditions. For storage and transport, hydrogen is therefore stored as a gas under high pressures of up to 700 bar or liquefied at temperatures below minus 250 °C (Preuster et al., 2017). Concerning the transportation of hydrogen, leveraging established fossil fuel infrastructure—specifically, natural gas pipelines—offers noticeable advantages. Utilizing existing infrastructure proves to be more cost-effective and resource-efficient (U.S. Department of Energy, 2023). However, while blending hydrogen into natural gas to transport a gas mixture is comparatively feasible for modest of proportions of hydrogen, converting the gas grid to distribute only hydrogen presents more complex technical, legal, and policy-based challenges (Jayanti, 2022). Furthermore, on an international scale, hydrogen transportation approaches that rely on molecular hydrogen demand the construction of new, considerably expensive infrastructure. Given this context, researchers are exploring alternative methods for hydrogen transportation that extend beyond merely repurposing existing pipelines. Current research and development work at FAU is therefore aimed at establishing innovative hydrogen storage and logistics approaches that are highly compatible with the existing infrastructure for the currently utilized fuels. This infrastructure compatibility offers the chance for a much faster introduction of hydrogen-based clean energy technologies on a system-relevant and global scale.

To realize this compatibility with existing energy infrastructures, the elemental gaseous hydrogen is bound to a carrier molecule in a heat-producing hydrogenation reaction. This creates a hydrogen-rich form of the storage system, the loaded storage compound, which can be easily stored and transported in a liquid or liquefied form. On demand, elemental hydrogen can be released from the charged storage compound in a reverse, heat-consuming dehydrogenation reaction. In this process, the discharged storage material is formed again and can be used for another hydrogen storage cycle. Reaction accelerators, the so-called catalysts, play a decisive role in the described storage and release reactions. They accelerate the rates of reaction and ensure that the desired hydrogenation and dehydrogenation reactions take place with the highest possible selectivity.

A technically very promising example of this approach is the so-called liquid organic hydrogen carrier (LOHC) technology, in which molecular hydrogen is reversibly bound to an aromatic liquid compound (Preuster et al., 2017). Research contributions of the FAU in the last decade have shown that the aromatic compound benzyltoluene is particularly suitable as hydrogen-lean storage compound (Jorschick et al., 2017; Rüde et al., 2022). Benzyltoluene is a readily available industrial product and has been applied since the 1960s as heat transfer oil. Many properties of the compound are known and very well suitable for its application in hydrogen storage, such as its high thermal stability and the high intrinsic safety of the compound. Based on this LOHC system, FAU researchers have developed a hydrogen storage and transport technology that has been commercialized in the meantime by the FAU spin-off Hydrogenious LOHC Technologies GmbH (www.hydrogenious.net). Since its foundation in 2013, Hydrogenious has developed into a global technology leader for hydrogen storage using LOHC technologies and today has 200 employees.

Interesting alternatives in the field of chemical hydrogen storage include the reversible chemical binding of hydrogen to the gases CO_2 or N_2, which also leads to liquid (methanol and diesel) (Artz et al., 2018) or liquefiable (ammonia and dimethyl ether) (Schüth et al., 2012) hydrogen-rich storage compounds. These compounds can be split on demand to produce hydrogen or used directly as chemicals or as climate-neutral combustion fuels (see Fig. 8.14).

An important difference between these CO_2/N_2 concepts and the LOHC technology is that LOHC-released hydrogen is of sufficient quality for re-electrification in a fuel cell after condensation of the liquid carrier. By contrast, splitting ammonia, methanol, or dimethyl ether for hydrogen production

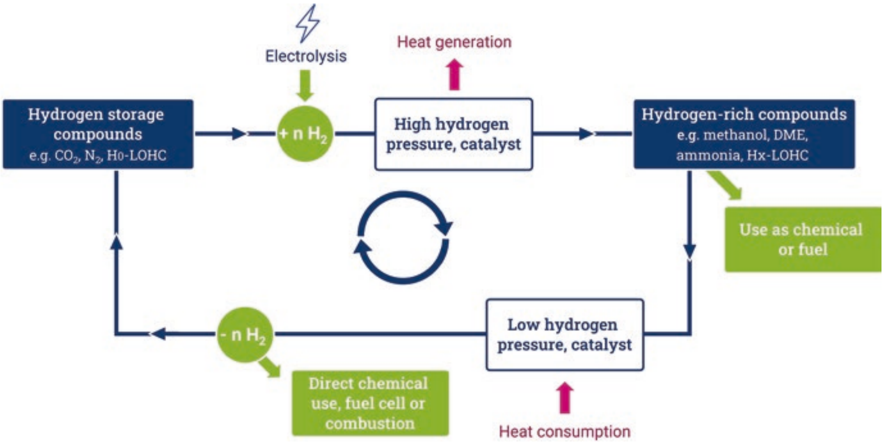


Fig. 8.14 Illustration of the working principle of chemical hydrogen storage

leads to gas mixtures of hydrogen and nitrogen or carbon dioxide, respectively. These mixtures have to be separated to obtain pure hydrogen for fuel cell operation. While the LOHC carrier compounds are transported in the hydrogen-rich state from the energy-rich location to the energy consumer and in the hydrogen-lean state back for recharging, the equivalent storage cycle is typically closed for CO_2- or N_2-based hydrogen storage technologies via the atmosphere. At the energy-rich location, CO_2 or N_2 is extracted from the atmosphere, and the same compounds are released to the atmosphere after hydrogen splitting and separation at the energy consumption site.

Overall, the technologies for chemical energy storage, and for the LOHC technology in particular, offer clear advantages over batteries and physical storage of elemental hydrogen if the stationary energy storage of large amounts of energy, global energy transport, and emission-free heavy-duty mobility are the focus. Chemical hydrogen storage can be realized at ambient temperature and ambient or low pressure to provide very high energy densities. Since the loaded storage material can be easily handled like today's fuel, the existing infrastructure for liquid energy carriers (tankers, tank wagons, and tank farms), which is accepted by the population and has proven itself over many decades, can be further used. There is no need to build expensive new supply infrastructure, nor does the hydrogen require complex cooling or compression. Most interestingly, these chemical hydrogen storage technologies are exportable and can also be used in countries whose gas and electricity distribution infrastructure has so far been poorly developed (Hank et al., 2020).

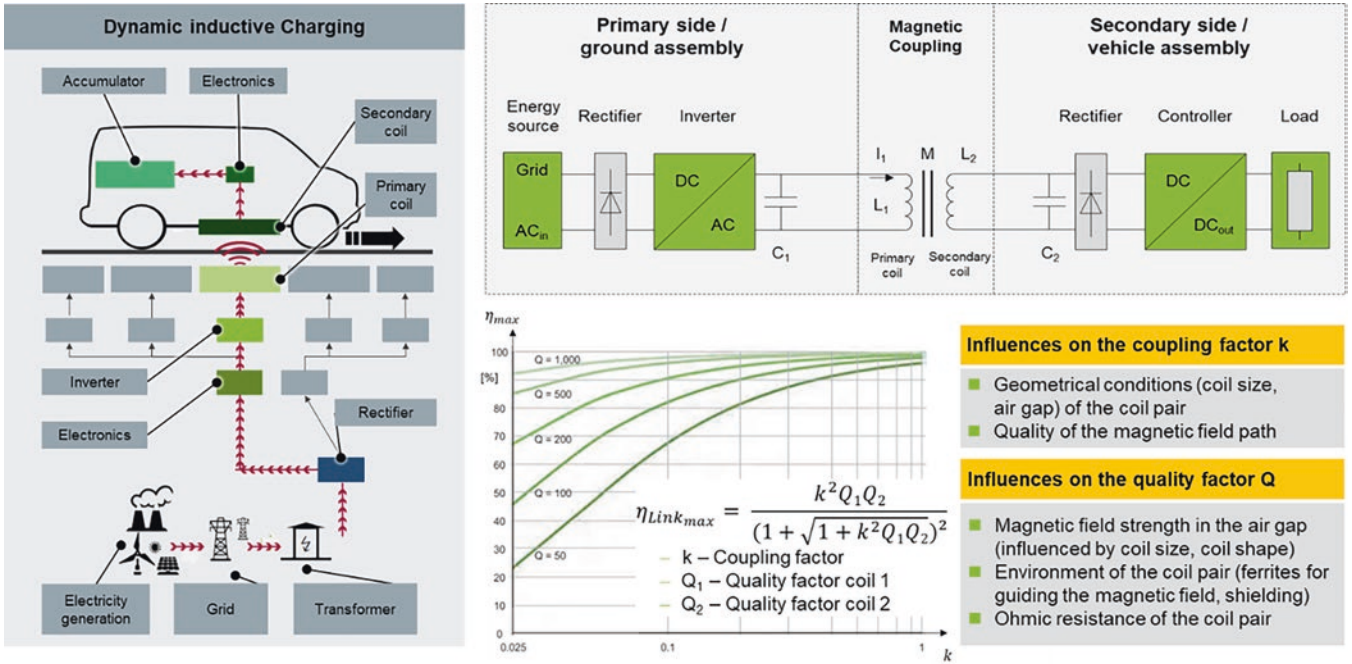
8.5.3 Eco-Efficient Electricity Distribution via an Electrified Road Infrastructure

The glaring disadvantage of the limited storage capacity and charging capacity of batteries cannot be overcome in the short term. Another major challenge at present is the expansion of the charging infrastructure. According to statistics from the German Federal Network Agency, there were 63,806 normal charging points and 12,755 fast charging points in Germany as of December 01, 2022 (Bundesnetzagentur, 2023). The German government plans to increase this number to 1 million publicly accessible charging points by 2030 (Bundesministerium für Digitales und Verkehr [BMDV], 2022). The European Union plans to install one charging station every 60 km along major traffic routes (European Parliament, 2022). The deployment of bidirectional charging and smart grids will create further synergies.

Other technologies can complement this strategy. For example, instead of storing energy in massive batteries and carrying them in the car, electric energy can be transferred directly from electrified roads to parked and even moving electric cars. Inductive power transfer (IPT) automatically starts the charging process when the vehicle is parked over a charging coil. By installing this technology on long-distance roads, the energy needed to drive can be provided continuously, the concentrated grid load caused by ultra-fast charging is reduced, and the size of the batteries can be significantly reduced. As a result, electric cars can become lighter and less expensive, and even heavy trucks can be driven electrically, efficiently, and with zero emissions for an unlimited driving range without additional recharging. Conversely, by eliminating the need to recharge at rest stops, the investment requirement for the immensely expensive fast-charging columns is decreased, the space required for charging cars is reduced, and travelers no longer waste time recharging their batteries on long-distance trips.

Again, after BMW introduced the i3 as the first purpose-designed electric car in Germany, with the plug-in-hybrid 530e, BMW was the first car company to bring wireless power transfer to the market in series production.

The primary coils (see Fig. 8.15), consisting of concentrically wound copper strands, are installed under the road surface in parking lots or on roads at intervals of about 1 m. A magnetic field pulsed at 85 kHz excites an electric voltage in the secondary coils, which are mounted on the underbody of the vehicles. More than 20 kW of power can be transmitted per coil, which is sufficient even at high speeds and under normal conditions for propulsion and simultaneous battery charging. Higher power requirements, such as for



$$\eta_{Link_{max}} = \frac{k^2 Q_1 Q_2}{(1+\sqrt{1+k^2 Q_1 Q_2})^2}$$

- k – Coupling factor
- Q_1 – Quality factor coil 1
- Q_2 – Quality factor coil 2

Influences on the coupling factor k

- Geometrical conditions (coil size, air gap) of the coil pair
- Quality of the magnetic field path

Influences on the quality factor Q

- Magnetic field strength in the air gap (influenced by coil size, coil shape)
- Environment of the coil pair (ferrites for guiding the magnetic field, shielding)
- Ohmic resistance of the coil pair

Fig. 8.15 Inductive charging is based on resonant magnetic flux coupling (own illustration based on Loisel et al. (2014))

trucks and buses, can be met by installing multiple secondary coils. With a precisely tuned oscillating circuit and excellent primary and secondary coil qualities, energy transfer efficiencies of over 90% can be achieved, even surpassing the efficiency of previous high-performance conductive energy transfers, since the additional electrochemical energy conversions in and out of the battery can be eliminated.

Since the magnetic fields of the primary coils are basically harmless to living beings and are only activated when a secondary coil system is coupled, the road traffic infrastructure can be electrified without hesitation. However, it will be necessary to educate the public in order to dispel any reservations they may have. The automatic identification of vehicles in the energy system, comparable to the registration of a cell phone in the mobile network, makes the payment process more convenient. The permanent connection of electric vehicles to the smart grid while parking and driving enables the use of vehicle batteries for an effective stabilization of the energy grid (vehicle-to-grid). Even if only half of all German cars were to be converted to electric drives, about one terawatt-hour (TWh) of storage capacity would be available (Loisel et al., 2014). (This is equivalent to about 25 times the capacity of all of Germany's hydroelectric storage power plants.) The introduction of this technology will, of course, require significant investment to retrofit existing infrastructure and expand the electrified road network. The additional infrastructure costs for electrified roads are estimated to be about €1 million per road kilometer (KTH and QiE, 2019).

Compared with other technologies, large-scale inductive charging is still a relatively nascent field. It brings to the fore fascinating research questions pertaining to its potential applications and development. Given the need for technology openness to accommodate various use scenarios, exploring these research avenues can help assess both the technological viability and economic feasibility of this charging method and whether it could complement other charging technologies in the future.

8.6 Conclusion

The mobility sector is currently in a state of uncertainty. Many market players are facing challenges due to technological change, increasing regulation, changing customer behavior, and the emergence of new competitors. Established technologies that have dominated for many years are losing importance and are being replaced by alternative technologies. The most obvious change in the powertrain is the ongoing replacement of the internal combustion engine and the substitution of fossil fuels. This major technological change is necessary to enable a completely emission-free future in the context of climate change, but is also motivated by environmental and health protection. Accordingly, there are strong interactions with the megatrends of decarbonization and sustainability.

The evolution is sequential. Bridging technologies such as hybridization facilitate the transition, while other technologies compete directly with each other as long-term solutions. At the same time, complements are possible for different applications and sectors, such as battery electric mobility and hydrogen as the fuel of the future. It can be assumed that battery electric vehicles will form the backbone of emission-free individual transportation in the future. Regeneratively produced hydrogen, which can be used in fuel cells and internal combustion engines, can provide a complementary solution. Potential applications include long-distance, heavy-duty, or off-highway transportation. In any case, there is a close interaction between the drive technology and the associated energy ecosystem. Renewably generated electricity and hydrogen must be available in sufficient quantities and at attractive economic conditions. In addition, distribution and convenience for the end user must be ensured. This requires a charging and refueling infrastructure that is as capable as the current one for fossil fuels. The European Union's targets of charging points every 60 km and hydrogen refueling stations at least every 200 km along major transport routes and in every city are a step in the right direction. The technology of inductive charging while driving might be another attractive option. In any case, massive investment in infrastructure is essential.

Other automotive megatrends include connectivity, autonomous driving, and mobility as a service (Gall & Sieper, 2021). These developments, which can be summarized under the term ACES, are mostly not directly related to the drive technology used, but benefit from the increasing electrification and digitization of vehicles. As a result, there is the potential to increase safety and comfort while reducing the environmental footprint. At the same time, the technological advances are having a major impact on the OEMs' and suppliers' businesses. Companies that are unable to respond to these developments and uncertainties will face major problems. However, this challenge can also be seen as an opportunity. New markets, products, and business areas are emerging. At the same time, the general public benefits significantly from sustainability, zero emissions, and increased safety.

So how can technologies for future contribute to sustainability?—We would like to highlight five takeaways from this chapter that invite further discussion:

1. The car of the future will be ACES—autonomous, connected, electric, and shared. Each of these characteristics has the potential to promote sustainability if well integrated.
2. As each technology has specific advantages and limitations, the transition to zero-emission mobility will not be based on one technology, but on a mix of technologies that can drive decarbonization across different use cases and contexts. Guided by clear decarbonization targets, technology openness can accelerate learning, experimentation, and flexibility.
3. Hydrogen solutions can be a solution to address the shortcomings of a pure electric vehicle. By reaping its advantages in terms of international energy flows, energy storage, range, and charging infrastructure, it can be an important complement to electromobility.
4. Zero-emission drivetrain technologies require an enabling energy ecosystem that includes not only sufficient renewable energy generation, but also the necessary charging infrastructure. In addition to electric charging stations, innovations in this charging ecosystem can include LOHC-based hydrogen transport and hydrogen delivery at existing gas stations as well as innovative forms of inductive on-road power transfer with the potential to drastically reshape current electric mobility.
5. Implementing technologies for the future requires not only engineering knowledge, but also the right mindset and the ability to partner with other stakeholders. In addition, market-based diffusion of green technologies requires successful business models. From a business model perspective, the system integration of technologies into viable solutions is more important than technologies alone. The implementation of such system integrations benefits from partnerships with others.

Technologies for the future are needed to disrupt the fossil-fuel-based status quo and to develop the products and value chains for zero-emission mobility. This chapter has thus concluded our discussion of the different individual steps on the Road to Net Zero. At the same time, it has shown that technology is related to strategy, products, value chains, and much more. Emphasizing this interplay between the different contributions of this book, the following and final chapter (Chap. 9) *The Road To Net Zero and Beyond* weaves together important threads of our previous discussions and concludes this book with a look into the future of collaborations that can drive the sustainability transformation.

References

AUDI AG (Ed.) (2019). Audi e-tron Bauteile E-Antrieb (Animation). Retrieved July 09, 2023, from https://www.audi-mediacenter.com/de/videos/video/audi-e-tron-bauteile-e-antrieb-animation-4846

Artz, J., Müller, T. E., Thenert, K., Kleinekorte, J., Meys, R., Sternberg, A., Bardow, A., & Leitner, W. (2018). Sustainable conversion of carbon dioxide: An integrated review of catalysis and life cycle assessment. *Chemical Reviews, 118*(2), 434–504. https://doi.org/10.1021/acs.chemrev.7b00435

Association des Constructeurs Européens d'Automobiles. (2022). Electric Vehicles: tax benefits & purchase incentives: In the 27 member states of the European Union (2022). Retrieved June 26, 2023, from https://www.acea.auto/files/Electric-Vehicles-Tax-Benefits-Purchase-Incentives-2022.pdf

Barretto, L. (2022). *Formula 1 on course to deliver 100% sustainable fuels for 2026*. Formula One World Championship Limited. Retrieved June 26, 2023, from https://www.formula1.com/en/latest/article.formula-1-on-course-to-deliver-100-sustainable-fuels-for-2026.1szcnS0ehW3I0HJeelwPam.html

Blois, M. (2022, June 23). Umicore wants to build the world's largest battery recycling plant. Chemical & Engineering News (C&EN). Retrieved June 26, 2023, from https://cen.acs.org/environment/recycling/Umicore-wants-build-worlds-largest/100/i23

BMW AG (Ed.) (2020). BMW Gen5 eDrive. Retrieved July 09, 2023, from https://www.press.bmwgroup.com/deutschland/photo/detail/P90392490/bmw-gen5-edrive

BMW AG (Ed.) (2022). Brennstoffzellsystem. Retrieved July 09, 2023, from https://mediapool.bmwgroup.com/download/edown/pressclub/publicq?dokNo=P90476503&attachment=1&actEvent=image

BMW Group. (2022, September 09). *More performance, CO2-reduced production, significantly lower costs: BMW group to use innovative round BMW battery cells in NEUE KLASSE from 2025* [Press release]. München. Retrieved July 20, 2023, from: https://www.press.bmwgroup.com/global/article/detail/T0403470EN/more-performance-co2-reduced-production-significantly-lower-costs:-bmw-group-to-use-innovative-round-bmw-battery-cells-in-neue-klasse-from-2025?language=en

Budde-Meiwes, H., Drillkens, J., Lunz, B., Muennix, J., Rothgang, S., Kowal, J., & Sauer, D. U. (2013). A review of current automotive battery technology and future prospects. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 227*(5), 761–776. https://doi.org/10.1177/0954407013485567

Bundesministerium für Digitales und Verkehr (BMDV). (2022). Masterplan Ladeinfrastruktur II der Bundesregierung. Retrieved June 26, 2023, from https://

bmdv.bund.de/SharedDocs/DE/Anlage/G/masterplan-ladeinfrastruktur-2.pdf?__blob=publicationFile

Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz (BMUV). (2021, September 29). Förderung der Elektromobilität durch die Bundesregierung. Retrieved June 26, 2023, from https://www.bmuv.de/themen/luft-laerm-mobilitaet/verkehr/elektromobilitaet/foerderung

Bundesministerium für Wirtschaft und Klimaschutz (BMWK). (2023). *Electric mobility in Germany*. Retrieved June 26, 2023, from https://www.bmwk.de/Redaktion/EN/Dossier/electric-mobility.html

Bundesnetzagentur. (2023, February 2). Elektromobilität: Öffentliche Ladeinfrastruktur. Retrieved June 26, 2023, from https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/E-Mobilitaet/start.html

Doppelbauer, M. (2020). *Grundlagen der Elektromobilität*. Springer Vieweg Wiesbaden. https://doi.org/10.1007/978-3-658-29730-5

Dr. Ing. h.c.F. Porsche AG (Ed.) (2021). Hochspannung - Porsche-Elektromotoren erklärt. Retrieved July 09, 2023, from https://newsroom.porsche.com/de/2021/innovation/porsche-elektromotoren%2D%2Dtaycan-hochspannung-christophorus-398-23885.html

European Environment Agency. (2019, December 11). Cumulative global fleet of battery electric vehicles (BEV) and plug-in hybrid electric vehicles (PHEV) in different parts of the world. Retrieved June 26, 2023, from https://www.eea.europa.eu/data-and-maps/figures/cumulative-global-fleet-of-battery

European Federation for Transport and Environment (Ed.). (2017, July 25). *Renewable electricity is a must to decarbonise land freight transport*. https://www.transportenvironment.org/discover/renewable-electricity-must-decarbonise-land-freight-transport/

European Parliament. (2022). Europaabgeordnete fordern Ladestationen für E-autos alle 60 km. Retrieved June 26, 2023, from https://www.europarl.europa.eu/news/de/press-room/20221014IPR43206/europaabgeordnete-fordern-ladestationen-fur-e-autos-alle-60-km

Gall, C., & Sieper, J. (2021, August 4). Wie Unternehmen sich auf die Mobilität der Zukunft vorbereiten können. Retrieved June 26, 2023, from https://www.ey.com/de_de/automotive-transportation/zukunftstrends-der-automobilindustrie-im-ueberblick

Hank, C., Sternberg, A., Köppel, N., Holst, M., Smolinka, T., Schaadt, A., Hebling, C., & Henning, H.-M. (2020). Energy efficiency and economic assessment of imported energy carriers based on renewable electricity. Sustainable Energy & Fuels, 4(5), 2256–2273. https://doi.org/https://doi.org/10.1039/D0SE00067A

International Energy Agency. (2022). *Global energy-related CO2 emissions by sector*. Retrieved June 26, 2023, from https://www.iea.org/data-and-statistics/charts/global-energy-related-co2-emissions-by-sector

International Energy Agency. (2023). *Transport: Improving the sustainability of passenger and freight transport*. Retrieved June 26, 2023, from https://www.iea.org/topics/transport

Jayanti, S. E.-P. (2022). Repurposing pipelines for hydrogen: Legal and policy considerations. *Energy Reports, 8*(16), 815–820. https://doi.org/10.1016/j.egyr.2022.11.063

Jorschick, H., Preuster, P., Dürr, S., Seidel, A., Müller, K., Bösmann, A., & Wasserscheid, P. (2017). Hydrogen storage using a hot pressure swing reactor. *Energy & Environmental Science, 10*(7), 1652–1659. https://doi.org/10.1039/C7EE00476A

Kapoor, R., & Klueter, T. (2021). Unbundling and managing uncertainty surrounding emerging technologies. *Strategy Science, 6*(1), 62–74. https://doi.org/10.1287/stsc.2020.0118

Kaul, A., Hagedorn, M., Hartmann, S., Heilert, D., Harter, C., Olschewski, I., Eckstein, L., Baum, M., Henzelmann, T., & Schlick, T. (2019). Automobile Wertschöpfung 2030/2050: Studie im Auftrag des Bundesministeriums für Wirtschaft und Energie. IPE Institut für Politikevaluation GmbH; fka GmbH; Roland Berger GmbH. Retrieved June 26, 2023, from https://www.bmwk.de/Redaktion/DE/Publikationen/Studien/automobile-wertschoepfung-2030-2050.pdf?__blob=publicationFile&v=16

KTH, & QiE, P. (2019). Detailed LCA/LCCA assessment of environment and cost impact of E-roads (Road Infrastructure Impact & Solutions). FABRIC. http://www.fabric-project.eu/www.fabric-project.eu/images/Deliverables/FABRIC_D53_4-LCA_eRoads_Final.pdf

Loisel, R., Pasaoglu, G., & Thiel, C. (2014). Large-scale deployment of electric vehicles in Germany by 2030: An analysis of grid-to-vehicle and vehicle-to-grid concepts. *Energy Policy, 65*, 432–443. https://doi.org/10.1016/j.enpol.2013.10.029

Parizet, E., Janssens, K., Poveda-Martinez, P., Pereira, A., Lorenski, J., & Ramis-Soriano, J. (2016). NVH analysis techniques for design and optimization of hybrid and electric vehicles. In N. Campillo-Davo & A. Rassili (Eds.), *NVH analysis techniques for design and optimization of hybrid and electric vehicles* (pp. 313–355). Shaker Verlag.

Preuster, P., Alekseev, A., & Wasserscheid, P. (2017). Hydrogen storage technologies for future energy systems. *Annual Review of Chemical and Biomolecular Engineering, 8*, 445–471. https://doi.org/10.1146/annurev-chembioeng-060816-101334

Preuster, P., Papp, C., & Wasserscheid, P. (2017). Liquid organic hydrogen carriers (LOHCs): Toward a hydrogen-free hydrogen economy. *Accounts of Chemical Research, 50*(1), 74–85. https://doi.org/10.1021/acs.accounts.6b00474

Reitz, R. D., Ogawa, H., Payri, R., Fansler, T., Kokjohn, S., Moriyoshi, Y., Agarwal, A. K., Arcoumanis, D., Assanis, D., Bae, C., Boulouchos, K., Canakci, M., Curran, S., Denbratt, I., Gavaises, M., Guenthner, M., Hasse, C., Huang, Z., Ishiyama, T., et al. (2020). IJER editorial: The future of the internal combustion engine. *International Journal of Engine Research, 21*(1), 3–10. https://doi.org/10.1177/1468087419877990

Rüde, T., Dürr, S., Preuster, P., Wolf, M., & Wasserscheid, P. (2022). Benzyltoluene/perhydro benzyltoluene – Pushing the performance limits of pure hydrocarbon liquid organic hydrogen carrier (LOHC) systems. *Sustainable Energy & Fuels, 6*(6), 1541–1553. https://doi.org/10.1039/D1SE01767E

Sartbaeva, A., Kuznetsov, V. L., Wells, S. A., & Edwards, P. P. (2008). Hydrogen nexus in a sustainable energy future. *Energy & Environmental Science, 1*(1), 79. https://doi.org/10.1039/b810104n

Schaeffler Technologies AG (Ed.) (2014). *E-Wheel Drive*. Retrieved July 09, 2023, from https://www.schaeffler.de/de/news_medien/mediathek/downloadcenter-detail-page.jsp?id=37159745

Schaeffler Technologies AG (Ed.) (2023). Technologien für hybride und rein elektrische Antriebssysteme. Retrieved July 09, 2023, from https://www.schaeffler.de/de/produkte-und-loesungen/automotive-oem/hybride_elektrische_antriebssysteme/

Schüth, F., Palkovits, R., Schlögl, R., & Su, D. S. (2012). Ammonia as a possible element in an energy infrastructure: Catalysts for ammonia decomposition. *Energy & Environmental Science, 5*(4), 6278–6289. https://doi.org/10.1039/C2EE02865D

Schwarzer, C. (2019, March 21). Bremsenergierückgewinnung und ihr Wirkungsgrad: Wer bremst, gewinnt. heise online. Retrieved June 26, 2023, from https://www.heise.de/autos/artikel/Bremsenergierueckgewinnung-und-ihr-Wirkungsgrad-4340576.html

Specht, M. (2020, January 23). Elektroautos sind die besseren Gebrauchtwagen: Weniger Verschleiß, längere Lebensdauer. Der Spiegel. Retrieved June 26, 2023, from https://www.spiegel.de/auto/fahrkultur/elektroautos-sind-die-besseren-gebrauchtwagen-weniger-verschleiss-laengere-lebensdauer-a-89f4d920-ed88-4c9e-9747-310f685f418a

Tschöke, H., Gutzmer, P., & Pfund, T. (2019). *Elektrifizierung des Antriebsstrangs: Grundlagen - vom Mikro-Hybrid zum vollelektrischen Antrieb*. Springer Vieweg Berlin Heidelberg. https://doi.org/10.1007/978-3-662-60356-7

Umweltbundesamt. (2022, March 16). Marktdaten: Mobilität. Retrieved June 26, 2023, from https://www.umweltbundesamt.de/daten/private-haushalte-konsum/konsum-produkte/gruene-produkte-marktzahlen/marktdaten-bereich-mobilitaet#car-sharing

U.S. Department of Energy (Ed.) (2023). *Hydrogen Pipelines. Hydrogen and fuel cell technologies office*. Retrieved, July 09, 2023, from https://www.energy.gov/eere/fuelcells/hydrogen-pipelines

van Basshuysen, R., & Schäfer, F. (Eds.). (2017). *Handbuch Verbrennungsmotor: Grundlagen, Komponenten, Systeme, Perspektiven* (8th ed.). Springer Vieweg Wiesbaden. https://doi.org/10.1007/978-3-658-10902-8

Verband der Automobilindustrie e. V. (2018). WLTP – neues Testverfahren weltweit am Start: Fragen und Antworten zur Umstellung von NEFZ auf WLTP. Retrieved June 26, 2023, from https://www.vdik.de/wp-content/uploads/2019/09/WLTP_Fragen-und-Antworten-zum-neuen-Testverfahren.pdf

Wang, E. (2021). *The potential of electric vehicles*. Princeton University. Retrieved June 26, 2023, from https://psci.princeton.edu/tips/2021/2/20/the-potential-of-electric-vehicles

Weigelt, M. (2022). Multidimensionale Optionenanalyse alternativer Antriebskonzepte für die individuelle Langstreckenmobilität. In *FAU Studien aus dem Maschinenbau* (Vol. Band 412). FAU University Press. https://doi.org/10.25593/978-3-96147-608-4

Zapf, M., Pengg, H., Bütler, T., Bach, C., & Weindl, C. (2021). *Kosteneffiziente und nachhaltige Automobile: Bewertung der realen Klimabelastung und der Gesamtkosten - Heute und in Zukunft*. Springer Vieweg Wiesbaden. https://doi.org/10.1007/978-3-658-33251-8

ZF Friedrichshafen AG (2017, June 22). *Für Achshybride oder reine E-Fahrzeuge: ZF integriert leistungsstarken elektrischen Antrieb direkt in innovative Hinterachse* [Press Release]. Retrieved July 09, 2023, from https://press.zf.com/press/de/releases/release_2782.html

ZF Friedrichshafen AG (Ed.) (2023). CeTrax – Elektrischer Zentralantrieb. Systemkompetenz für elektrische Sonderfahrzeuge. Retrieved July 09, 2023, from https://www.zf.com/products/de/special_vehicles/products_64419.html