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Identifying technological bottlenecks in nascent green innovation ecosystems

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AFFIDAVIT

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Abstract

Technological innovations are often seen as having the potential to change entire industries for the long term. However, the diffusion of these innovations is often an extremely complex problem, described as a “chicken and egg” causality dilemma. Such innovations often do not emerge individually but are dependent on directly and indirectly connected actors and their contributions. The innovation challenges within these actors are not evenly distributed, which leads to the fact that some contributions are inferior and thus limiting the diffusion of such innovations. Such contributions are called bottlenecks. This work aims to identify and analyze the change of these bottlenecks in battery electric and fuel cell electric vehicles over the period from 2000 to 2020.
In the context of this research project, the concept of "innovation ecosystems" was chosen as the framework for the study, which attempts to explain the interdependencies of the individual actors and their contributions around an innovation with analogies to biological ecosystems. By using this approach, the relevant contributions and their limiting effect on the value proposition to the customer of battery electric and fuel cell vehicles could be detected.

An approach based on secondary data, which were selected with the help of predefined criteria, was chosen as the research design. This secondary data was analyzed and evaluated using the qualitative content analysis method, according to Mayring. In order to increase the quality of the results of the analysis, these results were validated with primary data from three expert interviews.

The research findings show that the bottlenecks of battery electric and fuel cell electric vehicles have changed only to a limited extent during the study period. But the reason why contributions to the value proposition represent a bottleneck has changed in many areas. In addition, new contributions to the value proposition have gained attention in recent years, especially with regard to battery electric vehicles. The innovation ecosystem approach allows bottlenecks to be identified not only on the component level but also on the level of complementary products and services. In both technologies, components and complementary products and services represented bottlenecks throughout the entire study period.

Based on the findings of this study, further research should focus on how the different actors have dealt with the bottlenecks of the two technologies, respectively what measures they have taken to minimize the limiting effect of these bottlenecks on the value proposition to the customer.

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List of Abbreviations

ATZ	*Automobiltechnische Zeitschrift*
BEV	*Battery Electric Vehicle*
CARB	*California Air Resources Board*
CO_2	*Carbon Dioxide*
CPU	*Central Processing Unit*
DFMC	*Direct Methanol Fuel Cell*
EU	*European Union*
FCEV	*Fuel Cell Electric Vehicle*
GDL	*Gas Diffusion Layer*
HVAC	*Heating, Ventilation, and Air Conditioning*
HW	*Hardware*
ICE	*Internal Combustion Engine*
IJoAT	*International Journal of Automotive Technology*
KPI	*Key Performance Indicator*
KSAE	*Korean Society of Automotive Engineers*
MEA	*Membrane Electrode Assembly*
NEV	*New Energy Vehicles*
NiMH	*Nickel-Metal Hydride*
OBC	*On-board Charger*
OEM	*Original Equipment Manufacturer*
OS	*Operating System*
PC	*Personal Computer*
PEMFC	*Proton Exchange Membrane Fuel Cell*
PHEV	*Plug-In Hybrid Electric Vehicle*
PTC	*Positive Temperature Coefficient*
PZEV	*Partial Zero Emission Vehicles*
RQ	*Research Question*
SOFC	*Solid Oxide Fuel Cell*
SSCI	*Social Science Citation Index*
USA	*United States of Amerika*
ZEV	*Zero Emission Vehicle*

1 Introduction

In the 21st century, humanity is facing new challenges, which also significantly impact the automotive industry. The increasing environmental pollution caused by the industrial sector, among other things, and the associated global warming should finally demonstrate to us the necessity to act more sustainably. It is very worrying when we consider that the average temperature has increased by 0.6°C since the beginning of the 20th century, caused by the combustion of fossil raw materials (Martin et al., 2015, p.4). To illustrate the progress of global warming, Figure 1 provides an overview of the increase in the last century.

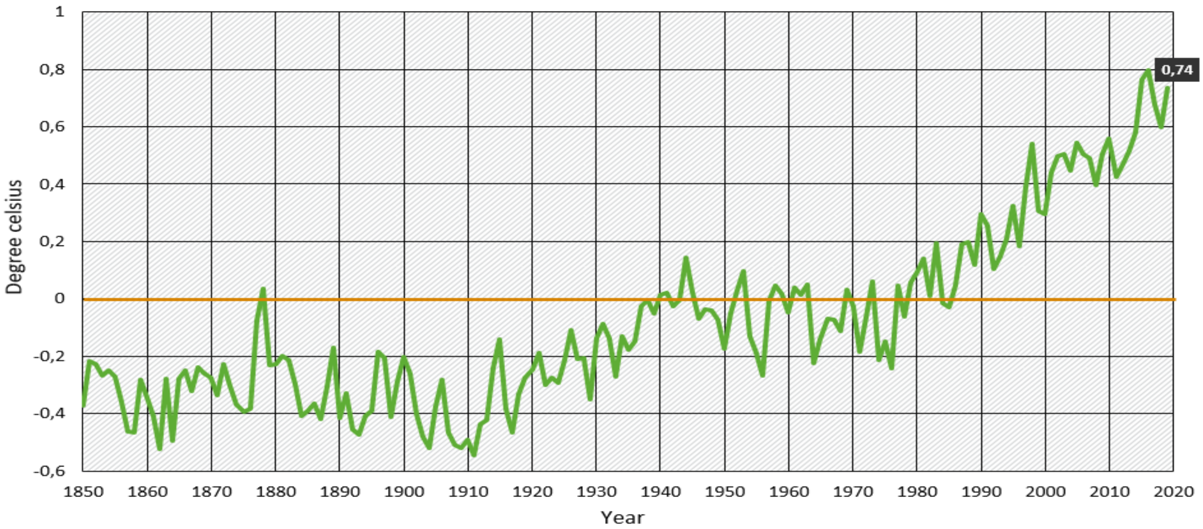

Figure 1: Deviation of global air temperature from the average 1961 to 1990 (Umwelt Bundesamt, 2020)

To initiate countermeasures, the first agreement on climate protection, the “Kyoto Protocol”, at the international level was signed in 1997 (Haensgen, 2002, p. 16). This protocol determined that the signatory countries must reduce their greenhouse gas emissions by approx. 5% in the period from 2008 to 2012 compared to the value of 1990 (Haensgen, 2002, p.18ff).

However, the issue regarding this “Kyoto Protocol” was that only a few industrialized countries were obligated to reduce their emissions. To overcome these difficulties, the “Paris Climate Agreement” followed in 2015. This agreement involved 190 countries defining national climate protection targets to limit global warming to below 2°C or, more preferable, below 1.5°C compared to the pre-industrial level. (BMU, 2017)

Since almost a quarter of the global anthropogenic CO_2 emissions (Figure 2) are caused by the transport sector, especially from individual road transport, reducing greenhouse gas emissions in this sector is a precondition to meet the climate targets (Miller and Facanha, 2014).

In the automotive sector, the United States of Amerika (USA), with its California Air Resources Board (CARB) legislation, was a pioneer in reducing exhaust emissions. In 2003, a mandatory Zero-Emission-Vehicle (ZEV) quota was introduced, with the objective to reduce greenhouse gas emissions. ZEVs refer to vehicles that do not have any local emissions, like battery electric vehicles or fuel cell electric vehicles. (Fischer et al., 2020, p. 402)

The first mandatory CO_2 limits in the EU were introduced in 2012, where 65 % of the new annual sold passenger cars were required not to exceed the CO_2 fleet emissions of 130 g/km. This quota was raised to 100% in 2015. In 2020, respectively 2021, this CO_2 fleet emission limit was lowered to 95 g/km. (Fischer et al., 2020, p. 428)

This means that a change in the mindset of the automotive industry is a prerequisite for achieving the corresponding CO_2 goals and consequently the goals of the “Paris Climate Agreement”. While the combustion engine has been undisputed for a very long time through its rapid improvement, the demand for green innovations is now becoming even greater (Dhand and Pullen, 2015a, p. 487). The basic concept behind green innovations is that the product has the potential for a reduced environmental impact over its entire life cycle compared to an existing alternative, and thus, is more ecologically sustainable (Schiederig et al., 2012, p. 181ff).

In the automotive industry, such green innovations are usually called alternative powertrains. These powertrains can either have an internal combustion engine (ICE) that operates with non-fossil fuels, or the powertrains are electrified (Verband der Automobilindustrie, 2009a, p. 4). The two most discussed powertrain topologies in this context are the battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV), whose functional concepts have been in existence for many years.

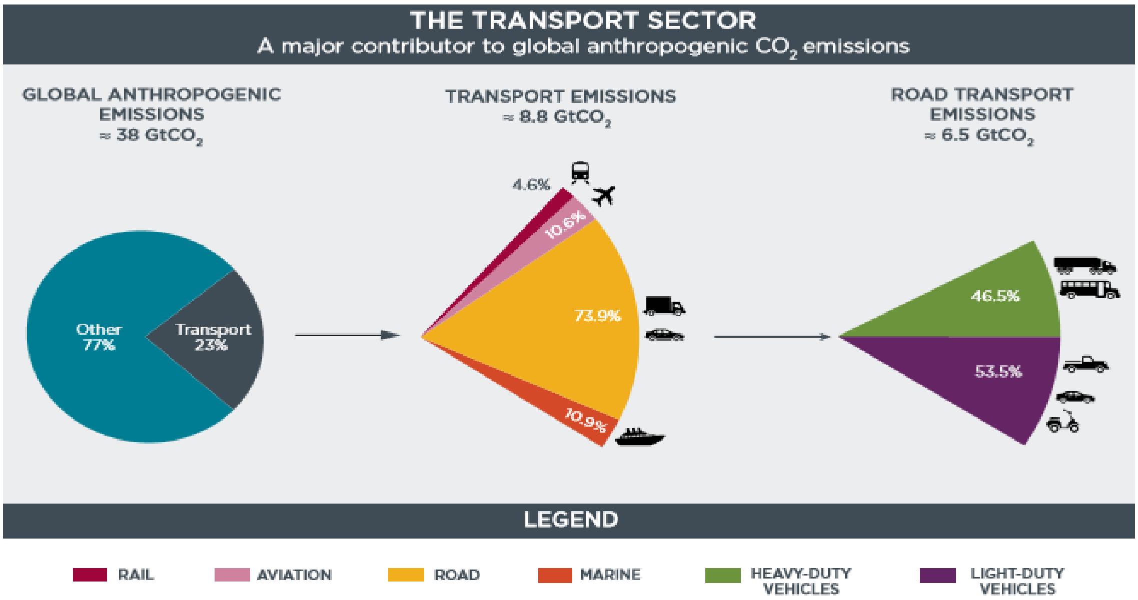

Figure 2: Global anthropogenic CO_2 emissions of different branches (Miller and Facanha, 2014)

The functional principle of the battery electric vehicle dates back to the 19th century, with the first electric car appearing in France in 1881. Approximately at this time, the mobile application of the internal combustion engines was also introduced (Kampker et al., 2013, p. 3f). In comparison to that, the principle of fuel cell application in the automotive sector is relatively young.

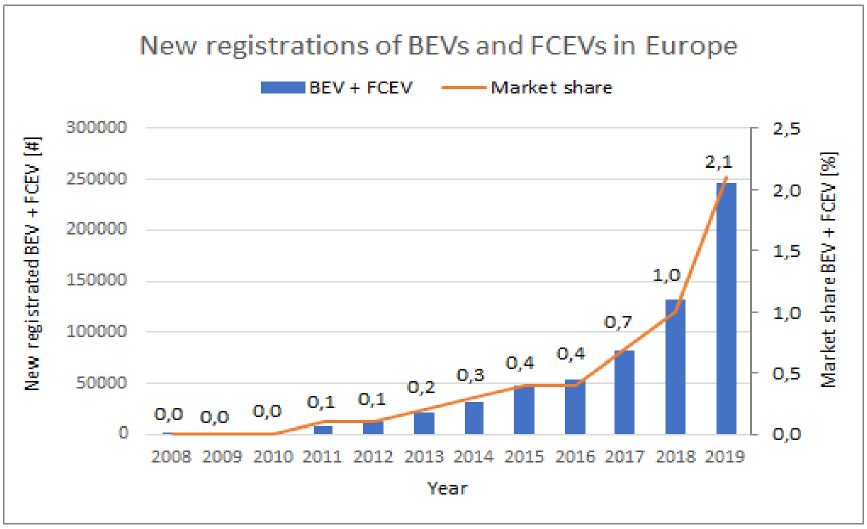

Figure 3: BEV and FCEV registration trend over the last ten years in the EU (European Alternative Fuels Observatory, 2020)

General Motors presented the first fuel cell vehicle in 1966, which operated with an alkaline fuel cell and had an onboard hydrogen and oxygen storage device (Verband der Automobilindustrie, 2009b, p. 5). From that time on, especially Daimler in Europa and some Asian players conducted intensive research in fuel cell technology to get this concept ready for serial production (Mercedes-Benz Museum GmbH, 2019).

As it can be seen, especially battery electric vehicles have a very long history, and yet internal combustion engine vehicles are still the dominant propulsion concept in individual personal transportation. Figure 3 underlines this claim by showing the development of the combined market share of BEVs and FCEVs over the last years, which is still a fraction compared to internal combustion engine vehicles.

1.1 Motivation

In order to find possible reasons why certain technologies have prevailed, whereas others like BEVs and FCEVs still have only a fraction of market share, it is important to understand the powertrain topologies and their components (Fischer and Neunteufel, 2018, p.313).
However, only the knowledge about the functional principle and the limitations of vehicle components is not enough as the limiting factor does not necessarily have to be a component. Innovations such as battery electric vehicles or fuel cell electric vehicles do not emerge individually, but there is a dependency upon an ecosystem of directly or indirectly connected actors and their complementary contributions. This concept is called innovation ecosystem, where the innovation is always at the center of interest. (Jacobides et al., 2018, p. 2256f; Adner and Kapoor, 2010, p. 309)

The problem is that some contributions in the ecosystem, which can either be a component or a complementary service or product, can be inferior due to poor quality, poor performance, low availability, or high cost, and thus limiting the evolution and growth of the entire ecosystem. These components or complements are consequently declared as a bottleneck. (Hannah and Eisenhardt, 2018, p. 3164; Kapoor, 2018, p. 6)

In many cases, green innovations are not driven by the market or its technology but promoted by governmental institutions despite the existence of technological bottlenecks (Geels et al., 2017, p. 464ff). Suppose an innovation, such as a battery electric vehicle, is subsidized by governmental institutions and has significant bottlenecks from a technological standpoint, which are not resolved. In that case, the attractiveness of the innovation for the customer drops significantly when the subsidies are removed. For this reason, it is of enormous importance for the individual actors to identify and solve these bottlenecks (Hannah and Eisenhardt, 2018, p. 3164).

1.2 Objective and Organization of Research

The main objective of this thesis is to identify the bottlenecks in the innovation ecosystems of battery electric and fuel cell electric vehicles. For this reason, it is necessary to get familiar with the term ecosystem in the field of business strategy and understand how bottlenecks can occur in such a setup. The already existing literature on bottleneck identification in such an innovation ecosystem is scarce. However, some pioneers such as Adner and Kapoor (2010) have already addressed this topic. From this literature, a method should be selected, using secondary longitudinal data from different sources to identify the bottlenecks. Obviously, it is a prerequisite for identifying such bottlenecks to understand the major parts and the functional principle of BEVs and FCEVs. Therefore, a literature review has to be performed. After this, the method will be applied, and the bottlenecks will be identified. The results of this analysis should be validated with primary data from expert interviews. The knowledge of these bottlenecks can provide an explanatory approach to why these two powertrain topologies are still in their infancy and have not yet made it to mass adoption. Figure 4 provides a graphical representation of the thesis procedure.

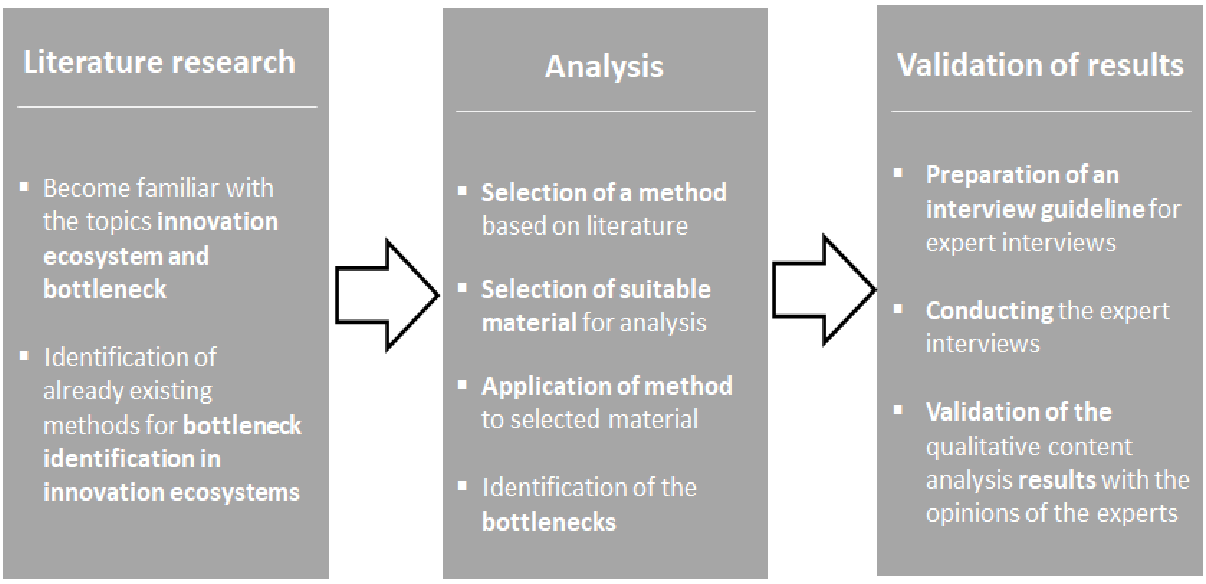

Figure 4: Procedure of the thesis

Therefore, taking the research objectives and research scope into consideration, the research questions (RQ) of this thesis are:

1. *Which methods to identify technological bottlenecks in innovation ecosystems are described in the literature?*
2. *How did the most important technological bottlenecks in the innovation ecosystems of BEVs and FCEVs change from 2000 to 2020?*

1.3 Structure of thesis

This thesis is organized into seven main chapters:

1. Introduction
2. Literature review
3. Research methodology
4. Results of the analysis
5. Validation of the results from the qualitative content analysis
6. Discussion
7. Conclusion
8. Limitations and future research

Chapter one includes the general introduction of the topic, motivation of the study, research objectives, research organization, and the research questions.

A literature review on innovation ecosystem and bottlenecks is provided in chapter 2. This review comprises the review of the innovation ecosystem, the basic definition of value, Porter´s value chain, value systems, different research streams on the ecosystem, and their characteristics. Further, a definition of the term bottleneck is given as input for the empirical part of this thesis.
Additionally, the current state of research of the bottleneck identification in an innovation ecosystem is described, in which five different methods are presented, and the first research question is answered.

Chapter 3 deals with the methodology of the empirical part of this thesis. Therefore, the quality content analysis and all activities, like data collection, deductive and inductive category creation, the iteration steps, and the intercoder-reliability check, are described in detail. Furthermore, the creation of the network of complementarity and the validation of the result with expert interviews are shown.

The empirical findings of the qualitative content analysis performed on secondary data are presented in Chapter 4. First, the results of the battery electric vehicles and then those of the fuel cell electric vehicles are presented.

In chapter 5, the results of the qualitative content analysis are compared and validated with the expert interviews conducted. Chapter 6 is dedicated to discuss the obtained results.

In chapter 7, the thesis is summarized, and the research questions are answered in the form of a conclusion. The final chapter of the thesis focuses on the study's limitations and gives recommendations for future research projects.

2 Literature review

The research in the field of value systems and bottlenecks is of great relevance for this thesis, and therefore the literature review on these topics is a prerequisite. This chapter deals on the one hand with the term value in general, and on the other hand, it presents different types of value systems. Particular attention is paid to the ecosystem-based value system, as this concept includes the research stream of the innovation ecosystem and is crucial for this thesis. Finally, the term bottleneck will be defined, and an insight on how they can emerge will be granted.

2.1 Value and value chain

The term value is often used in different contexts, and the interpretations vary a lot (Marinova et al., 2017, p. 1). In common usage, value refers to the benefit or merit associated to a product or service. Another frequently used definition of value refers to the monetary worth of a special service, product, or social benefit offered on the market. (Ahen, 2015, p. 80; Marinova et al., 2017, p. 1f)
However, since the term value is often used in combination with different processes, finding a general definition in the literature is difficult. Therefore, specific interpretations from different academic disciplines have evolved. As a result, value has acquired a universal meaning. But not only that, if we consider the definition from above, value as a benefit suggests that there is always a beneficiary which can be, for example, a person or a group. Thus, the term becomes relative as it has a specific dependency on the assets or the behavior of these beneficiaries. For this reason, value is, on the one hand, actor-depend, and on the other hand, value is related to the process or situation, the context in which the term is used. (Marinova et al., 2017, p. 2)

At the business level, value is generally conveyed through organizational objectives aimed to create or capture value (Chambers and Patrocínio, 2011, p. 4). Value creation refers to a process of resource utilization that adds value to a product or service, i.e., an actor's attempt to increase the value of its offering. However, only offering a product that adds value to the customer is not enough. The price and cost structure of the product must also allow that a (financial) return can be achieved from the value creation. (Chesbrough et al., 2018, p. 933; Verdin and Tackx, 2015, p. 2)

The research on the process of value creation in a business environment has a long history. Joseph Schumpeter (1934) identified the combination of technologies with existing organizational resources, which lead to new products and production techniques, to be the basis for value creation in a company (Schumpeter, 2003, p. 64ff)[1]. This view was also shared by Edith Penrose (1959), who developed a *"resources approach"* with the consideration of the resources-base of a firm and noted that the value creation is the result of an efficient resources management process in the creation of products and services (Penrose, 1959, p. 217ff). However, the most famous method which deals with the creation of value was published by Michael Porter in 1985. With the definition of a value chain, a new way of thinking about how various primary and secondary activities can contribute to the value creation on the company level was implemented. The concept of this framework can be seen in Figure 5.

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[1] The publication of the book "The theory of economic development" dates back to the year 1934. The source cited from 2003 describes an encyclopedia of Joseph Schumpeter's works.

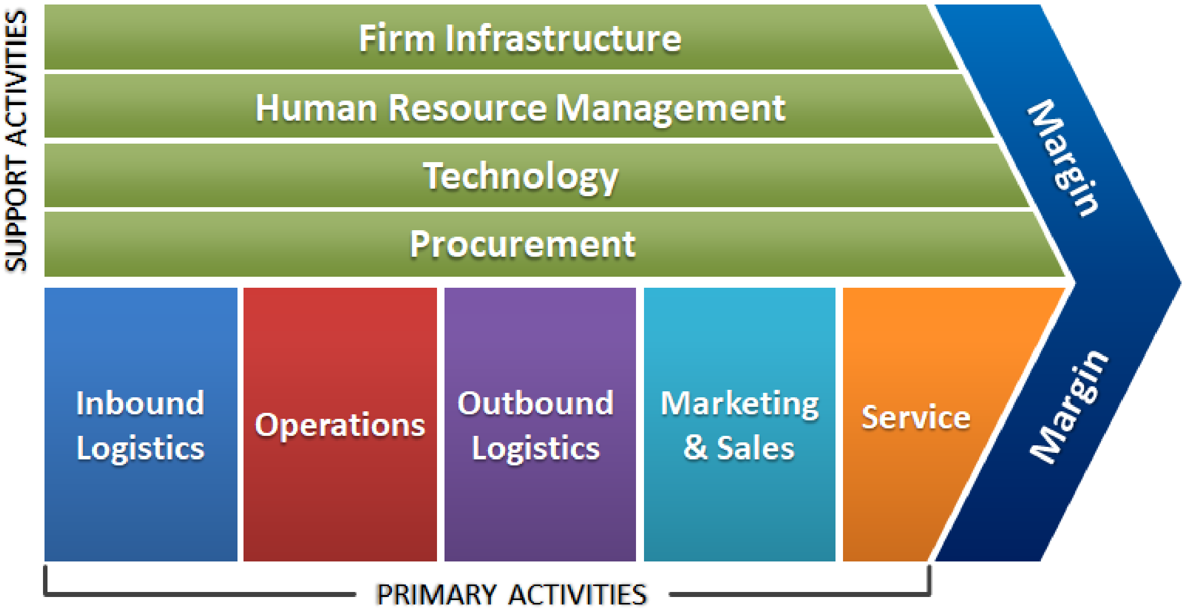

Figure 5: The generic value chain from Michael Porter (Porter, 1998)

The value chain approach divides the company into different activities that contribute to value creation and connect them to a chain. Michael Porter's basic idea behind this concept was to outline that a competitive advantage cannot be detected on a company level but is instead attributable to individual activities. (Porter, 1985, p. 33ff; Müller, 2015, p. 162)

The value activities are all physically and technologically distinct activities performed by the firm and are responsible for making a product valuable to its customers. The generic division of the activities is categorized into two groups, primary and support activities. The first group deals with the physical production of the products or services and the market´s supply, whereas the secondary ones serve as support for the primary activities. (Porter, 1985, p. 39ff; Welge et al., 2007, p. 369 ff)

How a company performs these activities is an indicator of their strategy, the approach how they implement their strategy, and the underlying economics of the activities themselves. In addition to the activities, the value chain also includes the margin and thus displays the created value. Margin is the difference between the total value and the costs to perform these activities and can be measured in various ways. (Porter, 1985, p. 38)

The primary purpose of the value chain is the analysis of each involved activity in order to figure out a competitive advantage. This should be performed on the business unit level (activities in a specific industry). A broader application, for example, on the firm level (firm with multiple business units) or industrial sector, can lead to opacity, and thus important sources of competitive advantage can get lost. For this reason, the value chain of a business unit or a firm is integrated into a larger number of activities, which Michael Porter defines as the value system. (Porter, 1985, p. 34ff)

2.2 Value system

Especially nowadays, due to the increased globalization of the markets, new challenges for companies occur. Consequently, it becomes more and more important to focus not only on a specific business unit of a company because a separate analysis is limited to a linear and unidirectional value creation process. The analysis of the whole value system with the included upstream suppliers and downstream channels and buyers allows to take a more complex look at the matter. (Wirtz, 2020, p. 79).

The structure of Michael Porter's value system network can be seen in Figure 6, where on the upper part of the figure, the value system of a single-industry firm and on the lower part, the framework for a diversified firm is illustrated.

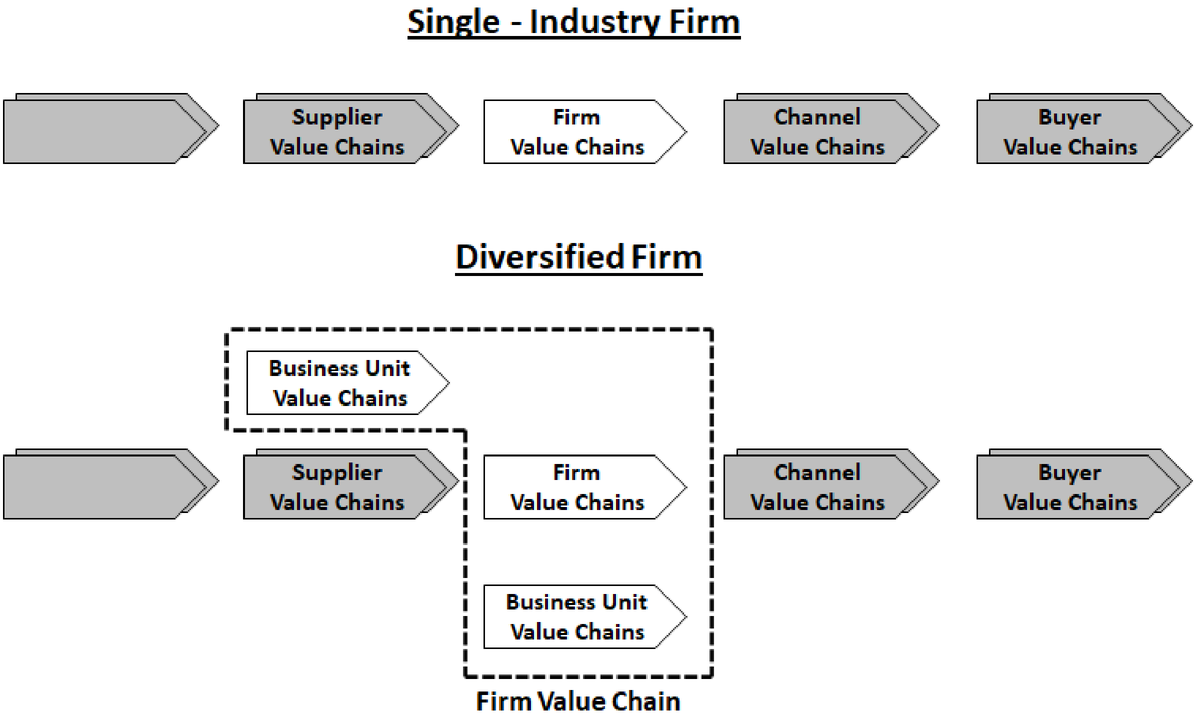

Figure 6: The value system (Porter, 1985, p. 35)

In this approach, the supplier represents the upstream value, which is purchased by the firm and acts as input for its products and, thus, influences its performance. On the downstream value side, many products pass through the value chain of channels that perform activities affecting both the buyer and the company activities. The end product of the firm can be, for example, a component of the buyer's product. To obtain a sustainable competitive advantage, the firm needs to understand the whole value system and not only their own activities. (Porter, 1985, p. 34)

The extension of the value chain to the level of value systems is of particular importance when talking about jointly created value, as value systems make it possible to capture this jointly created value. In this context, it is also essential to consider complementary products, i.e., products that were created in independent value chains and increase the value of the other product. (Wirtz, 2020, p. 80)

The complex relationships of these different value chains in the scope of the value system have a significant impact on the value creation process of a company and will be discussed more in detail later in this chapter. Additionally, the meaning and importance of complementary products or services and their influence on other products will also be outlined later.
In order to give a clear overview of the complexity of value systems and to show how they can be structured, the following three approaches will be discussed in this thesis:

- Hierarchy-based value system
- Market-based value system
- Ecosystem-based value system

2.2.1 Hierarchy-based value system

A "Hierarchy - based value system" is defined as a classical buyer-supplier relationship, where the concept of a system integrator is included as well. The term system integrator refers to integrating external components, capabilities, or knowledge into a firm’s product or service to make them more complex and obtain a competitive advantage on the market. (Jacobides et al., 2018, p. 2260; Hobday et al., 2005, p. 1109)
The final customer and the producer negotiate openly on the market, with the decision to buy a product being based on the customer's requirement specifications. This is called a transactional approach and leads to an arm's length relationship, which is characterized by a short-term orientation and a low level of trust. (He et al., 2011, p. 58; Morsy, 2017, p. 34)
In this hierarchical type of value system, the buyer has no possibility to configure his own product from different components, and therefore, he has to buy a combined offering. (Jacobides et al., 2018, p. 2260)

Taking a look at the supplier tier, which provides the components, e.g., to the system integrator, there can, on the one hand, be a cooperation behavior between various companies to make the components compatible to create value. On the other hand, there can be competition between multiple companies to capture value. While cooperation is mostly the key driver in the development phase of a product, competition often emerges when a product has reached a certain level of maturity in order to increase the market share. (Hannah and Eisenhardt, 2018, p. 3164ff)

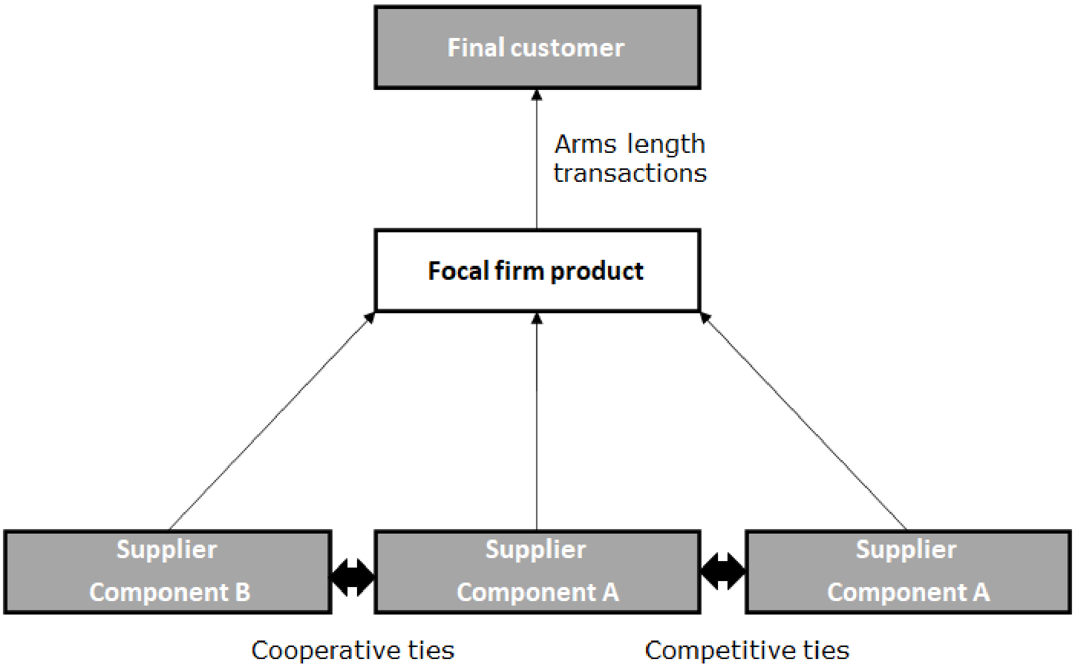

Figure 7: Systematics of a Hierarchy – based value system (Jacobides et al., 2018, p. 2261)

Figure 7 shows an example of what such a “Hierarchy-based value system” could look like including the three levels of operation (supplier, focal firm, final customer) and the different types of relationships in the supplier tier.

2.2.2 Market-based value system

The second type of value system is the “Market – based” one. The big difference to the above described "Hierarchy - based value system" is the absence of a system integrator, which leads to the consequence that the final customer buys separate products from various independent sellers and consumes them either separately or jointly (Hannah and Eisenhardt, 2018, p. 2261; Powell, 1990, p. 300). This means that the competition between various companies occurs on the sales level in this approach, as shown in Figure 8. Markets offer a high degree of flexibility, and no one needs to rely on someone else (Powell, 1990, p. 302). Companies with similar products or at least with products that serve the same purpose are in a competitive relationship with each other. They try to get a competitive advantage on the market, leading in most cases to an increase in their market share. (Crescenzi, 2010, p. 6; Jacobides et al., 2018, p. 2261)

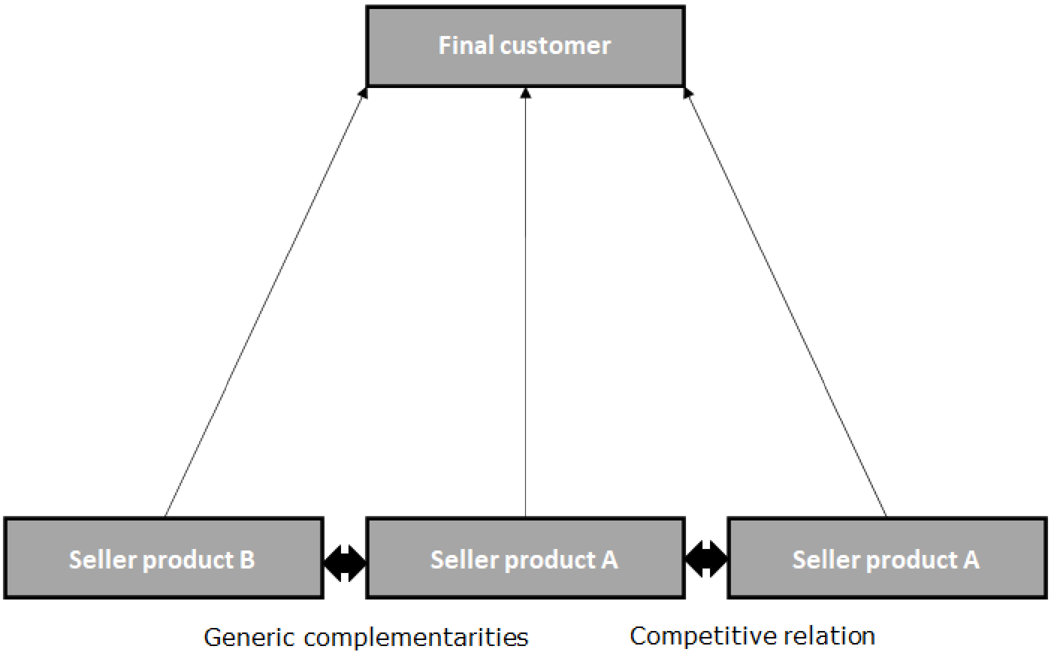

Figure 8: Systematics of a Market – based value system (Jacobides et al., 2018, p. 2261)

Another possibility that can occur on the market between diverse sellers of products, besides competitive behavior, is the emergence of generic complementarities**.** This term refers to different products that can be used together but do not have to be coordinated with each other. An example could be the preparation of a cup of tea. The following components are required to prepare a cup of tea - a teacup, boiling water, and a teabag. These ingredients will be combined by the consumer but can be bought separately on the market. Furthermore, these ingredients can also be mixed separately with other ingredients to create a different value proposition (not a cup of tea). This means that the producers of the individual components do not have to coordinate their structures with each other to create value. These generic complementarities are only one possibility of complementarities. The other ones will be discussed later in chapter 2.3.3.1 (Jacobides et al., 2018, p. 2262; Teece, 1986, p. 290)

2.2.3 Ecosystem-based value system

The last value system which will be outlined is the “Ecosystem-based” one. As shown in Figure 9, this system includes additional complementors whose products have a non-generic complementarity to the focal firm's product as well as to other complementary products. That means these complementors sell their products directly to the final customer. Consequently, the customer can choose from different components or services within the ecosystem and combine them with the focal firm's product. In principle, the ecosystem-based value system represents a combination of elements from the market-based value system and the hierarchy-based value system. (Jacobides et al., 2018, p. 2261)
For example, in the operating system of Windows, the customer decides which programs he buys and from which provider. Instead of purchasing a single combined offer like in the "Hierarchy-based value system", the customer can configure his product and extend it with various functions. However, since

the operating system and the programs are developed by different companies and have to be compatible to be jointly used, a non-generic (specific) complementarity occurs. This non-generic complementarity means that the individual actors have to coordinate their products with each other. This means they are interdependent. In contrast to the above-mentioned generic complementarities, which do not need specific coordination, these ones are specific to the product and require the creation of specific relationships and alignment structures to create value. (Jacobides et al., 2018, p. 2261ff; Teece, 1986, p. 289)

The operating system Android can be used as an example for such a non-generic complementarity. Various applications will not function without the operating system Android, whereas Android needs those apps to increase the value of the operating system. (Jacobides et al., 2018, p. 2263)

Compared to the other approaches, the “Ecosystem-based value system” requires the coordination of various interdependent complementors. This leads to relatively complex processes and structures and offers a new set of risks. (Adner, 2006, p. 101; Jacobides et al., 2018, p. 2261; Adner, 2017, p. 41f)

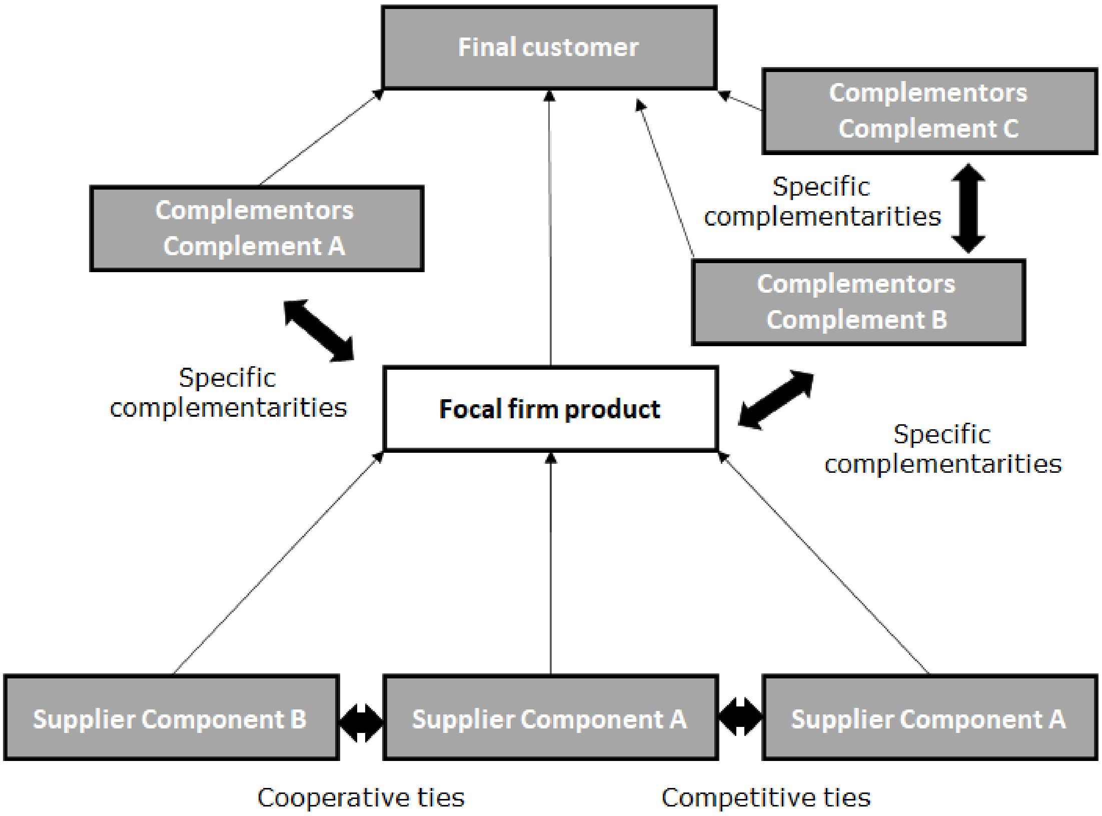

Figure 9: Systematics of an Ecosystem-based value system (Jacobides et al., 2018, p. 2261)

Due to the increasing importance of the ecosystems in the research of companies and products, the basics and the most crucial research concepts of the ecosystem-thinking approach will be described in detail in the following chapter (Bogers et al., 2019, p. 2). Furthermore, a deep understanding of this term is a prerequisite for identifying bottlenecks in such a setup and thus essential to meet the objectives of this thesis.

2.3 Definition and research on ecosystems

The use of the term ecosystem within the field of economics has grown enormously in recent years. A closer look at the Social Science Citation Index[2] (SSCI) underlines this claim, as 924 business or management articles that mention the topic ecosystem are listed in the time horizon from 1992-2018 and almost 90% of them are from the last decade (Bogers et al., 2019, p. 3).

In the field of business strategy, this term was first introduced by James F. Moore in 1993. In his publication "*Predators and Prey: A New Ecology of Competition,*" he argued that a "*company should not be seen as a member of a single industry, but as part of a business ecosystem that crosses a variety of industries. In this ecosystem, the innovation is the focus of interest and various companies develop capabilities around this innovation. The companies work cooperatively and competitively to support new products and satisfy customer needs in order to be successful on the market* " (Moore, 1993, p. 76).

Since then, various scholars have done their research on different aspects of the ecosystem, and thus deviating definitions and interpretations occurred. Early studies focused primarily on analyzing how ecosystems operate. In contrast to earlier research, more recent attempts provide a more precise definition of ecosystems, focusing on the conditions under which ecosystems may emerge and identifying the difference to other business constellations. The object of analysis in the field of research is, in most cases, the focal offer that is provided by the ecosystem. (Shipilov and Gawer, 2020, p. 100ff)

A simple but very expressive description would be that an ecosystem "*includes a set of interdependent actors which contribute to the value proposition of the focal offer*" (Kapoor, 2018, p. 2). This focal offer can either be a product or a service and acts as a link between supplier and consumer. Furthermore, these actors can be part of different industries and serve either as a component supplier or complementor. (Kapoor, 2018, p. 2)
But as already mentioned, this is only one example. An overview of different definitions of the term ecosystem is shown in Table 1.

Table 1: Overview of different definitions of the term ecosystem

Author	Definition of ecosystem
Moore, 1993, (p. 76)	*"Companies coevolve capabilities around a new innovation: they work cooperatively and competitively to support new products, satisfy customer needs, and eventually incorporate the next round of innovations."*
Iansiti and Levien, 2004, (p. 8)	*"[…] are characterized by a large number of loosely interconnected participants who depend on each other for their mutual effectiveness and survival."*
Adner, 2006, (p. 98)	*"[…] the collaborative arrangement through which firms combine their individual offerings into a coherent, customer-facing solution."*
Teece, 2007, (p. 1325)	*"[…] community of organizations, institutions, and individuals that impact the enterprise and the enterprise´ customer and suppliers."*
Boudreau and Hagiu, 2008, (p. 168)	*"[…] a collection of (many) firms engaged in joint production, whose choices and actions are interdependent."*
Clarysse et al., 2014, (p. 8)	*"[…] are characterized by a large number of loosely interconnected participants dependent on each other for their mutual performance. Each participant is specialized in a specific activity and it is the collective efforts of many participants that constitute value, while efforts individually have no value outside the collective effort."*

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[2] Social Sciences Citation Index™ is a citation index which includes 3400 journals across 58 social science disciplines (Clarivate, (2021).

Adner, 2017, (p. 42)	*"[…] the alignment structure of the multilateral set of partners that need to interact in order for a focal value proposition to materialize."*
Hannah and Eisenhardt, 2018, (p. 3165)	*"Although ecosystems are not networks, both share a similar tension between competition and cooperation […] firms in ecosystems balance cooperation to create value and competition to capture value."*
Jacobides et al., 2018, (p. 2264)	*"An ecosystem is a set of actors with varying degrees of multilateral, non-generic complementarities that are not fully hierarchically controlled."*
Kapoor, 2018, (p. 2)	*"An ecosystem encompasses a set of actors that contribute to the focal offer's user value proposition."*

The various types of definitions have arisen by focusing on different research topics. Basically, the research on ecosystems in the field of strategic management can be distinguished into three main streams: (Jacobides et al., 2018, p. 2256f)

- Business ecosystem
- Platform ecosystem
- Innovation ecosystem

2.3.1 Business ecosystem

The first stream focuses on the firm and the environment in which it operates and defines the ecosystem as a large, loosely coupled network of various parties that influences the company, its customers and suppliers. This network includes complementary partners, suppliers, regulatory authorities, standards-setting bodies and educational research institutions. (Shipilov and Gawer, 2020, p. 100; Teece, 2007, p; Heikkilä and Kuivaniemi, 2012, p. 19)
This means it refers to a community of interacting actors who influence each other through their activities. Basically, the company is always in the focus of analysis. Some scholars also refer to the community's shared fate which means that the individual performance of the actors is tied to the overall performance of the ecosystem (Iansiti and Levien, 2004).

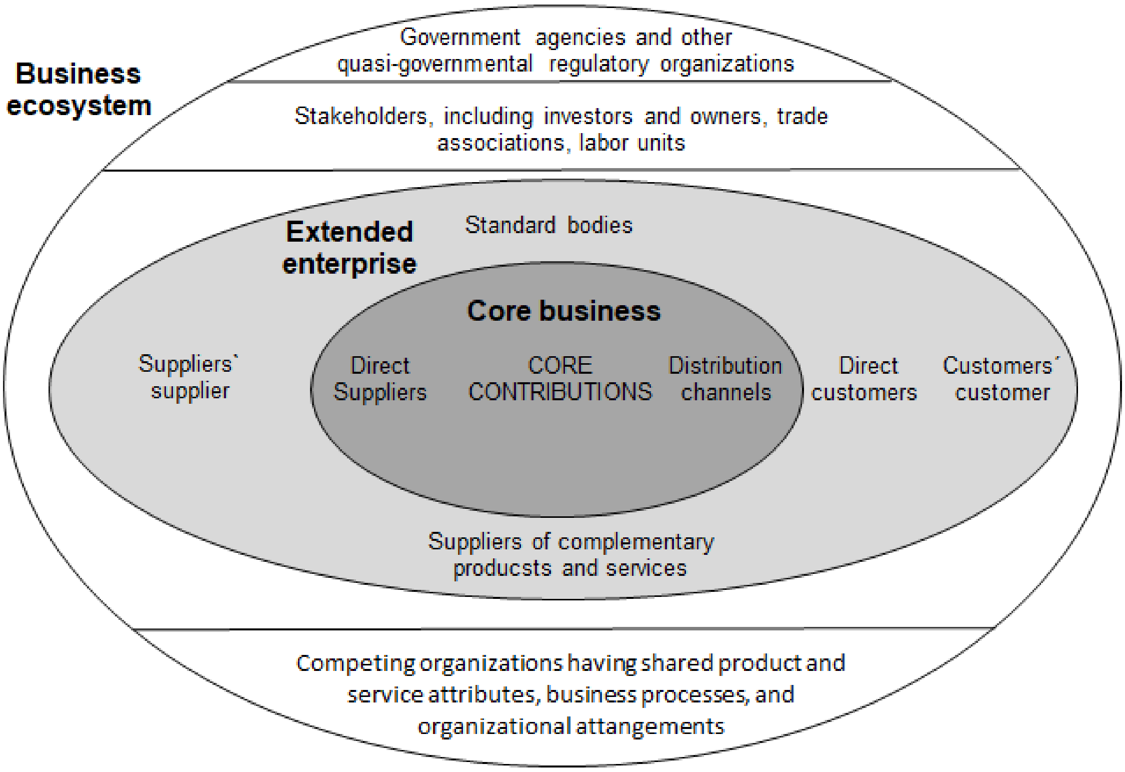

Figure 10: Business ecosystem according to Moore (1996)

Figure 10 shows James F. Moore´s (1996) concept of the business ecosystem. In the center of this model is the core business layer of a company, which forms the heart of a business. This business is usually performed by a single company that additionally coordinates the distribution channel and the supplier. The next layer, described as the extended enterprise, extends the view to the corporate supply chain of customers and second-tier suppliers, as well as to the standard-setting bodies. The last layer, described as the business ecosystem, includes stakeholders such as investors or research institutions and governmental agencies and other parties, which are not directly involved in business operations but have an influence on the company's overall performance. (Heikkilä and Kuivaniemi, 2012, p. 20; Moore, 1996)

Due to the variety of actors included in the concept of business ecosystems, it is pretty difficult to precise the scope of research, leading to difficulties in analyzing the interactions between the actors (Shipilov and Gawer, 2020, p. 100).

2.3.2 Platform ecosystem

Research on “platform-based” ecosystems primarily focuses on an organization of actors around a technology platform (Jacobides et al., 2018, p. 2257). A technology platform refers to a set of elements used by firms in common and includes components, tools, rules, and technical standards to support interoperability (Boudreau, 2010, p. 1851). The main objective of this concept is not the value proposition for the end-user but rather for the platform itself, which is usually a core technology that offers the connection possibility of various complementary products or services. These products or services of peripheral companies are connected to each other via technical interfaces or open-source technology. (Shipilov and Gawer, 2020, p. 101)

The big benefit of such a platform is based on the fact that products can be designed and developed independently from other components and thus, complementary innovations can be created. Furthermore, the platform enables complementors directly or indirectly access to their central customer group. (Ceccagnoli et al., 2012, p. 263ff; Shipilov and Gawer, 2020, p. 101)

Platforms are defined by the architecture of the technical interfaces, in which modularity plays a key role, by the ecosystem of complementary product suppliers and by a platform leader who ensures stability and growth of the platform. Modularity refers to a technological characteristic where different companies design and produce various technical components and combine them via technical interfaces to a final product. The definition of these technical interfaces is intended to minimize the coordination effort between the individual companies. The so-called “platform leader” or “hub”, who defines system-level goals, members' roles, standards and interfaces, is responsible for this coordination. (Shipilov and Gawer, 2020, p. 101; Jacobides et al., 2018, p. 2258)

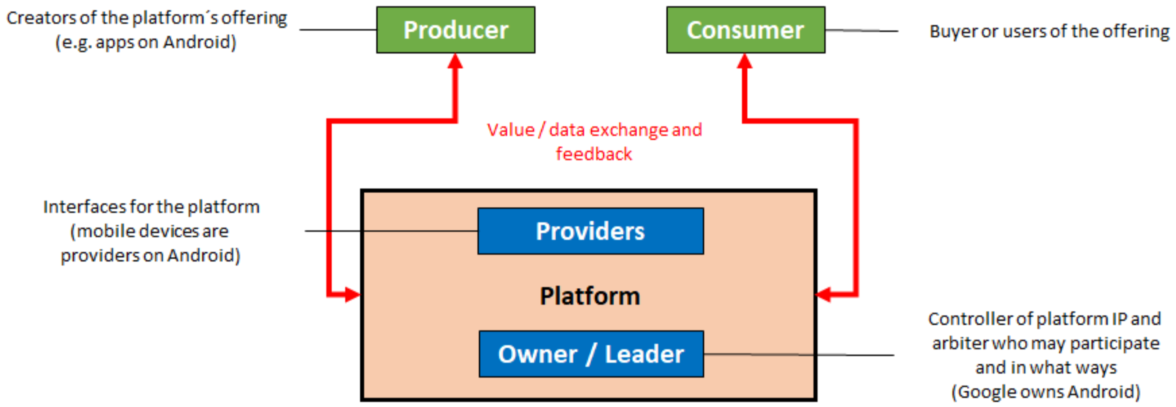

Figure 11: The players in a platform ecosystem (van Astyne et al., 2016)

An example of a platform can be the Android operating system, which serves as a central point of contact for app developers and mobile device producers. The more complementors connect to the platform, the more value the platform creates for end-users as well as for ecosystem members. The owner/leader of this platform is Google, which is driving growth through innovation and continuous development, thereby attracting more and more complementors to its ecosystem. The complementors see an excellent opportunity for success in the operating system of Android. (Gawer and Cusumano, 2014, p. 420 ff; van Astyne et al., 2016)

Figure 11 gives an overview of what such a platform ecosystem could look like and shows the main actors in the example of Android. Additionally, it includes the inflow as well as the outflow of information and data.

2.3.3 Innovation ecosystem

The research on the innovation ecosystem is a crucial part of this thesis and for this reason, this topic will be described in more detail. Additionally, important terms, limitations and activities will be pointed out.

The innovation ecosystem concept came widely known through Ron Adner's (2006) article *"Match your Innovation Strategy to Your Innovation Ecosystem"* in the Harvard Business Review [3]. In this publication, he defines an innovation ecosystem as *"the collaborative arrangements through which firms combine their individual offerings into a coherent, customer-facing solution"* (Adner, 2006, p. 2). The origin of this concept is based on Moore's (1993) business ecosystem. Compared to that, the research on the innovation ecosystem offers a more detailed view on the ecosystem. This is because the ecosystem is related to an innovation, a focal value proposition, which is viewed from the customer perspective and does not only deal with the interdependence of the actors across the ecosystem. (Shipilov and Gawer, 2020, p. 100; Granstrand and Holgersson, 2020, p. 2)
Since then, the interest in innovation ecosystems has grown rapidly, which has led to the emergence of a wide variety of definitions. An extract of them can be seen in Table 2.

Table 2: Overview of different definitions of the innovation ecosystem concept

Author	Definition of innovation ecosystem
Adner, 2006, (p. 2)	*"The collaborative arrangements through which firms combine their individual offerings into a coherent, customer-facing solution."*
Carayannis and Campbell, 2009, (p. 206)	*"A 21st Century Innovation Ecosystem is a multi-level, multi-modal, multi-nodal and multi-agent system of systems. The constituent systems consist of innovation meta-networks (networks of innovation networks and knowledge clusters) and knowledge meta-clusters (clusters of innovation networks and knowledge clusters) as building blocks and organized in a self-referential or chaotic fractal (Gleick, 1987) knowledge and innovation architecture (Carayannis, 2001), which in turn constitute agglomerations of human, social, intellectual and financial capital stocks and flows as well as cultural and technological artifacts and modalities, continually co-evolving, co-specializing, and co-opting. These innovation networks and knowledge clusters also form, re-form and dissolve within diverse institutional, political, technological and socio-economic domains including Government, University, Industry, Non-governmental Organizations and involving Information and Communication Technologies, Biotechnologies, Advanced Materials, Nanotechnologies and Next Generation Energy Technologies."*

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[3] Harvard business review is a management magazine, which is published every two months from the "Harvard Business Publishing" (https://hbr.org/)

Rubens et al., 2011, (p. 1737)	*“We use the term “innovation ecosystems” to refer to the inter-organizational, political, economic, environmental, and technological systems of innovation through which a milieu conducive to business growth is catalyzed, sustained and supported. A vital innovation ecosystem is characterized by a continual realignment of synergistic relationships that promote harmonious growth of the system in agile responsiveness to changing internal and external forces.”*
Autio and Thomas, 2014, (p. 3)	*“Hence we define an innovation ecosystem as: a network of interconnected organizations, organized around a focal firm or a platform, and incorporating both production and use side participants, and focusing on the development of new value through innovation.”*
Gobble, 2014, (p. 55)	*“Innovation ecosystems are dynamic, purposive communities with complex, interlocking relationships built on collaboration, trust, and co-creation of value and specializing in exploitation of a shared set of complementary technologies or competencies.”*
Adner, 2017, (p. 42)	*“The ecosystem is defined by the alignment structure of the multilateral set of partners that need to interact in order for a focal value proposition to materialize.”*
Walrave et al., 2018, (p. 104)	*“We therefore define an innovation ecosystem as a network of interdependent actors who combine specialized yet complementary resources and/or capabilities in seeking to (a) co-create and deliver an overarching value proposition to end users, and (b) appropriate the gains received in the process.”*
Gomes et al., 2018, (p. 32)	*“We proposed a conceptual framework, in which we characterized the innovation ecosystem construct with respect to the following features: an innovation ecosystem is set for the co-creation or the jointly creation of value. It is composed of interconnected and interdependent networked actors, which includes the focal firm, customers, suppliers, complementary innovators and other agents as regulators. This definition implies that members face cooperation and competition in the innovation ecosystem; and an innovation ecosystem has a lifecycle, which follows a co-evolution process.”*
Granstrand and Holgersson, 2020, (p. 3)	*“An innovation ecosystem is the evolving set of actors, activities, and artifacts, and the institutions and relations, including complementary and substitute relations, that are important for the innovative performance of an actor or a population of actors.”*

For this thesis, an innovation ecosystem should be seen as a set of actors contributing to the central value proposition. The basic requirement for considering the actors as a member of the ecosystem is a non-generic complementarity of their contributions to the central value proposition (Jacobides et al., 2018, p. 2264; Kapoor, 2018, p. 2). This central value proposition refers to a focal innovation supported by a set of upstream components and downstream complements, where improvements in either increase the attractiveness of the focal innovation (Adner and Kapoor, 2010, p. 309). The crucial factor is that the success of an individual innovation depends on the success of other innovations in the external company environment (Adner and Kapoor, 2010, p. 306).

Figure 12 gives an overview, what an innovation ecosystem could look like. Basically, a distinction between two different positions in the ecosystem should be made. On the one hand, the output from the suppliers, the so-called components, serves as input for the focal actor. On the other hand, the output of the focal firm serves as input for the customer. In order to consume this product, other products may be required that need to be bundled by the customer. This product group is called complements. The difference between components and complements appears in the location of the activity flow where they are bundled. (Adner and Kapoor, 2010, p. 309)

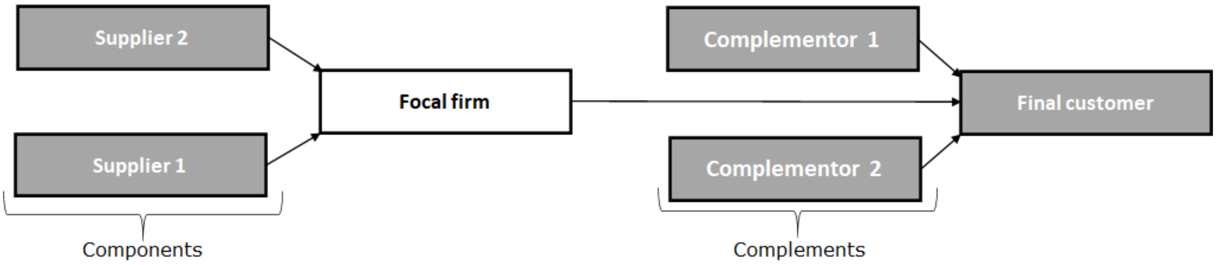

Figure 12: Generic schema of an innovation ecosystem (Adner and Kapoor, 2010, p. 309)

To get a better understanding, consider the example of a BEV, where the “Original Equipment Manufacturer” (OEM), as the focal firm, faces significant challenges in the design, development and modular structure of the vehicle. In addition to their internal challenges, they also rely on component suppliers who produce batteries, e-motors, etc. These suppliers sometimes also face significant challenges in the development of new innovations. The OEM has to integrate them in its vehicle body to deliver the customer a complete vehicle. However, to be able to use the vehicle at all, innovations from other actors in the OEM's environment are required as well. For example, a sufficient fast-charging infrastructure must be in place to achieve short charging times. Only the combination of a well-designed vehicle with an acceptable electrical driving range and the availability of charging stations ensures that the BEV value proposition materializes. (Adner and Kapoor, 2010, p. 306; Kapoor, 2018, p. 2f)

This example reflects the statement mentioned above that market acceptance can only be achieved by a focal innovation if the upstream suppliers realize innovations in the components of the focal product and the complementors do the same. In order to create value in an innovation ecosystem, it is not enough to solve only the internal innovation challenges. All the actors in the complete ecosystem have to solve their challenges as well. This means evaluating the performance in an innovation ecosystem can only be conducted by considering both the focal innovation challenges and the challenges of the external actors. (Adner and Kapoor, 2010, p. 306f)
Furthermore, it must be considered how the various interdependent actors interact with each other and handle the trade-off between cooperation and competition, which can occur simultaneously and differently at multiple ecosystem levels. (Hannah and Eisenhardt, 2018, p. 3614)

As it can be seen, the research in an innovation ecosystem can be quite complex due to the interdependencies of various actors. Therefore, it is essential to take a closer look at these actors and their characteristics.

2.3.3.1 Actors in an innovation ecosystem

Actors in an innovation ecosystem can be described as those who perform a set of activities to create and produce different offers. The two different actor groups in such a system, suppliers and complementors, differ fundamentally in the nature of their interdependence on the focal firm, which is caused by the complementarities. (Kapoor, 2018, p. 6f)

Types of complementarity

Complements are pervasive in the economic system, especially in technology development (Teece, 2018, p. 1373). In economics, the concept of complementarity is based on a definition that dates back to Francis Y. Edgeworth (1925), who stated that the value of a variable increases with another variable (Teece, 2018, p. 1373). However, the underlying principle of complementarity is a complex topic. This is represented by David J. Teece´s (1986, p. 1373) statement, “*the literature on complements is both confused and complex”* [4].

In general, we distinguish between generic and non-generic complementarities, where the former has already been outlined in chapter 2.2.2.

Unlike generic complementarities, non-generic ones require coordination between actors, leading to the need for a specific “alignment structure” (Jacobides et al., 2018, p. 2262; Adner, 2017, p. 42).

In order to define how non-generic complementarities can influence the innovation ecosystem, these complementarities were subdivided into unique and supermodular complementarities, according to Jacobides, et al. (2018, p. 2261) [5] .

Unique complementarities are based on the simple adoption that product A needs product B to perform the desired function (Hart and Moore, 1990, p. 1135) [6] and create value. More generally, unique complementarities can be described that the presence of product B maximizes the value of product A. As a result, a joint consumption of the two products brings a greater utility than a separate one and thus the value of the two complements will be increased. An example of a unique complementarity could be the OS platform/app ecosystem, where the app does not function without the OS platform. (Jacobides et al., 2018, p. 2261f)

Supermodular complementarities have a long history, starting with Francis Y. Edgeworth [7] , who studied how changes in the demand of one product affect the demand of another one. This was followed up by an analysis of Edgeworth´s study from Samuelson (1974). In 1994, Milgrom and Roberts, developed an analytical definition. They noted, *"a group of activities are (Edgeworth) complements if doing more of any subset of them increases the returns to doing more of any subset of the remaining activities."* (Milgrom and Roberts, 1994, p. 6)

This means that supermodular complementarity exists when more from one product makes the other product more valuable (Jacobides et al., 2018, p. 2262). If we look back to the OS platform/app ecosystem example, it can be seen that the presence of apps makes the platform more valuable and vice versa the breadth installation of the OS increases the value of the app (Jacobides et al., 2018, p. 2263).

These non-generic complementarities require a certain degree of coordination within the ecosystem but without the need for hierarchical control. This is because the introduction of standards or basic requirements allows actors to make their own decisions and yet create a complex, interdependent product or service. (Jacobides et al., 2018, p. 2263)

Types of interdependence

In the field of management, the interdependence between actors has been chiefly considered from three different perspectives: technological, economic, and cognitive (Thomas and Autio, 2019, p. 11).

The first one, technological interdependence, refers to the co-specialization of the individual actors in the innovation ecosystem (Jacobides et al., 2018, p. 2264; Autio et al., 2017, p. 34). The requirement for actors to provide inputs to the ecosystem that are compatible with each other and thus support an output at the system level creates a co-evolved dependency between those actors (Jacobides et al., 2018, p. 2265; Thomas and Autio, 2019, p. 11).

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[4] Teece made this statement according to Samuelson, (1974, p. 1255) notation –*“The time is ripe for a fresh, modern look at the concept of complementarity … the last word has not yet been said on this ancient preoccupation of literary and mathematical economists. The simplest things are often the most complicated to understand fully.”*

[5] Jacobides et al., (2018, p. 2261) reason for this subdivision – *“we focus on two types of complementarities that can be expressed unambiguously in mathematical terms and characterize relationships between actors within ecosystems.”*

[6] Hart and Moore, (1990, p. 1135) definition of unique complementarity - *“Two assets* a_m *and* a_n *are (strictly) complementary if they are unproductive unless they are used together.”*

[7] A more detailed analysis was conducted by Samuelson, (1974)

The second type, economic interdependence, refers to the value received by each participant in an ecosystem, depending on the simultaneous availability of compatible offerings from other actors. These interdependencies can also arise from technological ones. (Thomas and Autio, 2019, p. 12)
The last one, the cognitive interdependence, refers to the corporate culture of the actors in the ecosystem, i.e., the values, beliefs and rules according to which the individual actors carry out their activities and make decisions. Collective identity in the ecosystem promotes commonality of perspectives and helps actors to better respond to environmental change. (Thomas and Autio, 2019, p. 12f)

Especially in the distinction of suppliers and complementors regarding their type of interdependence, a closer look at the technological interdependencies can be helpful. A supply-side sequential interdependence characterizes the relationship between a firm and its supplier since the components which were produced by the supplier were implemented in the focal offer where the firm has the decision right regarding which components it integrates into the product (Kapoor, 2018, p. 7; Bishop and Mahajan, 2005, p. 462). On the other hand, the interdependence between the focal firm and its complementors is characterized by a demand-side pooled interdependence, since the downstream actor (user) has the right to decide which complements he combines with the focal offer (Kapoor, 2018, p. 7; Bishop and Mahajan, 2005, p. 461).

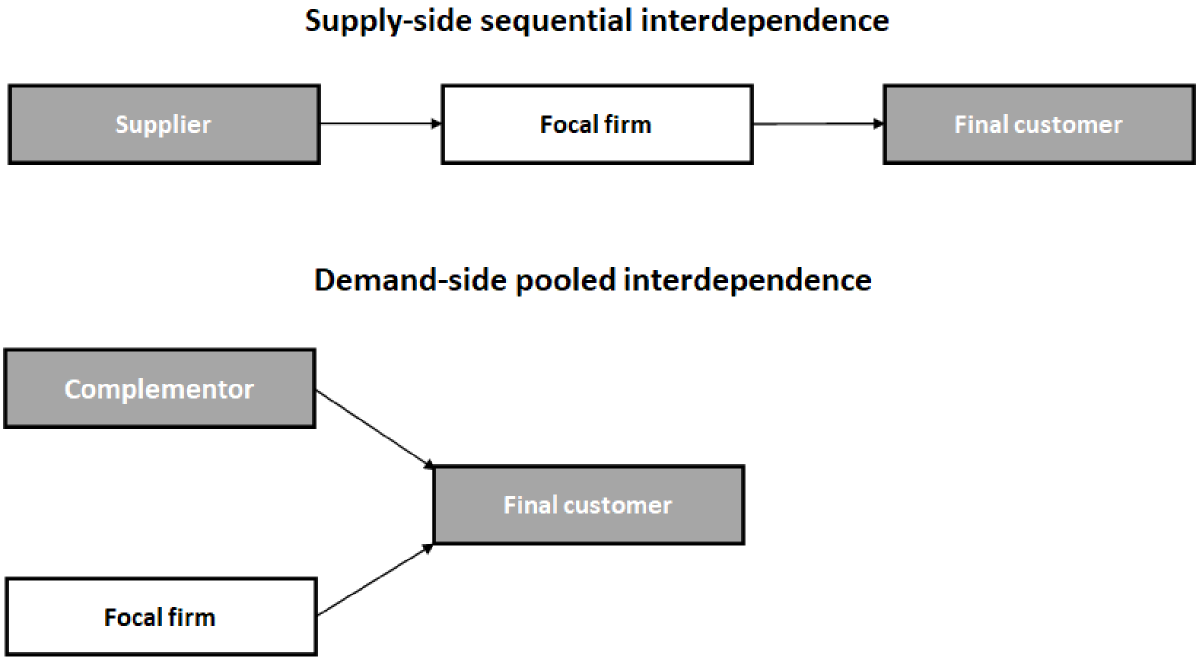


Figure 13: Supplier vs. complementor interdependence in an innovation ecosystem (Kapoor, 2018, p. 8)

This fundamental difference in the interdependence between the actors in an innovation ecosystem, illustrated in Figure 13, leads to different approaches, functions and processes.
Regarding the suppliers, the primary goal of a company is to generate a dyadic governance structure, which builds on both formal (contracts, KPIs, etc.) and relational mechanisms (trust, commitment, etc.) to coordinate the collaboration as effective as possible (Kapoor, 2018, p. 7).
In contrast, the goal of a company with its complementors is to create an “alignment structure” (Adner, 2017, p. 42f) consisting of multilateral partners which have to interact to ensure joint-value creation (Kapoor and Lee, 2013, p. 275; Kapoor, 2018, p. 7). The alignment structure consists of formal and relational mechanisms and refers to the mutual agreement of the differently defined positions and activity flows of individual companies within the ecosystem and takes standards for interoperability into account (Kapoor, 2018, p. 8).

In this context, the term multilateral partners refers to a set of partners whose relationships require critical interactions. In other words, the relationships between the partners cannot be decomposed into two-partner interactions. An example would be if the contract between companies A and B does not materialize because the contract between companies A and C did not materialize. (Adner, 2017, p. 42)

Actor activities in an innovation ecosystem

The activities performed by the individual actors in the ecosystem are various tasks that are necessary to create the components and complements and therefore contribute to the focal offer´s user value proposition of the ecosystem. These activities constitute a significant stream of research in the concept of the innovation ecosystem. It is often crucial to improve these activities to make a product more valuable and thus accelerate the growth of an ecosystem. (Kapoor, 2018, p. 6f; Adner and Kapoor, 2016)

Such an activity can also be a reason for a growth limitation of the entire ecosystem by negatively influencing a component or complementary product or service. For this reason, these activities could be responsible for a component/complement to be inferior.

2.4 Ecosystem lifecycle

An innovation ecosystem is characterized by the fact that it evolves through different phases in the process of its evolution. This means that a structured community emerges from a random collection of actors. According to Moore (1993), the evolution of an innovation ecosystem consists of four phases: birth, expansion, leadership, and self-renewal. (Moore, 1993, p. 76)

These four evolutionary phases are defined by different characteristics shown in Figure 14.

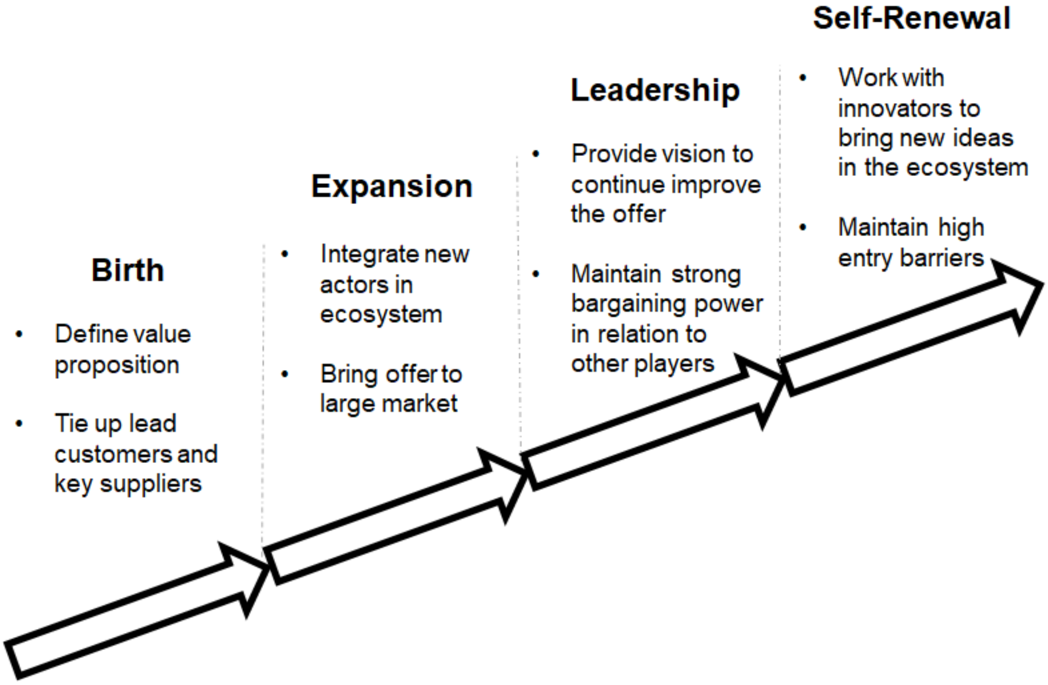


Figure 14: Stages of the ecosystem lifecycle (Moore, 1993, p. 77)

In the first stage, the focus is on defining the value proposition to the customer around an innovation, i.e., the customer's requirements have to be understood by all actors in the ecosystem. Understanding these customer requirements is the prerequisite for the actors within the ecosystem to collaborate on shared objectives. In this phase, an ecosystem leader must evolve, who takes the responsibility to initiate continuous improvement that draws the ecosystem towards a grander future. In this process, the ecosystem leader ensures that the key organizations cooperate and, consequently, that value can be delivered to the customer. In this phase, it is of enormous importance to tie these key organizations and the lead customers to the ecosystem and protect the innovative ideas from competing ecosystems. (Moore, 1993, p. 76ff)

In the second phase of the ecosystem life cycle, it is crucial to have a business concept valued by a broad customer group that extends the ecosystem to new application areas. In these new application areas, there may be a battle with other ecosystems. Therefore, the integration of established companies, which have enormous power, especially in the areas of marketing and sales and mass production and distribution, can result in a competitive advantage. Thereby stimulating the market demand is essential, but this needs to be done with a view on the own capacities, which should not be exceeded by the demand. Another important aspect of this stage is to prepare for the future leadership stage. This implies developing and maintaining relationships with customers and suppliers to limit ecosystem followers in their aim to become a leader in stage 3. (Moore, 1993, p. 79f; Dedehayir and Seppänen, 2015, p. 147)

The leadership stage is characterized by the fact that the ecosystem has reached a certain value, making it worth fighting for it. At the same time, the ecosystem has reached a certain stability of its sub-systems and processes. Together with a strong vision for the future from the ecosystem leader, these basic conditions lead the supplier and customer to work collaboratively to improve the offering continuously. In this phase, issues such as standardization, interfaces, and the modularity of the organization are addressed. An important task of this phase is the continuous improvement of performance and the innovation of new products and services to have a strong bargaining power and prevent key customers and key suppliers from switching to other ecosystems. (Moore, 1993, p. 80f)

The fourth phase of the ecosystem lifecycle emerges when an upcoming new ecosystem threatens a mature ecosystem or when changes in environmental conditions, such as customer behavior or legislative changes, allow new ecosystems to emerge. The way how an ecosystem deal with these changes in the conditions is a significant challenge. The continuous improvement of products and services within the ecosystem and thus the driving of innovation is crucial for the long-term success of an ecosystem. This goes hand in hand with the fact that the ecosystem must repeatedly renew itself over time. However, if this challenge of self-renewal is not accepted, the ecosystem will die. (Moore, 1993, p. 81ff)

2.5 Bottlenecks

The term bottleneck is frequently used in everyday life and therefore, it comes to a wide variety of different definitions, e.g., "*a narrow place that hinders a flow of traffic*" (Baldwin, 2015, p. 6). The origin of the bottleneck concept in science can be traced back to the field of "Linear Optimization" and denotes the part of a company's or industry's system that is in short supply (Jacobides et al., 2006, p. 27).

In recent years, many scholars have already dealt with the term bottleneck and argued that bottlenecks are an essential factor in understanding the direction of technological change in complex systems (Baldwin, 2015, p. 6).

Carliss Y. Baldwin (2015, p. 7) defines bottleneck as *"the critical part of a technical system for which no or only a poor alternative exists."* According to her, the following characteristics are a prerequisite to be classified as a bottleneck. The component must be an important part of the entire system, required for the system functionality, and no suitable alternative should be available. In order to detect this bottleneck, the whole system has to be analyzed to evaluate the optimal system performance and identify reasons for their limitation. (Baldwin, 2015, p. 7)

Hannah and Eisenhardt (2018, p. 3172) describe a bottleneck according to the physical properties or availability of individual components by defining them *"as the component that most constrains the growth or performance of the ecosystem due to poor quality, poor performance, or short supply."*

In addition to the performance and the availability of components, Rahul Kapoor (2018, p. 6) also defines the costs as a crucial factor and describes bottleneck as the" *component offers in the ecosystem whose performance, cost, or scarcity constrains the focal offer's value proposition, thereby limiting its demand or growth*. " Koch-Ørvad et al. (2019, p. 604) refer in their definition to bottleneck challenges, which "*are components that constrain the overall performance and alignment of the ecosystem and can be caused by one or more partners and can be distributed unevenly across the ecosystem.*" This definition is based on Adner and Kapoor (2010, p. 310), who attribute the existence of bottlenecks to the unevenly distributed challenges within the ecosystem.

As these examples highlight, many scholars have dealt with the topic of bottlenecks in ecosystems in recent years. An excerpt of definitions, which are relevant for this thesis can be seen in Table 3.

Table 3: Overview of different definitions of the term bottleneck

Author	Definition of bottleneck
Teece, 1986, (p. 295)	*"However, if the innovation is not tightly protected and once ´out´ is easy to imitate, then securing control of complementary capacities is likely to be the key success factor, particularly if those capacities are in fixed supply - so-called ´bottlenecks´."*
Jacobides et al., 2006, (p. 28f)	*"Rather, the dependencies arise from ´bottlenecks´: de facto exclusion of possible producers limits entry into particular segments of the industry architecture, whereas mobility (both in terms of switching costs and potential entry) is high in others." ;" […] ´bottlenecks´ can only be seen in a relative, as opposed to an absolute sense. That is, a ´bottleneck´ in a sector is the sector which has the least mobility; and as soon as the situation changes, whether because of an exogenous factor or endogenous change, another part of the segment will become the ´bottleneck´."; "Bottlenecks […] then, not only drive the direction of innovative activity […] but also determine how an innovative combination creates and distributes value."*
Adner and Kapoor, 2010, (p. 310)	*"The existence of bottlenecks in an ecosystem is evidence that challenges are distributed unevenly across ecosystem roles. While challenges in any location within the ecosystem will constrain the focal firm's ability to create value with its product, challenges located in different positions constrain its value creation and value capture in qualitatively different ways. Specifically, whereas upstream component challenges limit value creation by constraining the focal firm's ability to produce its product, downstream complement challenges limit value creation by constraining the customer's ability to derive full benefit from consuming the focal firm's product."*
Makinen and Dedehayir, 2012, (p. 7)	*"Bottlenecks curb the development of the ecosystem as a whole, and their removal therefore emerges as most pertinent in promoting ecosystem evolution."*
Baldwin, 2015, (p. 7)	*"I define a bottleneck as a critical part of a technical system that has no — or very poor — alternatives at the present time. There may be one or many bottlenecks in a given system, but each has the dual properties that (1) it is necessary to the functioning of the whole; and (2) there is no good way around it. Thus, to know that something is a bottleneck, the observer must see it in relation to a larger system, know what constitutes good system-level performance, and understand how the bottleneck constricts that performance."*
Hannah and Eisenhardt, 2018, (p. 3172)	*"We define a bottleneck as the component that most constrains the growth or performance of the ecosystem due to poor quality, poor performance, or short supply (Adner, 2012; Ethiraj, 2007)."*

	“Firms that occupy bottlenecks (i.e., produce the bottleneck component) thus have the chance to reduce the constraint on ecosystem growth, and bottlenecks may contain none, one, or even many firms.”
Kapoor, 2018, (p. 6)	*“Any system composed of multiple components is subject to bottlenecks that constrain the performance of the system. In an ecosystem, bottlenecks are component offers in the ecosystem whose performance, cost, or scarcity constrains the focal offer’s value proposition, thereby limiting its demand or growth.”* *“[…] an ecosystem can have multiple bottlenecks that can lie upstream or downstream within the architecture of input-output flows, and that bottlenecks can change over time.”*
Koch-Ørvad et al., 2019, (p. 604)	*“Bottleneck challenges are components that constrain the overall performance and alignment of the ecosystem. These challenges can be caused by one or more partners and can be distributed unevenly across the ecosystem (Adner and Kapoor, 2010; Hannah and Eisenhardt, 2018).”*
Masucci et al., 2020, (p. 2)	*“There is increasing evidence from the emerging literature on business ecosystems of how incentive misalignment or technical challenges experienced by ´complementors´ – firms specializing in products and services that are complementary to a hub firm’s core technology/ business – can constrain the production and supply of the required complements.”*

Another important point that must be considered is that the position of the bottleneck influences value creation and value capture in different ways. If the bottleneck occurs within the upstream suppliers, this limits the value creation of the focal firm as products cannot be produced at all or at least in sufficient quality or quantity. However, if the bottleneck occurs within the downstream complementors, this will affect the customer's ability to take full benefit out of the focal firm’s product. (Adner and Kapoor, 2010, p. 310)

For this thesis, the identification of bottlenecks in the innovation ecosystem of BEVs and FCEVs, it is essential to establish a uniform definition of the term bottleneck.

The prerequisite for a component and a complementary product or service to be declared as bottleneck is that it is a main contribution to the focal offer's value proposition, thereby necessary for its functioning, and no suitable substitution for this component or complement exists on the market. (Baldwin, 2015, p. 7; Kapoor, 2018, p. 6)

In order for potential bottlenecks to materialize, they have to constrain the evolution of the innovation ecosystem by posing limits on the ecosystem's central value proposition. This constrained evolution can be characterized by missing actor alignment, low system performance, small ecosystem size, low generated value, low demand, etc. (Masucci et al., 2020; Koch-Ørvad et al., 2019; Makinen and Dedehayir, 2012; Kapoor, 2018). The reasons for the constrained evolution of the ecosystem are attributable to the contributions of the central offer´s value proposition. For the scope of this study, these contributions (components or complements) must either have inferior technical performance, low quality, low availability, or high cost in relation to other contributions to the same value proposition to be declared as a bottleneck. (Hannah and Eisenhardt, 2018, p. 3172; Kapoor, 2018, p. 6).

High costs and low availability are self-explanatory and clearly defined. The definition of performance and quality is often confusing, and the difference is not explicitly defined in the literature. Especially the term quality is used in many different contexts (Jakoby, 2019, p. 4), but for the purpose of this thesis, it is essential to make a clear distinction between those two terms.

For this reason, the term performance is defined according to Osteras et al. (2006, p. 179) as “desired performance”. This refers to the theoretical performance of a product at the beginning of the lifecycle and reflects the customer's expectations of the product. In contrast to that, quality is defined according

to Osteras et al. (2006, p. 179) “actual performance”, which means the change of the theoretical performance over the lifetime of a product.
However, based on Jacobides et al. (2006, p. 29) definition, bottlenecks can only be observed relative to the whole system and not absolute, but this does not mean that there can only be one bottleneck in a system at a time (Kapoor, 2018, p. 6).

This definition of the term bottleneck should be the basis for investigating the innovation ecosystem of battery electric vehicles and fuel cell electric vehicles to identify components or complements that can be declared as a bottleneck. Some scholars have already applied methods to identify bottlenecks in an ecosystem and from these methods, one should be selected. For this reason, the next chapter deals with those already applied methods.

2.6 Current state of research for the bottleneck detection in ecosystems

The ecosystem perspective in the field of business strategy is a relatively new approach to assess various interdependencies between actors (Moore, 1996; Iansiti and Levien, 2004) and to analyze the evolution of a value proposition (Ritala et al., 2020). Consequently, the already existing literature on bottleneck identification in such an innovation ecosystem is pretty scarce. However, some pioneers such as Adner & Kapoor (2010) or Hannah and Eisenhardt (2018) have already addressed this topic. These existing methods in the field of bottleneck detection will be shown and discussed in this chapter. This theoretical background for the identification of bottlenecks also leads to the answer of the first research question:

- ***RQ1:*** *Which methods to identify technological bottlenecks in innovation ecosystems are described in the literature?*

2.6.1 Bottleneck identification via a quantitative evaluation

In their study *“Value creation in innovation ecosystems: How the structure of technological interdependence affects firm performance in new technology generations,”* Adner and Kapoor (2010) addressed the topic of innovation challenges in an innovation ecosystem and how their distribution within the ecosystem influences the firm performance. Therefore, they developed hypotheses and tested them in the context of the semiconductor lithography equipment industry. The methodology of this study was based on primary and secondary data. They conducted more than 30 semi-structured interviews with experts from different positions in the ecosystem, like toolmakers, suppliers, etc. These interviews were taken as input for creating a keyword list, which should serve as a guide for the article search from secondary data. This keyword search was performed in various industry trade journals for the predetermined investigation period and analyzed by counting the number of mentioned innovation challenges for a specific technology generation in the articles. The next step focused on the assignment of the challenges to the corresponding key components and key complements and, consequently, the bottleneck determination. (Adner and Kapoor, 2010, p. 317ff)

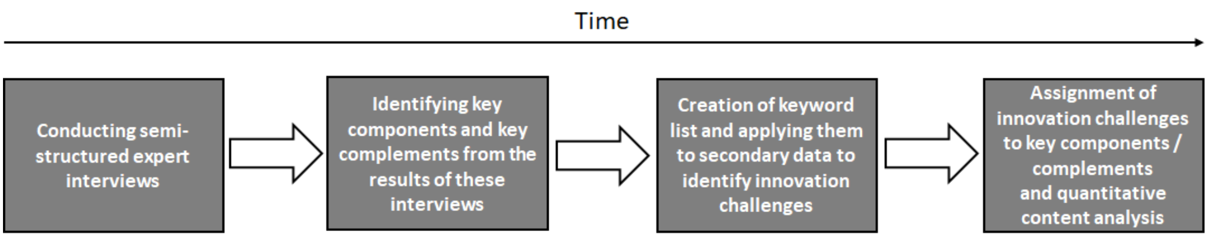
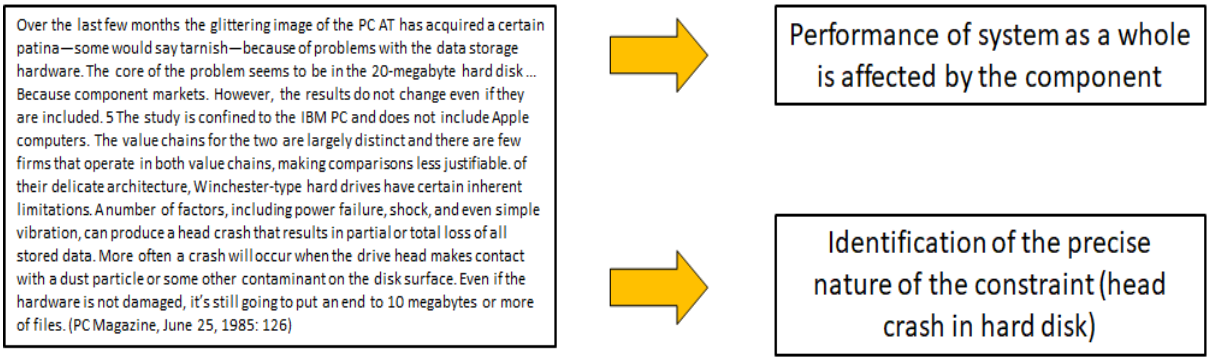


Figure 15: Graphical representation of Adner and Kapoor´s study in the field of “value creation in the innovation ecosystem”(Adner and Kapoor, 2010)

This study performed by Adner and Kapoor is based on a quantitative content analysis. A graphical representation of this construct for identifying bottlenecks is shown in Figure 15.

2.6.2 Bottleneck identification via a qualitative evaluation

The following exemplary approach, which is shown, originates from Ethiraj's (2007) article "*Allocation of inventive Effort in Complex Product Systems,"* in which hypotheses regarding the allocation of inventive effort were developed and tested in the field of personal computer technology. For this purpose, the five most important and crucial hardware (HW) components were defined based on a literature research. One task of the empirical study dealt with detecting limiting components in the environment of personal computers (PC). For this purpose, Ethiraj examined and analyzed product reviews in PC magazines, intending to detect limiting factors in the predefined time period. From this analysis, he was able to deduct information about the limitation of the system performance and detect the constraints' precise nature, which made it possible to assign them to a component (an example can be seen in Figure 16). (Ethiraj, 2007, p. 570ff)



Over the last few months the glittering image of the PC AT has acquired a certain patina—some would say tarnish—because of problems with the data storage hardware. The core of the problem seems to be in the 20-megabyte hard disk... Because component markets. However, the results do not change even if they are included. 5 The study is confined to the IBM PC and does not include Apple computers. The value chains for the two are largely distinct and there are few firms that operate in both value chains, making comparisons less justifiable. of their delicate architecture, Winchester-type hard drives have certain inherent limitations. A number of factors, including power failure, shock, and even simple vibration, can produce a head crash that results in partial or total loss of all stored data. More often a crash will occur when the drive head makes contact with a dust particle or some other contaminant on the disk surface. Even if the hardware is not damaged, it's still going to put an end to 10 megabytes or more of files. (PC Magazine, June 25, 1985: 126)

Figure 16: Example of the bottleneck identification in Ethiraj´s study (Ethiraj, 2007, p. 572)

This means that if a problem with a component was identified in these reviews, this component was declared as a bottleneck. The result was the detection of primary bottlenecks for every year of the investigated time period. By applying this method to several magazines, Ethiraj eliminated a possible bias or a magazine-based view and made the results more objective. As validation of the results, he presented the reviews to three graduate students in the field of computer science, who unanimously agreed to the results obtained. (Ethiraj, 2007, p. 571ff)

The method used to detect bottlenecks represents a qualitative content analysis and delivers high qualitative results. The procedure and the individual steps of the bottleneck identification in this study can be seen in Figure 17.

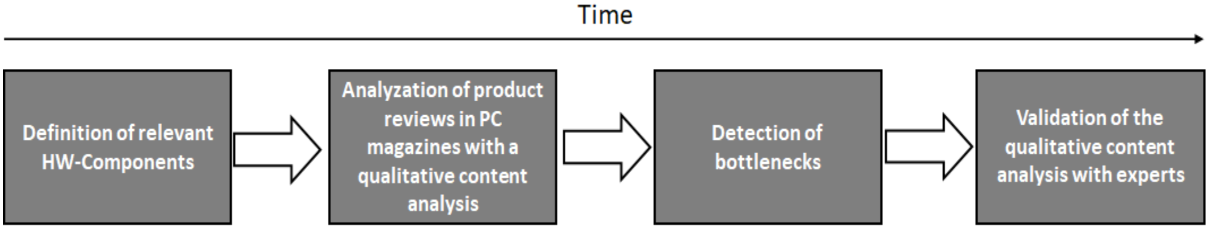


Figure 17: Graphical representation of Ethiraj´s study in the field of "Allocation of inventive Effort in Complex Product Systems" (Ethiraj, 2007)

2.6.3 Bottleneck identification via a qualitative and quantitative evaluation

The article *“How firms navigate cooperation and competition in nascent ecosystems”* by Hannah and Eisenhardt (2018) deals with the difficulties in managing cooperation and competition in an ecosystem. For this purpose, they conducted a theory-building, multiple case study (five ventures) in the U.S. residential solar industry ecosystem, which included the hardware components like panels or racking and business areas like sales finance or installation. The data for the analysis was gathered from a variety of sources. In the first step, semi-structured interviews with focal firm executives were performed. This was followed by interviews with industry experts and complementors, and finally, follow-up interviews were conducted. In addition to the interview data, Hannah and Eisenhardt used archival data from press articles, company press releases, technology blogs, conference presentations, and analyst reports. At the beginning of the analysis, the data were synthesized into a comprehensive case history for each venture, which tracks the main activities of the firms over time. Based on the interviews and the support by archival data, the bottlenecks for a selected point in time (year) were determined and the shifting of these bottlenecks was analyzed. After this case analysis, a cross-case analysis was performed to detect emerging patterns across cases. (Hannah and Eisenhardt, 2018, p. 3617ff)

In principle, the approach to identifying bottlenecks, which is included in Hannah and Eisenhardt's empirical study, has the potential to be more objective than other approaches due to the rich data on which it is based. The procedure and the individual steps of the bottleneck identification in this study can be seen in Figure 18.

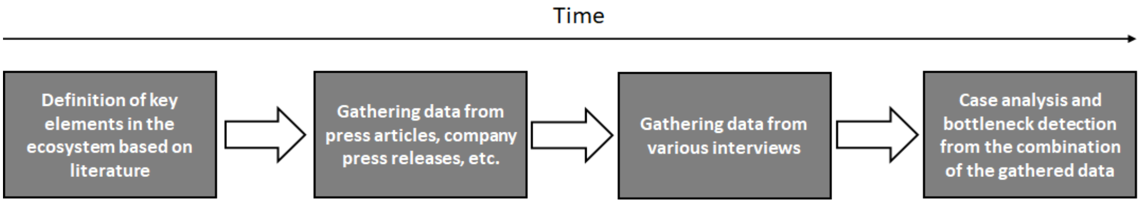


Figure 18:Graphical representation of Hannah and Eisenhardt´s study “How firms navigate cooperation and competition in nascent ecosystems” (Hannah and Eisenhardt, 2018)

2.6.4 Bottleneck identification with performance comparison

The approach which Daim et al. (2014) chose in their study *“Identifying and forecasting the reverse salient in video game consoles”* was based on a performance comparison of different technologies. The objective of this study was to determine the historical performance gap between video game hardware subsystems and their personal computing counterparts. For this purpose, a list of thirty different video consoles (e.g., PlayStation 3, Xbox 360, etc.), including different console generations, top sellers as well as the biggest flops, from various vendors for a predefined period of time were selected, and the most relevant performance indicators (Central Processing Unit and graphics hardware), which characterize the technology progress in the video game consoles industry, were determined. These performance indicators for the different consoles types were gathered from secondary data such as “Wikipedia”, the manufacturer websites, or databases. Since the 30 different video consoles were not continuously on the market during the observation period, the next step in this study was determining the most important consoles for any given year. Thereby the technical specifications of all these consoles were averaged to get a representative value for the comparison with the PC counterparts. After this, the same procedure was carried out for the corresponding PC counterparts (200 different CPUs and 184 models of graphic hardware) to produce a simple and objective comparison. As a result of this comparison, the individual performance gaps of the different specifications were determined. However, to perform a comparative analysis between the specifications, it was necessary to normalize the specifications. For this purpose, Daim et al. (2014) used the ratio of the performance utilized to the performance available, which led to the determination of the underlying trends. (Daim et al., 2014, p. 181)

This simple comparison method can provide an enormous added value, but a prerequisite is the formulation of comparable parameters, which characterizes the progress in the observed technology. The procedure and the individual steps of the bottleneck identification in this study can be seen in Figure 19.

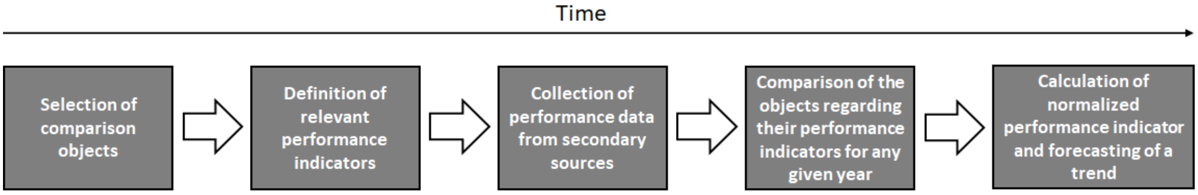
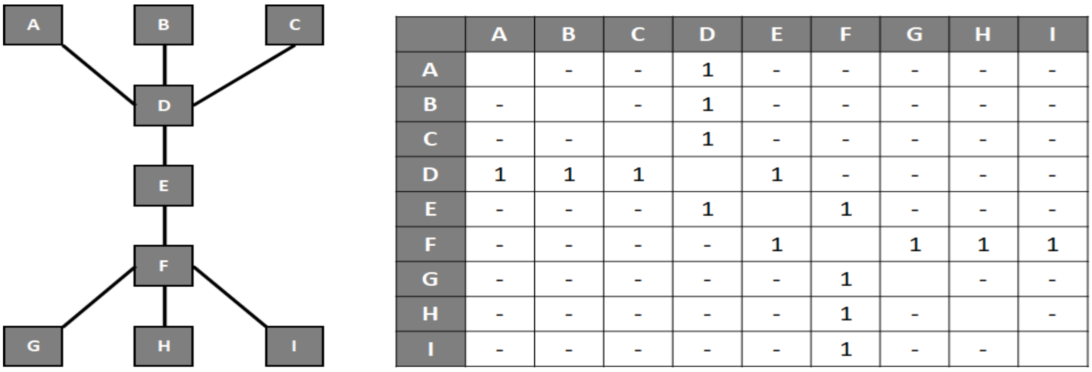


Figure 19: Graphical representation of Daim´s, et al. study “Identifying and forecasting the reverse salient in video game consoles” (Daim et al., 2014)

2.6.5 Bottleneck identification from the system structure

Shipilov and Gawer (2020) described in their article *"Integrating Research on Inter-Organizational Networks and Ecosystems,"* another interesting approach for the identification of bottlenecks. In this paper, they defined component centrality as the crucial factor in a network of complementarities for determining to which extent a component can become a bottleneck. This approach stems from the field of graph theory, which suggests that there are different centralities of interest, where the degree centrality is the basis. (Shipilov and Gawer, 2020, p. 110ff)
The degree centrality in graph theory refers to the number of links incident on a node (Sharma and Surolia, 2013, p. 558). Transferred to the network of complementarity, this means that the value of the degree centrality of a component increases with an increasing number of actor connections. In order to get a better overview of this basic pattern of complementarities, an example of a nine-component ecosystem is illustrated in Figure 20. (Shipilov and Gawer, 2020, p. 108ff)



	A	B	C	D	E	F	G	H	I
A		-	-	1	-	-	-	-	-
B	-		-	1	-	-	-	-	-
C	-	-		1	-	-	-	-	-
D	1	1	1		1	-	-	-	-
E	-	-	-	1		1	-	-	-
F	-	-	-	-	1		1	1	1
G	-	-	-	-	-	1		-	-
H	-	-	-	-	-	1	-		-
I	-	-	-	-	-	1	-	-	

Figure 20: Illustration of a basic pattern of complementarities in a nine-component-system (Shipilov and Gawer, 2020, p. 111)

In this example, component D (degree centrality of 4) is more likely to become a bottleneck than the components A, B, or C (degree centrality of 1) since component D has a direct interdependency with three other components. (Shipilov and Gawer, 2020, p. 110ff).
This means that a component is more likely to be a bottleneck if several other components depend on this component. In other words, if a focal component in the ecosystem has a poor performance or is taken out of the ecosystem, other components within the ecosystem will suffer much more from that than from a poor-performance component located at the periphery of an ecosystem's complementarity network. In their study, Shipilov and Gawer deduce eigenvector centrality (a measure of the influence a component has on the network) as the crucial parameter for identifying bottlenecks since the component's interdependency is related to the influence of an individual component on the entire ecosystem’s success. (Shipilov and Gawer, 2020, p. 110ff)

This approach of representing the complementarity of components/complements as a network can be done, for example, by conducting expert interviews to identify different components/complements within a system, followed up by the evaluation of the complementarity strength of them by the experts. This can provide a significant added value by helping to understand the interdependency of the components and complements. (Shipilov and Gawer, 2020, p. 112)

2.6.6 Summary of presented methods for the bottleneck identification

The five methods described for the bottleneck identification in an innovation ecosystem have already been applied in various technical industries (PC, semiconductor lithography, etc.). Some of these methods seem to fit better to the specific application area of this thesis than others.

The first described method, identifying bottlenecks via quantitative evaluation, is very well suited for longitudinal studies and is well applicable for secondary data analyses. However, in this method, the qualitative aspects of the bottlenecks cannot be evaluated, which would lead to only a limited quality of the results.

The second described method, identifying bottlenecks via a qualitative evaluation of secondary data, is well suited for longitudinal studies and results in qualitative findings, but the quality is strongly dependent on the selected data sources. The selection process of the data sources represents, especially in this method, a big challenge because the content should contain details for representative results. In addition, this method requires the analysis of several different data sources to avoid bias.

The third method presented, the identification of bottlenecks via a quantitative and qualitative evaluation, is likely to achieve a very high result quality. This is because both primary and secondary data are used for the analysis. The performance of the key elements is measured quantitatively (e.g., numbers derived from state-level databases) and qualitatively (e.g., qualitative assessment from media). The disadvantage of this approach is that the bottlenecks were primarily identified from interviews. For this reason, a large number of interviewees would be needed to cover the complete spectrum of the innovation (BEV and FCEV) on the one hand and to avoid bias on the other hand.

The fourth method, identifying bottlenecks via a performance comparison, can deliver an added value if it is possible to find comparison parameters. However, for this study, identifying bottlenecks in BEVs and FCEVs' innovation ecosystem, it is not a reasonable option since the objective is not to compare these two technologies but to look at them separately to find the individual technological bottlenecks.

The last described method, the identification of bottlenecks from the system structure, can provide highly objective results. However, creating the system structure can be challenging since a large amount of data is needed to obtain meaningful results. In addition, this method is only suitable to a limited extent for longitudinal studies. Especially when data is gathered from interviews by experts, they would have to recall how the interdependencies have changed over time. Moreover, this method does not reflect all aspects of bottlenecks (performance, quality, availability).

For these reasons, no single method is completely suitable for identifying bottlenecks in the innovation ecosystem of BEVs and FCEVs. However, the qualitative evaluation of bottlenecks described in chapter 2.6.2 and the concept for identifying bottlenecks from the system structure described in chapter 2.6.5 form the basis of the methodology used in this thesis. Nevertheless, several steps were partially adapted to the research topic and modified accordingly. The used methodology, with all its included steps, is now described in the next chapter.

3 Research methodology

In this chapter, the methodological choices of this research are described to answer the second research question:

- ***RQ2**: How did the most important technological bottlenecks in the innovation ecosystems of BEVs and FCEVs change from 2000 to 2020?*

For this purpose, the research design and research process choices are explained, and a detailed description of the individual research steps is provided. It is important to emphasize that the ecosystems of battery electric vehicles and fuel cell electric vehicles were analyzed separately, but synergies between those two topologies and their associated components/complements were considered if they were available.

The research design and the corresponding research process are divided into three main parts: qualitative content analysis, the network of complementarity, and research validation. This procedure is illustrated in Figure 21.

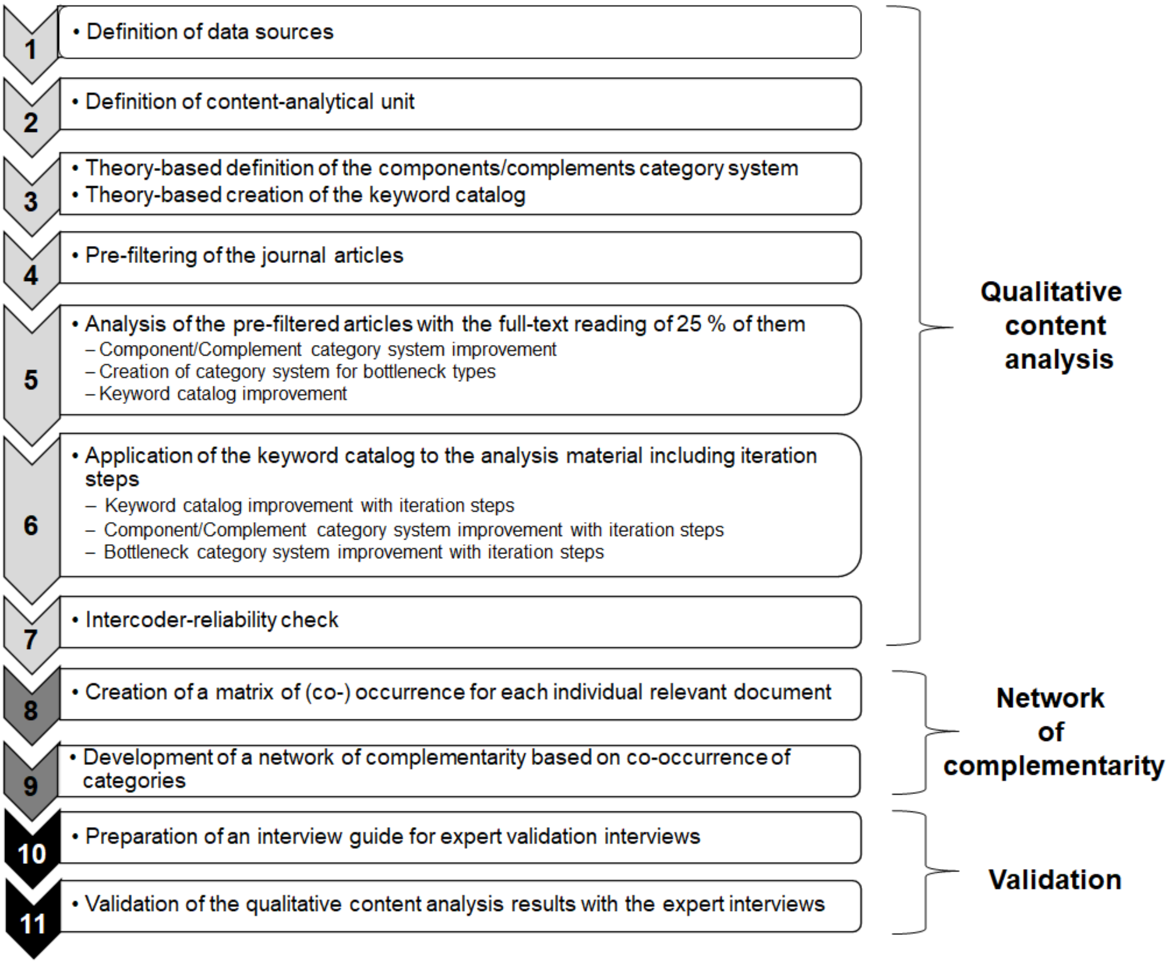


Figure 21: General procedural model of this thesis

The first part of the research design, the qualitative content analysis, is based on Mayring's (2015) concept. In this qualitative content analysis, data sources were selected and the articles of these data sources were analyzed. For this purpose, a category system was created based on the technological

structure of BEVs and FCEVs, which was inductively refined during the analysis. In addition, a keyword catalog was created to identify text passages that reflect a bottleneck by using a keyword search. As a consequence, not the entire analysis material had to be read in full text.
Furthermore, a category system for the four dimensions of bottlenecks (high costs, low quality, low performance, low availability) was defined to obtain more detailed results. In the final step of the qualitative content analysis, the supervisors of this work performed an intercoder reliability check. The individual steps of the analysis are explained in more detail in chapter 3.1.

Based on the results of this qualitative content analysis and Shipilov and Gawer´s (2020) concept, which describes that components/complements within an ecosystem can be represented as a network, a matrix of (co-) occurrence was created for articles that contained more than one bottleneck category (e.g., battery and charging station infrastructure). From these (co-) occurrence matrices, a network of complementarity was derived, reflecting which component/complement is more likely a bottleneck. This step is explained in more detail in chapter 3.2

The last step of this empirical part of the thesis, which is described in detail in chapter 3.3, was to validate the results from the secondary data analysis with expert interviews. For this purpose, an interview guideline was created to proceed in a correspondingly structured manner during the interview.

3.1 Qualitative content analysis

A content analysis makes it possible to quantify and analyze the meanings and relationships of themes and concepts within texts (Gheyle and Jacobs, 2017, p. 2).
A fundamental distinction in the content analysis is made between the quantitative and the qualitative approach. The first one focuses on the generation of hypotheses, sampling of data, a transparent priori coding scheme, and the finding of numerical concepts through mathematical operations of fragmented single variables to identify relationships between these variables (Gheyle and Jacobs, 2017, p. 3; Mayring, 2015, p. 17).
In contrast to that, the basic idea behind the qualitative content analysis is to retain the advantages of the quantitative content analysis (systematic approach, etc.) and transfer and further develop them into qualitative-interpretative analysis steps. In this process, the analysis tries to capture the full complexity of the analysis material and focuses on interpreting and understanding the material (Mayring, 2015, p. 17, 2014, p. 39). This method can handle large amounts of material, where a rule-guided systematic procedure is always defined in advance. (Mayring and Fenzl, 2014, p. 543; Mayring, 2014, p. 39)

The central instrument of a qualitative content analysis is the category system. The categories of this category system are formed either deductively or inductively. In the inductive category formation, the categories are formed during the material analysis. In contrast, in the deductive approach, the categories are defined before the material is worked through, mostly based on a literature research, and the text passages are then assigned to these categories accordingly. Usually, the frequency of occurrence of the categories is determined and statistically analyzed afterwards. The categories represent a short description of the objects of analysis and are closely oriented to the analysis material. During the material analysis, only text passages are considered, which refer to one of these categories. (Mayring and Fenzl, 2014, p. 544; Mayring, 2015, p. 85)
The basic process model of a qualitative content analysis is shown in Figure 22. In this process model, as already described above, a distinction is made between inductive and deductive category formation.

The first step of the analysis includes the concretization of the research question to find a link to the theory. This involves building on the experiences of others to achieve progress in the field of know-how (Mayring, 2015, p. 60).

In the next step, the material, which has to be analyzed, must be defined and formally characterized, i.e. the form in which the material is available must be described. For content analyses, a written text is always required. These texts do not have to be written by the author himself but can also have their origin, for example, from an interview with an expert. (Mayring, 2015, p. 55)

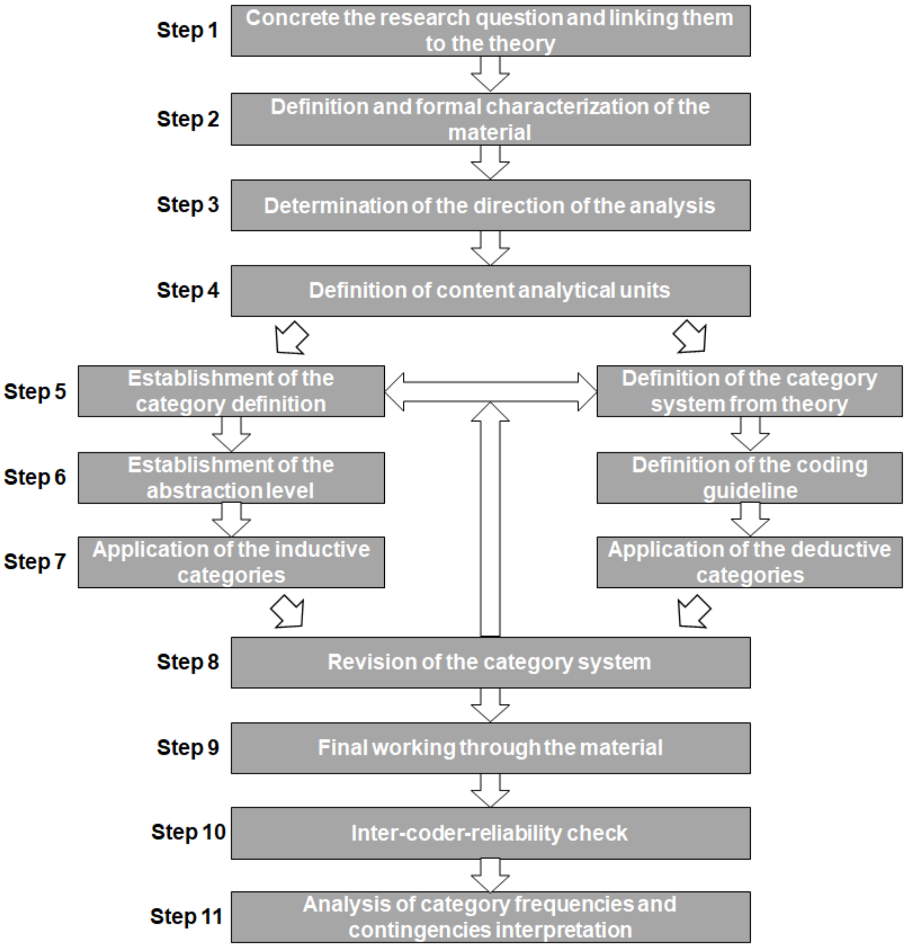


Figure 22: A process model of inductive category formation and deductive category application (Mayring and Fenzl, 2014, p. 550; Mayring and Brunner, 2006; Mayring, 2014)

In the third step, the direction of the analysis must be defined. In principle, the purpose behind the analysis of a language material can have different reasons. For example, a text may be analyzed to get some information about the author, or the object of interest may be the subject treated in the text. This direction of the analysis must be determined in advance. (Mayring, 2015, p. 59)

This step is followed up by the definition of the content analytical unit since a central element of content-analytical procedures is not to interpret the text as a whole but to divide it into segments (Mayring, 2014, p. 51).

In the fifth step, a distinction is made between inductive and deductive category formulation. In the inductive category formation, the theme of categories and the level of abstraction have to be determined in advance. This means that theory-based selection criteria are determined to define the selection process in category formation and the abstraction level of the categories. After this, the material is worked through line by line, and as soon as a text passage fits a selection criterion, a category is formed based on the abstraction level. The next time a passage fits a selection criterion, either a new category is created, or this text passage is assigned to an existing one. (Mayring, 2015, p. 87, 2014, p. 81)

In the deductive category formation, a category system is defined based on literature in advance. A coding guideline is created to determine when a text passage is assigned to a category. Basically, each category is defined by three characteristics - the category definition, the anchor example, and the coding rules, as can be seen in an example in Table 4. (Mayring and Fenzl, 2014, p. 551)

Table 4: Example of a category in the qualitative content analysis including the definition, an anchor example, and the coding rules (Mayring, 2015, p. 111)

Category	Category definition	Anchor example	Coding rules
High self-confidence	*A high subjective conviction for having successfully coped with the situational demands, which means:* - *To be clear about the demands and their coping possibility* - *To have a positive, hopeful feeling in handling the situation* - *To be sure to have coped with the demands on one's own efforts.*	*"Of course, there had been some little problems, but we solved them all, either by myself or by the student, depending on who made the mistake. Everyone can make mistakes."* *"Sure, there had been problems, but in the end, we had a fine relationship. We got it all together."*	*All three aspects of the definition have to point to "high" self-confidence, no aspect only "medium" self-confidence.* *Otherwise, it belongs to a other category.*

According to this predefined coding guideline, the material is worked through, and the categories are tested regarding their applicability.

Step number 8 includes a revision and a reformulation of the category system. This step has to be performed in the deductive and inductive category formation and is followed up by the final material run-through (Mayring, 2014, p. 95).
Finally, the inter-coder reliability check is performed to obtain reliable results, and the frequency of category-mention is evaluated quantitatively (Mayring and Fenzl, 2014, p. 554).

After the theoretical and procedural description of the qualitative content analysis, according to Mayring (2015), the individual steps of the conducted qualitative content analysis, which can be seen in Figure 21, will now be discussed in more detail.

3.1.1 Definition of data sources

The first step in the procedure was the selection of the material for the analysis. For this purpose, the journals for the qualitative content analysis were selected based on predefined selection criteria. An overview of these criteria is shown in Table 5.

Table 5: Criteria for selection of data sources

Selection criteria
Availability from 2000 to 2020
Peer-reviewed international trade journal
Journal with focus on the automotive industry, including their trends and issues
At least two different journals from different geographical locations

The first criterion is based on the longitudinal study, making it necessary to cover the whole time period. The consequence is that as soon as a journal missed one year of this study period, this journal was excluded as this would distort the study.

In order to obtain high qualitative results, the second criterion is based on the fact that the articles had to be peer-reviewed to consider only scientific publications.

The third criterion is based on the fact that journals should be identified, reflecting the limitation of the value proposition to the customer. This means that the journals should not come from fundamental research, like fundamental chemical or physical research for batteries or fuel cells but should be based on application-specific issues (automotive sector).

Furthermore, it was important to select at least two different journals from different geographical locations to avoid bias or influence from country-specific car manufacturers.

In order to find suitable data sources, an intensive research on "Scopus" [8], “Springer Professional” [9] and "Google" with 20 examined journals and magazines was performed, but unfortunately, the majority of this material did not fulfill the predefined time frame of availability over the period from 2000 to 2020.

Furthermore, especially in the US market, a large number of consumer magazines are on the market, which fulfills the availability requirements, but the articles in the magazines do not meet the peer-reviewed criterion. An overview of all in the selection process investigated magazines and journals is shown in Appendix A.

Finally, two journals were found that met the selection criteria:

- Automobiltechnische Zeitschrift (ATZ)
- International Journal of Automotive Technology (IJoAT)

Automobiltechnische Zeitschrift (ATZ):

The ATZ is a German technological journal, which focuses on the automotive industry, especially on passenger and commercial vehicles. It provides information from the research and development of every possible aspect in automotive engineering. The articles in the journal are written by scientists and authors from the automotive industry. This journal was available in German as an e-paper from 1998 to 2020 on the "Springer Professional" platform. The English version of this journal, called “ATZworldwide,” has been available since 2001. (Reichenbach, 2021)

Since the “ATZ” fulfills all predefined selection criteria for the data sources, it was detected as a suitable source and was further used for the following qualitative content analysis.

International Journal of Automotive Technology (IJoAT):

The “International Journal of Automotive Technology” is a Korean journal that aims to publish and disseminate research results from all areas of automotive technology, including BEVs and FCEVs. The articles in the journal are written by researchers from different fields of expertise that contribute to the automotive industry. Additionally, these articles are peer-reviewed. The journal was first published in 2000 by the Korean Society of Automotive Engineers (KSAE) and is issued every other month, which means six times a year. (Bae, 2021)

Thus, the "International Journal of Automotive Technology" fulfilled the selection criteria and was deliberately chosen as the second journal for the qualitative content analysis to cover the Asian market in this thesis.

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[8] *“Scopus is the world largest abstract and citation database of peer-reviewed research literature with over 22000 titles from more than 5000 international publisher.”* (Elsevier B.V., 2021).

[9] "Springer Professional" is an online library founded by Springer Fachmedien Wiesbaden GmbH. On this platform are all books, which are published by Springer accessible and in addition, 532 journals from different areas of sciences are listed. (Springer Fachmedien Wiesbaden GmbH, 2021).

3.1.2 Definition of content-analytical unit

After the data source selection process had been finished, the direction of the analysis and the content-analytical unit had to be determined. The research questions clearly defined the direction of the analysis. That is why the analysis focuses on the content of articles. The analysis of the material was done article by article, i.e., an issue of a journal included up to 25 articles that are analyzed individually. The content-analytical unit had to contain at least the component or the complementary product or service and the associated reason for the limitation. Furthermore, a double coding of a text passage, i.e., two components/complements, was also possible. In the analysis, the two journals were examined one after the other. This means, first of all, the ATZ starting with the year 2020 up to the year 2000 was analyzed and afterwards the IJoAT. The results were evaluated on a year-specific basis.

3.1.3 Theory-based definition of the category system and the keyword catalog

The qualitative content analysis was performed by using a combination of deductive and inductive category formation. Therefore, the next step in the procedure involved developing a deductive category system for battery electric vehicles and fuel cell electric vehicles based on a literature research. This category system should be based on the technological structure of the two powertrain topologies, i.e., include on the one hand the components (e.g., battery) and on the other hand complementary products and services (e.g., charging station). In addition to the categories, a keyword catalog should be created as well, in which keywords are assigned to a category. This keyword catalog is required to detect text passages, which represent a bottleneck even if the article is not read in full text.

To get a basic understanding of the two powertrain technologies and their associated components and complements, a keyword search with the terms "electric vehicle," "battery electric vehicle," "fuel cell," and "fuel cell electric vehicle" was performed on the ″Springer Professional″ platform.

In the first step, this keyword search on the ″Springer Professional″ platform was only applied to books and book chapters. This means that no online articles or articles in journals were considered. The reason for including only books and book chapters in the first step of the keyword search is that these books/book chapters usually deal with the complete powertrain of a technology. Consequently, it was possible to get a holistic overview of the functional principle and the individual components and complementary products of BEVs and FCEVs.

In contrast, articles in journals usually focus on specific components/complements and their challenges. Such a detailed view on individual components/complements would not have been helpful in the first step because this high level of detail would not foster a basic understanding of the powertrain technologies.

In total, book chapters from twelve different books were read in full text in this step. These book chapters focused on the basics of the powertrains of BEVs and FCEVs. In these twelve chapters, the two powertrain topologies' key components and complementary products and services were presented. In most cases, these book chapters were divided into subchapters, where the header of these subchapters already included the name of a component or complement. Subsequently, a category for each component or complement that was described in detail was formed.

In the next step, to refine the category system, the bibliography of the twelve books was reviewed to find relevant literature. The relevant literature referred to sources that specifically contained the word “challenges” in their title or referred to an already defined category. After that, this relevant literature was read in full text. If a component/complement was described in detail in these sources, which was not yet in the category system, a new category was created for this component/complement.

In the last step, the keyword search with the keywords "electric vehicle," "battery electric vehicle," "fuel cell," and "fuel cell electric vehicle" in the ″Springer Professional″ platform was applied to journals. This step was necessary to extend the category system and the keyword catalog. For this purpose, a number of 19 papers were read in full text, which were selected based on their header. The header had to contain either an already defined category or the word "challenges." If a component or a complement was described in the papers, for which no category was formed yet, the category was created accordingly. The exact procedure for creating the keyword catalog is described in subchapter 3.1.3.4. However, articles from the selected journals (ATZ and IJoAT) for the qualitative content analysis were not considered.

3.1.3.1 Deductively created categories for BEVs

The category system for the ecosystem of battery electric vehicles that was developed in this step of the analysis can be seen in Table 6. Since it is crucial for the further course of the analysis, to understand the function of the individual components listed in this category system, these components are briefly described in Appendix B. The complementary products and services will not be discussed, as the category name already reflects their function.

Table 6: Deductively created categories for the innovation ecosystem of battery electric vehicles

Type of contribution	Category
Component	Battery
	E-Motor
	Transmission
	Power electronics
	Thermal management
	Vehicle body and chassis
Complement	Charging station infrastructure
	Electrical energy
	Disposal, transportation, and recycling
	Workshop and dealership

3.1.3.2 Deductively created categories for FCEVs

The category system for the ecosystem of fuel cell electric vehicles that was developed in this step of the analysis can be seen in Table 7.

Table 7: Deductively created categories for the innovation ecosystem of fuel cell electric vehicles

Type of contribution	Category
Component	Battery
	Hydrogen tank and supply
	Fuel cell
	Oxygen supply
	E-Motor
	Transmission
	Power electronics
	Thermal management
	Vehicle body and chassis
Complement	Hydrogen station infrastructure
	Availability and transport of hydrogen
	Disposal and recycling
	Workshop and dealership

Since it is crucial for the further course of the analysis, to understand the function of the individual components listed in this category system, these components are briefly described in Appendix C. The complementary products and services will not be discussed, as the category name already reflects their function.

3.1.3.3 Coding guideline for BEVs and FCEVs

After the categories were deductively formed, the next step included the creation of a coding guideline for the qualitative content analysis. This coding guideline is based on Mayring's (2015, p. 111) concept. This concept indicates that for each category, the corresponding inclusion criteria, which defines what is considered in a category, an anchor example, which serves as a text passage template for the associated category in the qualitative content analysis and, the exclusion criteria, which are intended to create delamination in the case of ambiguous assignment or overlaps between two categories, were defined.

This coding guideline is shown for battery electric vehicles in Appendix D and for fuel cell electric vehicles in Appendix E.

3.1.3.4 Deductively created keyword catalog for BEVs and FCEVs

In this section of the analysis, as already mentioned, a keyword catalog was deductively created beside the category formation. This keyword search should reduce the time effort necessary for the analysis because the full-text reading of all articles of the ATZ and the IJoAT was not required anymore.

In order to create this catalog, the already detected material for the category formation was used (see chapter 3.1.3). In addition to that, a keyword search on the ″Springer Professional″ platform with the keywords "Challenges EV" and "Challenges Fuel Cell" was performed. Ten additional papers were read (in addition to the twelve book chapters and 19 articles already described), and keywords were derived from this material.

In the first step, a keyword was added to the catalog whenever the papers/book chapters reported on challenging parts of the components and complementary products and services (e.g., electrolyte, anode, etc.). Challenging parts refers to parts of the components/complements that cause a limitation of the whole component or the complementary product/service.

However, since this was not sufficient to ensure the completeness of the keyword catalog, the next step was to add the reasons for the limitation of the components to the keyword catalog. These reasons refer to the physical properties of the individual components and complements (e.g., energy density, cold start ability, etc.).

Since keywords based on the physical properties and the subparts of the components/complements only led to limited results, especially for the complementary products, the category name or associated designations of the individual categories were added to the catalog in the last step (e.g., smart grid, workshop, etc.).

Nevertheless, the creation of the keyword catalog turned out to be extremely difficult, as different terms are frequently used as a synonym (e.g., electric grid, power grid, etc.), and the spelling of some keywords (e.g., bipolar plate, bi-polar plate, etc.) differentiate very often.

This was another important reason why this keyword catalog was extended and improved inductively during the analysis, which is outlined in chapter 3.1.5. The deductively created keyword catalogs for BEVs and FCEVs are shown in Appendix F and Appendix G.

After creating the deductive category system with the corresponding coding guideline and the deductive keyword catalog had been finished, the articles from the selected material, i.e., the

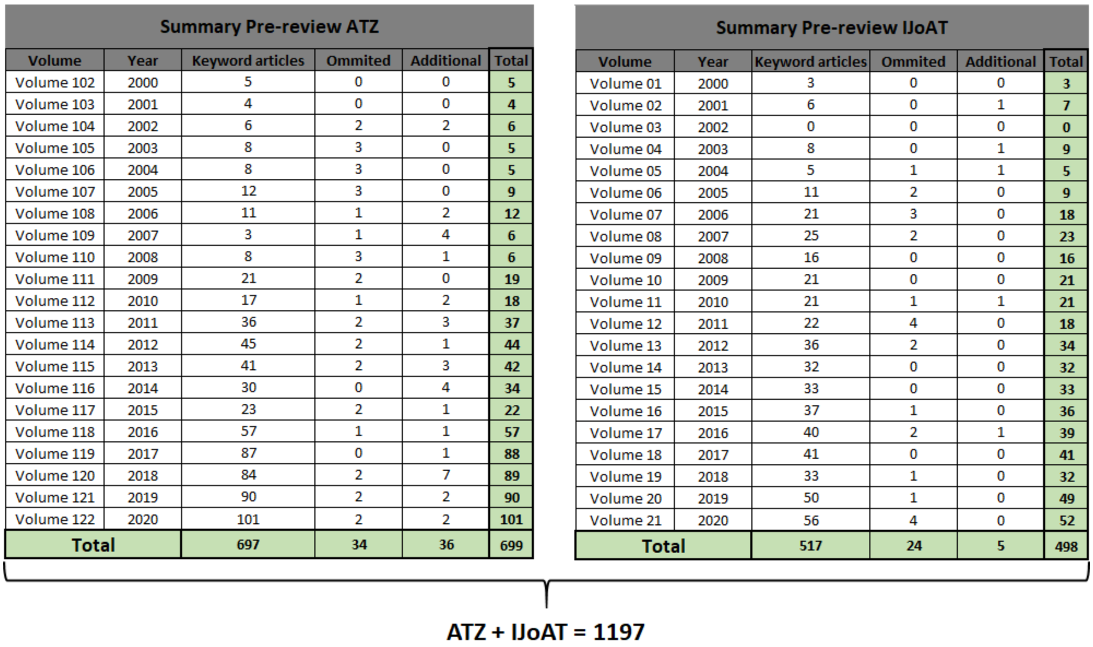
"Automobiltechnische Zeitschrift" and the "International Journal of Automotive Technology", were analyzed.

3.1.4 Pre-filtering of the journal articles

Since the “ATZ” and the “IJoAT” are general automotive journals, which cover a wide variety of topics across the automotive industry and are not specialized in battery electric vehicles and fuel cell electric vehicles, it was essential to perform an article pre-filtering process to exclude irrelevant content from the analysis and therefore save time and effort.

In the case of the “ATZ,” the English version of the journal was used for the analysis, i.e., “ATZworldwide,” which includes the same articles as the German-language “Automobiltechnische Zeitschrift”. However, since the “ATZworldwide” was published for the first time in 2001, the German version was used for the first year (2000) of the analyzed period. The “IJoAT” is consistently available in English language but includes only a limited number of published articles in the first years of the period under review, as shown in Appendix H.
This resulted in a combined total number of articles in the time period from 2000 to 2020 of 4343 (see Appendix H for the distribution across the years), which served as input for the pre-filtering process.

The pre-filtering process of the journal articles was performed by applying a keyword search in the “MAXQDA”[10] software. For this purpose, all 4343 articles were uploaded into the program and a lexical search was performed with the keywords "BEV", "FCEV", "Electric vehicle", "Electric car", "Fuel cell" and "Hydrogen". In order to ensure that no articles covering relevant topics (e.g., hybrid vehicles where possible synergies to BEV and FCEV exists) were excluded, the header of each individual article was read and analyzed as well. In this process, 41 articles were additionally found, which were not detected by the keyword search.
In contrast to that, other papers were omitted because the abbreviation "BEV" was repeatedly found in words such as "bevel" or "beverage", or keywords were only found in the bibliography of an article. A detailed list of the pre-reviews of the two journals is shown in Figure 23.



Summary Pre-review ATZ

Volume	Year	Keyword articles	Ommited	Additional	Total
Volume 102	2000	5	0	0	5
Volume 103	2001	4	0	0	4
Volume 104	2002	6	2	2	6
Volume 105	2003	8	3	0	5
Volume 106	2004	8	3	0	5
Volume 107	2005	12	3	0	9
Volume 108	2006	11	1	2	12
Volume 109	2007	3	1	4	6
Volume 110	2008	8	3	1	6
Volume 111	2009	21	2	0	19
Volume 112	2010	17	1	2	18
Volume 113	2011	36	2	3	37
Volume 114	2012	45	2	1	44
Volume 115	2013	41	2	3	42
Volume 116	2014	30	0	4	34
Volume 117	2015	23	2	1	22
Volume 118	2016	57	1	1	57
Volume 119	2017	87	0	1	88
Volume 120	2018	84	2	7	89
Volume 121	2019	90	2	2	90
Volume 122	2020	101	2	2	101
Total		697	34	36	699

Summary Pre-review IJoAT

Volume	Year	Keyword articles	Ommited	Additional	Total
Volume 01	2000	3	0	0	3
Volume 02	2001	6	0	1	7
Volume 03	2002	0	0	0	0
Volume 04	2003	8	0	1	9
Volume 05	2004	5	1	1	5
Volume 06	2005	11	2	0	9
Volume 07	2006	21	3	0	18
Volume 08	2007	25	2	0	23
Volume 09	2008	16	0	0	16
Volume 10	2009	21	0	0	21
Volume 11	2010	21	1	1	21
Volume 12	2011	22	4	0	18
Volume 13	2012	36	2	0	34
Volume 14	2013	32	0	0	32
Volume 15	2014	33	0	0	33
Volume 16	2015	37	1	0	36
Volume 17	2016	40	2	1	39
Volume 18	2017	41	0	0	41
Volume 19	2018	33	1	0	32
Volume 20	2019	50	1	0	49
Volume 21	2020	56	4	0	52
Total		517	24	5	498

ATZ + IJoAT = 1197

Figure 23: Number of articles used for the qualitative content analysis based on the pre-filtering process

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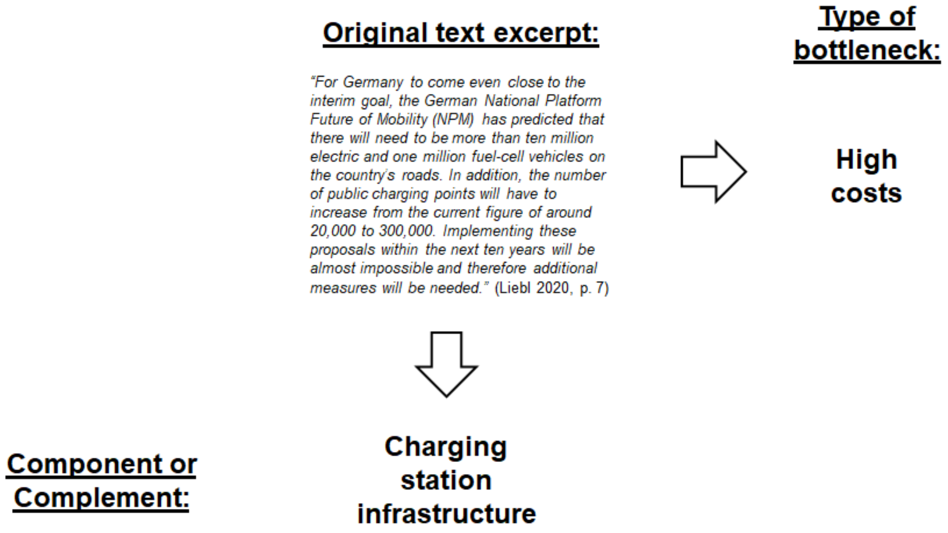
[10] “MAXQDA” is a software-package for qualitative data analysis and mixed methods research from the company “VERBI” and belongs to the “computer assisted qualitative data analysis software”. (Rädiker and Kuckartz, 2019, p. 2).

In total, 1197 articles were detected as relevant in this step of the analysis and thus served as input for the qualitative content analysis, which was conducted with the support of "MAXQDA" software and is described in more detail in the following subsections.

3.1.5 Analysis of the pre-filtered articles with the full-text reading of 25 % of them

The next step of the qualitative content analysis included the full-text reading of 280 "ATZ" articles from 2018 to 2020, representing approximately 25 % of the entire material. In this full-text reading, text passages, which matched the definition of bottlenecks, were coded according to the deductively created category system. When text passages matched the definition of bottlenecks and referred to a component or complementary product or service but could not yet be assigned to a category, new categories were formed inductively. Furthermore, the type of bottleneck (high costs, low performance, low quality, low availability) was coded for every text passage to detect why a component/complement had a limiting effect on the overall system. This means that each text passage was coded with a component or a complementary product or service on the one hand and with the type of bottleneck on the other hand. Figure 24 shows a coding example from the beginning of the article's full-text reading to give a better overview.



"For Germany to come even close to the interim goal, the German National Platform Future of Mobility (NPM) has predicted that there will need to be more than ten million electric and one million fuel-cell vehicles on the country's roads. In addition, the number of public charging points will have to increase from the current figure of around 20,000 to 300,000. Implementing these proposals within the next ten years will be almost impossible and therefore additional measures will be needed." (Liebl 2020, p. 7)

Figure 24: Coding example of a text passage at the beginning of the full-text reading

3.1.5.1 Component/Complement category system improvement

Since the reasons why a component or a complementary product or service represents a bottleneck can very often be traced back to a subcomponent, the categories were subdivided into subcategories.

Consequently, this level of detail would get lost if only a higher-level assignment to a main component/main complement would be performed. Furthermore, this would significantly reduce the quality of the analysis results.

Thus, for instance, the deductively created category "Power Electronics" for battery electric vehicles was inductively subdivided into the subcategories "HV protection system" and "Onboard charger". An illustration of the inductive extended category system for BEVs and FCEVs can be seen in Table 8. A further improvement of this category system was accomplished in the iteration steps described in chapter 3.1.6, and the final coding guideline is also presented in this chapter.

Table 8: Inductively extended categories for the innovation ecosystem of BEVs and FCEVs

Battery electric vehicle			**Fuel cell electric vehicle**		
Category	**Subcategory**		**Category**	**Subcategory**	
Components					
Battery	Battery cell	Battery anode	Fuel cell	Membrane Electrode Assembly (MEA)	Fuel cell catalyst
		Battery cathode		Bipolar plates	
	Battery production			Fuel cell production	
E-Motor	-		Oxygen supply	Air filter	
Transmission	-		Hydrogen system	Hydrogen tank	
Power electronics	HV protection system		Battery	-	
	Onboard charger		E-Motor	-	
Thermal management	Heating, Ventilation , and Air Conditioning (HVAC)		Transmission	-	
	Thermal management of battery		Power electronics	HV protection system	
	Thermal management of power electronics		Thermal management	Thermal management of powertrain	
				Heating, Ventilation and Air Conditioning (HVAC)	
Vehicle body and chassis	-		Vehicle body and chassis	-	
Complementary products and services					
Electric charging infrastructure	Charging station		Hydrogen refueling infrastructure	-	
	Digital integration		Availability and transport of hydrogen	-	
Electric grid	-		Disposal and recycling	-	
Disposal and recycling	-		Workshop and dealership	-	
Workshop and dealership	-		-	-	

Subcategories were only created for components and complementary products and services if these subcomponents (e.g., battery anode) were directly identified as bottlenecks in a text passage. By looking at the complementary products and services, it is noticeable that only a few subcategories were formed. This is because the splitting of, e.g., dealer and workshop, did not bring any added value because of the very low number of mentionings of these complementary services in the analyzed articles.

Nevertheless, some text passages were still directly assigned to one of the main categories (e.g., e-motor). Especially text passages that identified the battery as a bottleneck could frequently only be assigned to the main category battery and not to one of its subcategories. In these passages, batteries and their limitations were only discussed generally, and no subcomponent was explicitly mentioned.

3.1.5.2 Creation of category system for bottleneck types

In the course of the full-text reading of the articles, an additional category system was formed for the four types of bottlenecks. In other words, the high costs, low quality, low performance, and low availability were divided into subcategories. This procedure was done to increase the objectivity of the assignment and, more importantly, to increase the level of detail in the analysis results. Thus, the limitation of a component/complement at a specific point in time can be identified in more detail. For example, it makes a big difference if the battery has a limited lifetime or causes a safety risk. Without the subdivision of the four bottleneck types, the text passage would be assigned to the low-quality dimension in both cases.

Nevertheless, the direct assignment to a main category was still possible if no detailed information was available in the text passages. A list of these sub-dimensions (1st order codes) can be seen in Table 9.

Table 9:Bottleneck types with their associated 1st order codes

Type of bottleneck	1st order code
High costs	Costs of raw material
	Costs of electricity
Low quality	Safety risk
	Limited lifetime expectation
Low availability	Lack of infrastructure
	Lack of capacity (production)
	Lack of capabilities
Low performance	Limited range
	Low reliability
	Long charging time
	High weight
	Performance fluctuations
	Missing interoperability
	High complexity
	Bad dynamic behavior

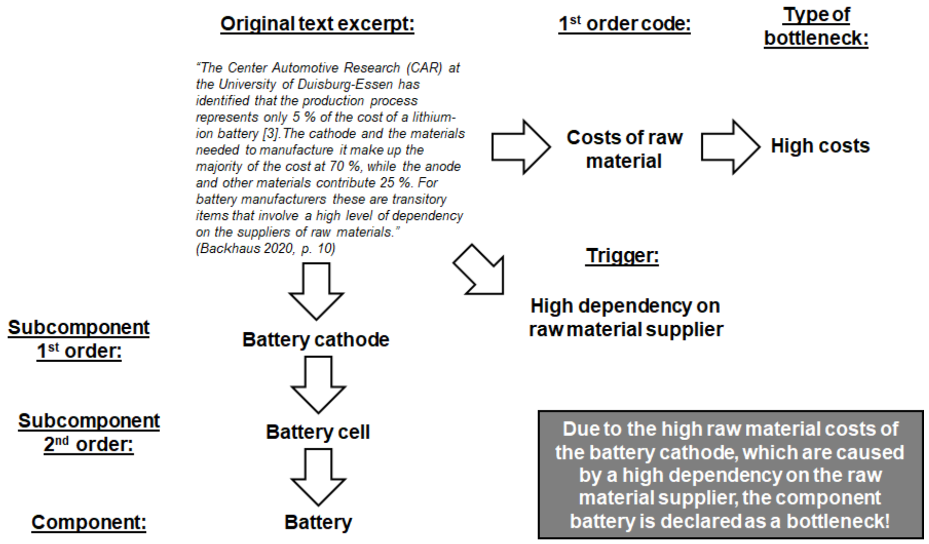
3.1.5.3 Trigger of a bottleneck and assignment example

In order to increase the accuracy of the assignment, an additional attempt was made to document influencing factors, i.e., the trigger for a bottleneck to occur (e.g., legal obstacles, shortage, etc.). However, this could only be partially realized due to the lack of information in the text passages.

The assignment of a text passage to one of the subcategories, to the type of bottleneck and the trigger for the bottleneck, will now be discussed using an example.

As shown in Figure 25, the first step was to assign a text passage to a subcomponent, respectively, the battery cathode. After this, the subcomponent can be unambiguously assigned to a component on a higher level according to the category system (in this case, the battery cell and, subsequently, the battery). The second coding step is based on the four bottleneck dimensions and their corresponding subdivisions. Since the costs of raw materials are mentioned in this text passage as very high, the assignment to the 1st order code "costs of raw material" is possible. This 1st order code, in turn, is, according to the category system part of the main bottleneck dimension, "high costs". In addition, the text passage describes the trigger for the high costs of raw material as well. In this case, the high costs for the raw material are caused by a high dependency on the raw material supplier.

The result of the analysis of the text passage is: Due to the high raw material costs of the battery cathode, which are caused by a high dependency on the raw material supplier, the component battery is declared as a bottleneck!



"The Center Automotive Research (CAR) at the University of Duisburg-Essen has identified that the production process represents only 5 % of the cost of a lithium-ion battery [3]. The cathode and the materials needed to manufacture it make up the majority of the cost at 70 %, while the anode and other materials contribute 25 %. For battery manufacturers these are transitory items that involve a high level of dependency on the suppliers of raw materials." (Backhaus 2020, p. 10)

Due to the high raw material costs of the battery cathode, which are caused by a high dependency on the raw material supplier, the component battery is declared as a bottleneck!

Figure 25: Coding example of a text passage after the precision of the categories and the bottleneck types

3.1.5.4 Keyword catalog improvement

Another task in this step of the analysis involved the revision and improvement of the keyword catalog, which was applied to the other 75% of the analysis material in the following step. This is described in detail in chapter 3.1.6. The goal of this task was to adapt the deductively created keyword catalog, which is shown in Appendix F for BEVs and Appendix G for FCEVs, in such a way that the keyword search identifies every text passage, which represents a bottleneck.

For this purpose, the keywords were formulated in a more general way. This means that, i.e., the keywords “charging speed”, “charging time,” and “charging plug” from the deductively created keyword catalog were adapted to the keyword “charging” to reduce the number of keywords and to counteract the problem of different names or spellings of various terms. This approach led to a more general naming of the keywords in the catalog but resulted in significantly more effort in the keyword search, represented in chapter 3.1.6. The minimum requirement for the keyword catalog was to have at least one keyword for each main category, which could also be the category name itself. An overview of all keywords of the keyword catalog is illustrated in Appendix I.

This catalog was further extended during the application (highlighted keywords in Appendix I), but this extension will be discussed in more detail later. The next step in the procedure was applying these keywords to the rest of the analysis material, which is the content of the following subchapter.

3.1.6 Application of the keyword catalog to the analysis material

The purpose of using the keyword search in the course of the qualitative content analysis was to reduce the time effort which a full-text reading of all articles would entail. The keyword search was conducted with the support of the “MAXQDA” software. In the first step, the predefined keyword catalog was applied to all pre-filtered ATZ articles from 2000 to 2017 (see chapter 3.1.4). The search was done in chronological order, starting in 2017. The general naming of the keywords in the catalog led to a tremendous effort to scan the keyword hits to identify text passages that declare a bottleneck.

The basic plan was to read the entire paragraph containing the keyword and to search for potential bottlenecks. However, due to the general naming of the keywords, almost all paragraphs of the articles contained a keyword. Thus, nearly all articles, with a few exceptions, were read in full text, as this meant comparatively less effort than clicking through the individual keyword occurrences. Those articles, in which only a single keyword was identified, were read according to the original concept, i.e., reading the paragraph in which the keyword was detected. Additionally, the neighboring paragraphs were read to determine whether this could be a relevant text passage or not. If the neighboring paragraphs contained a bottleneck text passage, the article was read in full text. If a text passage that declares a bottleneck was identified in the neighboring paragraphs or the paper and no keyword was included, the catalog was extended by the corresponding keyword.

After completing the analysis of all pre-filtered articles of the journal "Automobiltechnische Zeitschrift" from 2000 to 2017, the first iteration step followed.

3.1.6.1 Keyword catalog improvement with iteration steps

The purpose of the iteration was to apply the new keywords found during the application of the keyword catalog to the previously analyzed material. This should ensure that no text passages, which declare a bottleneck, were overlooked. However, since the keyword catalog was already designed in such general terms that it hit almost all relevant text passages, the keyword catalog was only extended with a few keywords before the first iteration step.

After completing this iteration step, in which additional text passages that declare a bottleneck had been detected, the extended keyword catalog was applied to the articles of the "International Journal of Automotive Technology".

In the second and last iteration step, i.e., after completing the first material run, the final keyword catalog (see Appendix I) was applied to the entire material to ensure no text passage that declares a bottleneck was overlooked. However, the last iteration step did not result in any new bottleneck occurrences, which can be traced back to the small number of new keywords.

3.1.6.2 Component/Complement category system improvement with iteration steps

In addition to the keyword catalog, the category system for the components/complements was also extended and improved based on new occurrences in the iteration steps. In this process, new subcategories were formed for the innovation ecosystem of BEVs as well as for the innovation ecosystem of FCEVs.

This resulted in the final category system for battery electric vehicles, shown in Appendix J, including the category definition, the anchor examples, and the coding rules. For fuel cell electric vehicles, this category system is illustrated in Appendix K.

3.1.6.3 Bottleneck category system improvement with iteration steps

In the process of applying the keyword catalog to the analysis material and the associated iteration steps, new subgroups were also formed for the four bottleneck dimensions, which are highlighted in Table 10.

Table 10: Final 1st order codes for the four bottleneck dimensions

Type of bottleneck	**1st order code**
High costs	Costs of raw material
	Costs of production
	Costs of electricity
Low quality	Safety risk
	Limited lifetime expectation
Low availability	Lack of infrastructure

	Lack of capacity
	Lack of capabilities
	Lack of raw material
Low performance	Limited range
	Low reliability
	Long charging time
	High weight
	Performance fluctuations
	Missing interoperability
	Low efficiency
	High complexity
	Bad dynamic behavior
	Limited capacity

3.1.6.4 Summary of the application of the keyword catalog

Basically, the deductive first step, performed in chapter 3.1.3, and the subsequent full-text reading of 25% of the entire material and the associated improvement of the category system, the keyword catalog, and the precision of the bottleneck types, performed in chapter 3.1.5, created a solid foundation for the analysis. This means that the category system, the keyword catalog, and the subdivision of the bottleneck types only had to be improved minimally in this analysis section, including the iteration steps. Thus, no text passages, which represent a bottleneck, should have been overlooked due to paying high attention to the analysis procedure.
However, as it is common practice in qualitative research to obtain reliable coding results, the two supervisors of this thesis conducted an intercoder reliability check whose theoretical basis and procedure will be discussed in more detail in the next chapter (Mayring, 2015, p. 124).

3.1.7 Intercoder-reliability check

In order to provide a scientific added value, a qualitative content analysis must be tested based on quality criteria. In social science research, the focus is primarily on two parameters, which is, on the one hand, the reliability and, on the other hand, the validity of the results obtained. In this context, reliability is regarded as the basic prerequisite for validity. These two classical quality criteria can be determined with many different methods, but their transferability to the qualitative content analysis is often seen very critically since different methods do not reflect the applicability in the content-analytical approach. For example, the parallel test as reliability check, which includes applying the research question on a sample using different instruments, is problematic because the equivalence of different instruments in analyzing language material is given very rarely. (Mayring, 2015, p. 123f, 2014, p. 107f)

In this section of the analysis, reliability is in the focus of interest. The validity of the results will be discussed in chapter 3.3. Concerning reliability, the intercoder reliability check is the commonly used procedure in qualitative content analyses. Several people carry out the entire analysis and compare the results to reach an inter-coder agreement. (Mayring, 2015, p. 123f, 2014, p. 107f)

The intercoder reliability check in this thesis was performed on selected sections of the analysis material. This concerned those text passages in which a clear assignment to a category or to a bottleneck type was very difficult or even not possible. For this purpose, the two supervisors of this work were asked to code these ambiguous text passages according to the in chapter 3.1.6 developed category system and the subdivision of the bottleneck types. These text passages were subsequently coded independently by both supervisors and then compared with the coding results from the previously performed qualitative

content analysis. If there were differences in the coding of text passages between the results of the qualitative content analysis and the supervisors' coding, these text passages and their different interpretations were put into a document and discussed to achieve a mutual agreement.
After the intercoder-reliability check was finished, all text passages which had not been covered by this check were rechecked and, if necessary, aligned with the interpretations agreed in the check to ensure consistent coding. However, this was only the case for a minimal number of text passages since the critical ones were included in the intercoder-reliability check.

All text passages of the analysis material, which represented a bottleneck in the ecosystem of BEVs or FCEVs, are shown, with their corresponding codings according to the category system and to the subdivision of the four dimensions of bottlenecks, in Appendix L for the BEV and Appendix M for the FCEV.

The intercoder-reliability check completed the qualitative content analysis. The validation of the results is discussed in chapter 3.3. In the course of the study, it became apparent that many double codings (two categories) of text passages and multiple codings in one analysis article (e.g., ATZ article) occurred. Therefore, it was possible to create a network of complementarity, which will be described in the next step.

3.2 Network of complementarity

To determine which limiting components and complementary products and services influence each other and thereby jointly limit the value proposition to the customer, a network of complementarity was formed for the ecosystem of BEVs and FCEVs in the course of this thesis. This approach is, as already mentioned, based on Shipilov and Gawer's (2020) assertion that the complementarity of components and complementary products/services can be represented as a network. For this purpose, a matrix of (co-) occurrence was formed for each of the 1197 pre-filtered analysis articles if the article contained more than one bottleneck category (e.g., battery and charging station infrastructure). First, these matrices of (co-) occurrences reflect which components or complements were mentioned in the same context. Secondly, they outline the limitations of the components and complements, making it easier to find logical correlations between the mentioned bottleneck categories. An overview of all these matrices of (co-) occurrences for battery electric vehicles is shown in Appendix N. Appendix O provides an overview of these matrices for fuel cell electric vehicles.
As a result of the large number of articles that jointly identified components/complements as a bottleneck and, consequently, the large number of matrices of (co-) occurrences, it was possible to form a complementarity matrix in which one can see which bottleneck components and complements have a complementarity on each other.
This made it possible to calculate the degree centrality of the individual components/complements to determine which component/complement plays a central role in the ecosystem and thus represents the key bottleneck. Furthermore, the frequency of joint mentions could be used to determine the causality of the complementarity.
The results and the graphical representation of the networks are presented in chapter 4.2 for BEV and in chapter 4.4 for FCEV.

3.3 Validation of the results

The second quality criterion, validity, described in chapter 3.1.7, was achieved for this thesis with the help of expert interviews. Expert interviews are qualitative interviews in which people are interviewed as specialists for specific topics (Hopf and Schmidt, 1993, p. 15). This means that the expert interview stands for a particular method used for a specific purpose. Thus, experts are not the object to be studied, but they witness the relevant processes for the analysis. (Gläser and Laudel, 2010, p. 12)

As part of the qualitative research, these expert interviews are primarily conducted as non-structured interviews, where neither questions nor answers are standardized, or as semi-structured interviews, where certain guidelines are implemented in a non-structured interview. In contrast to that, quantitative research uses mostly structured interviews, in which both the questions and the answer options are the same for all interviews. This means that closed questions are asked in a fixed order. (Gläser and Laudel, 2010, p. 41)
For the validation of this thesis, semi-structured expert interviews were chosen. The next step included the draft of an interview guide, which will be explained in detail in the following subchapter.

3.3.1 Preparation of an interview guide for expert validation interviews

The interview guide includes the most important questions that must be answered in each interview. However, neither the formulation of the questions nor the order in which the questions are asked is binding. This is intended to ensure that the interview proceeds as naturally as possible, i.e., that the interviewees themselves come up with specific topics. In order to answer a question completely, follow-up questions are usually necessary. However, these are not noted in the guide. (Gläser and Laudel, 2010, p. 42)

The creation of the interview guide for this study included a subdivision of the time horizon from 2000 to 2020 into three time segments to validate the results of the qualitative content analysis as precisely as possible. A detailed subdivision into even more time segments, e.g., splitting up the time period in single years, did not seem to make sense, since remembering back to a single year would probably not be possible and would lead to difficulties in answering the questions by the experts and thus distort the results. It was attempted to define the time segments, which were not always clearly separable from each other, identical for both ecosystems, BEV and FCEV, to create a unified picture. Furthermore, the key questions were formulated uniformly for each of the three time segments, for BEVs and FCEVs, to obtain objective results over the entire study period.

The final guide which was used for the interviews can be found in Appendix P. The application of the guide while conducting the interviews is described in the following chapter.

3.3.2 Validation of the qualitative content analysis results with the expert interviews

After creating the interview guide, the next step was to select the experts for the interviews.
Since it was crucial for the scope of this work that the validation experts have scientifically based expertise in the field of both BEVs and FCEVs, it was obvious to select people who are generally involved in the research and development of alternative powertrains. Therefore, the validation of the results of both powertrain topologies can be performed with the same people. The number of validation interviews was already fixed to a number of three before the start of the thesis, and all of the interviews were performed via Cisco Webex[11]. In the preliminary phase of the interviews, a presentation that included a summary of the work was sent to the interview partners to give them an overview of the study. The interviews with the three selected interviewees lasted on average 1 ½ hour.

At the beginning of each interview, a presentation was shown to introduce the objective of this thesis and provide information on the purpose of the interviews. In addition, it was mentioned that when answering the questions, the interviewees should refer as precisely as possible to the time section currently under discussion. A visual support continuously assisted the entire interview period in the form

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[11] Cisco Webex is a video and web conferencing application from the company Cisco Systems, Inc.

of a presentation, which was intended to ensure that the interviewee constantly referred to the correct time period.

With the agreement of the interviewees, it was possible to make an audio recording of the interviews to be able to transcribe them afterward. All interviews were anonymized while being transcribed, as this is common practice when conducting expert interviews (Gläser and Laudel, 2010, p. 42)
The interviews were analyzed by applying a qualitative approach, i.e., the text passages reflecting a bottleneck in the transcripts were coded using the category system and the subdivisions of the bottleneck types, which was created in chapter 3.1.6 and analyzed accordingly. The validation interviews and their comparison with the results of the qualitative content analysis are presented in the next chapters.

These eleven steps, which are discussed in this chapter, illustrated the approach throughout the empirical part of this thesis. A high volume of data was acquired and analyzed by combining the qualitative secondary data analysis with validation through primary data, which led to the presented, discussed, and interpreted results in the next chapters.

4 Results of the analysis

In this chapter, the main findings of the qualitative content analysis are presented. The main objective of this research is to identify the change of bottlenecks in the innovation ecosystem of BEVs and FCEVs over the period from 2000 to 2020. For this reason, in the first section, the obtained results for BEVs are presented. After that, the constructed network of complementarity based on these results is shown. In the second section of this chapter, the results for the innovation ecosystem of FCEVs are presented. The network of complementarities constructed for the ecosystem of FCEVs concludes this chapter.

4.1 Results of the qualitative content analysis for the ecosystem of the BEV

At the beginning of the study period (2000 to 2020), around the 2000s, relatively few articles in the selected journals focused on the powertrain topology of battery electric vehicles. Consequently, only a small number of bottlenecks were detected in the early 2000s, which can also be seen in Figure 26.
However, during the analysis, it became apparent that in this period (early 2000s), the electrification of the powertrain, in the form of hybrid electric vehicles, began. At this time, the main issues of battery electric vehicles concerned the battery and its low performance, which was attributable to the low capacity, the high weight, and long charging times (see Figure 29).
The fact that electrified powertrains picked up steam over the study period can be seen in Figure 26, which illustrates that the number of detected BEV bottlenecks in the journal articles strongly increased over the study period.

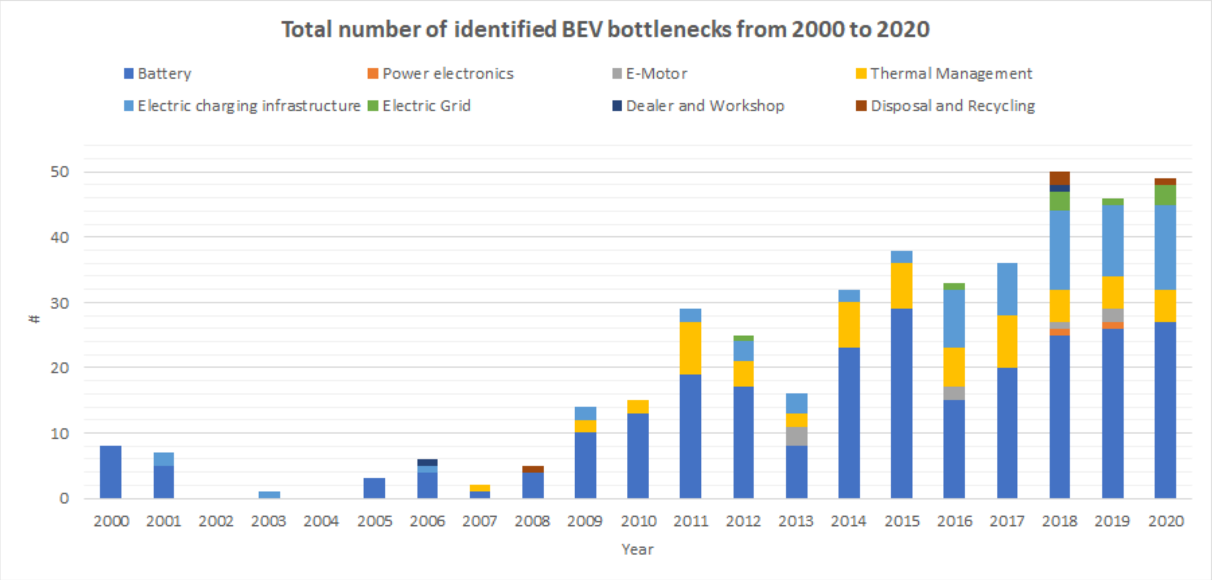


Figure 26: Total number of identified BEV bottlenecks in the ATZ and IJoAT in the period from 2000 to 2020

However, this figure makes the impression that the technology has more bottlenecks in 2020 than at the beginning of the millennium. Since the number of analyzed articles (pre-filtered articles) has also increased significantly, Figure 27 shows the identified BEV bottlenecks relative to the total number of articles published in the two journals dealing with BEVs and FCEVs. This chart also confirms the statement from above, that especially at the beginning of the study period, the battery was the decisive limiting factor.

In particular, the year 2000 shows a disproportionate number of bottlenecks in relation to the articles dealing with BEVs and FCEVs. This can be explained by the limited number of published articles in the two journals. Furthermore, in this year, the IJoAT was founded and published their issues for the first time, in which they presented different powertrain topologies with their potentials and challenges. The majority of the eight detected BEV bottlenecks in the year 2000 can be traced back to one of this IJoAT article.

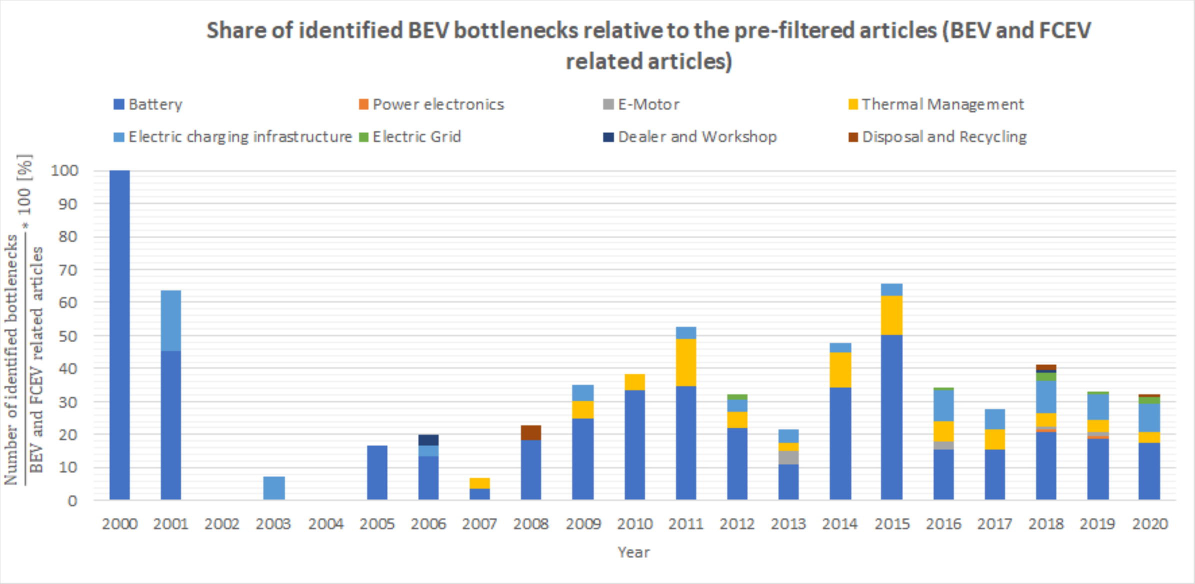


Figure 27: Share of identified BEV bottlenecks relative to pre-filtered ATZ and IJoAT articles in the time period from 2000 to 2020

In the following years (2000 to 2007), it was noticeable that more and more attention was paid to the topic of hybrid electric vehicles, which were seen in various ATZ and IJoAT articles as an intermediate step towards the complete electrification of the powertrain. In these HEV articles, no bottlenecks were detected that could be transferred to the BEVs since the synergies between those two powertrain concepts exist for components like the power electronics or the e-motor, but not for the most limiting element at this time, the battery. The battery of an HEV is not comparable with the battery of a BEV because the requirements regarding energy and power density are completely different (Stephens et al., 2017, p. 5-1).

The data indicated that even in this period (2000 to 2007), in which comparatively few articles addressed the BEV topic, complementary products and services in the form of the electric charging infrastructure and dealer and workshops were already a bottleneck.

From 2008 onwards, it became apparent that more and more articles in both journals referred directly to BEVs and no longer only focused on hybrid electric vehicles, which is also reflected by the number of detected bottlenecks (Figure 26 and Figure 27).
Starting at this time, more and more manufacturers also paid attention to other issues besides the battery technology. This included topics such as thermal management, for comfort, efficiency, and safety reasons, or the recycling process of the batteries to reduce costs.

From 2016 onwards, in addition to the battery and the thermal management, some complementary products and services also turned out to be bottlenecks. Especially in the ATZ, the charging infrastructure was due to the lack of availability and fast charging capability, often seen as a bottleneck for the ecosystem’s growth. In recent years, due to the multiplication of battery electric vehicles operated by end customers, the electric power grid or rather the required expansion in rural areas was also seen as a bottleneck.

After this overview of the analysis' results, the detailed results (subcomponents, type of bottlenecks) for the individual components and complementary products and services in the category system are shown in the following subsections.

4.1.1 Battery

The detected text passages, representing a battery bottleneck in most cases, referred directly to this main component, which made the assignment to a subcomponent only partially possible. Nevertheless, some text passages were found from 2010 onwards, see Figure 28, which directly refer to the battery cell, the battery management system, or the battery production.

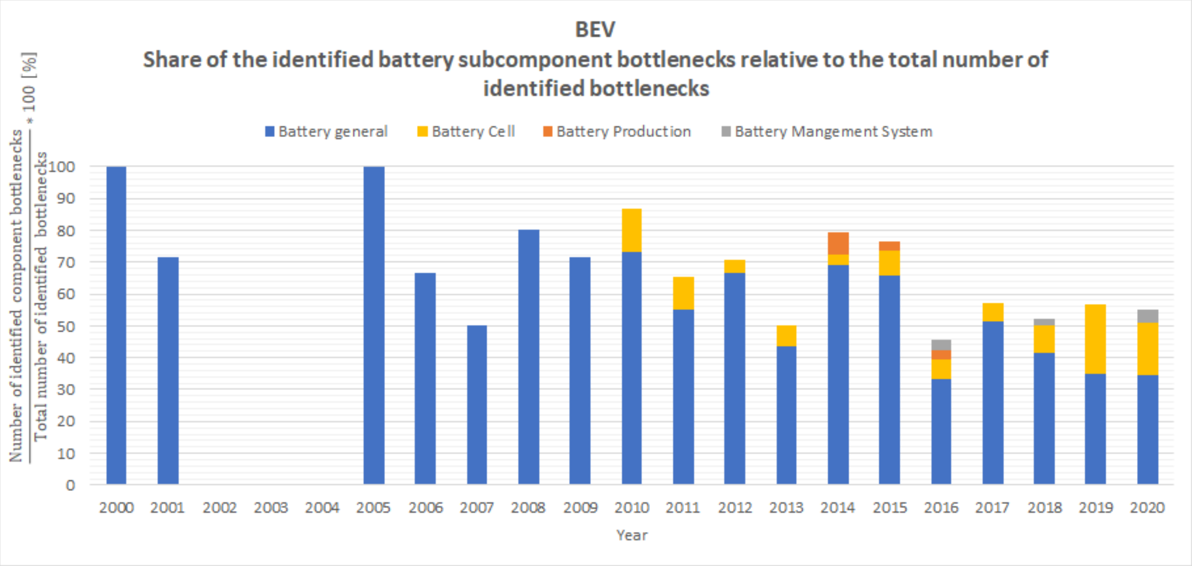


Figure 28: Share of the identified battery subcomponent bottlenecks in the innovation ecosystem of BEVs relative to the total number of identified bottlenecks

As already mentioned above, the battery was the key bottleneck for the value proposition to the customer over the analysis's entire period. At the beginning of the 2000s, issues concerning the low range, high weight, and long charging times of the batteries resulted in this bottleneck. These issues were triggered by the fact that the batteries used had only a low energy density and were not fast-charging capable at that time.

As a result of progress in battery technology, the gravimetric energy density (trade-off between battery weight and achievable driving range) increased significantly but was mainly in the mid-2000s, still significantly too low to achieve an acceptable driving range. Thus, the performance remained a reason why the battery was identified as a bottleneck. Furthermore, battery quality issues also became more and more limiting for the BEVs value proposition to the customer. In fact, from 2006 onwards, the limited lifetime of batteries, caused by damage from deep discharging and aging effects, was a significant issue for battery electric vehicles.

With the introduction of the lithium-ion technology, the battery cost issue received more and more attention and was identified as one of the main limiting factors at the beginning of the 2010s. The high battery costs can be traced back to the required raw materials (Lithium, Cobalt) and the high production costs (battery production in Figure 28) resulting from missing scaling effects. Figure 29 underlines this claim, with battery costs being a crucial limitation, especially from 2009 to 2015.

At that time, the quality of the battery in terms of durability was still a major issue. Additionally, new problems regarding the battery's safety emerged. The safety issues can be attributed to the flammability of the electrolyte in lithium-ion batteries, which can lead to a thermal runaway of the battery cells.

The performance of the batteries continued to limit the BEVs' value proposition to customers at this time (from 2009 onwards). This performance issue was caused by the low energy densities of the batteries, which resulted in a tradeoff between weight and achievable driving range, and thus also affected the capacity of the batteries. Another issue limiting the battery's performance, which became increasingly important from 2008 onward, was the dynamic behavior of the battery, which was limited by a low power density.

The analysis showed that the BEVs gained momentum (from 2008 onwards). But especially in the early 2010s, there were many unresolved issues, many limitations still had to be identified, and the costs were far from what would have been acceptable for most end customers. However, as an increasing number of articles in the two journals addressed the topic of BEVs, and consequently, more bottlenecks were detected, the battery was still the key bottleneck (see Figure 28: 50% of all bottleneck text passages in 2013 refer to the battery), but other components and complements were also mentioned increasingly as having limiting effects for the ecosystem’s growth.

In 2013, due to the improvement of various technological parameters (energy density, etc.), other issues, such as the long charging times, came back into focus, as other technical hurdles that previously overshadowed everything else were solved. However, in the last two years of the analysis period (2019 and 2020), it became apparent that the long charging times were no longer a battery-related issue.

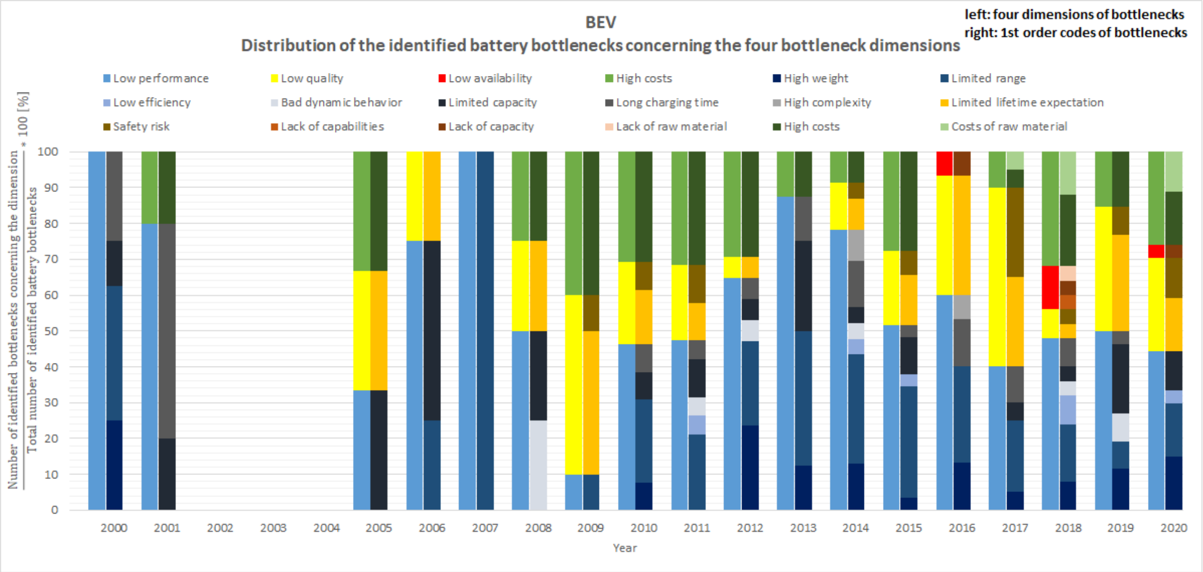


Figure 29: Distribution of the identified battery bottlenecks concerning the four bottleneck dimensions in the innovation ecosystem of BEVs

Furthermore, the battery still has enormous limitations concerning another subcategory of performance, the achievable driving range, which is still insufficient for a broad group of end customers. In recent years, the availability of batteries has also become a rising issue, as some battery production companies have reached their production capacity limits, and the raw material procurement process has become challenging. These difficulties in the procurement of raw materials directly impact the battery costs, which further remains a limiting factor until 2020, as well as the quality in terms of lifetime expectation and safety risks.

Additionally, the complexity and difficulty for an efficient implementation of the battery management system has been addressed repeatedly in the last five years, which can be seen in Figure 28. In this context, the efficient management of the energy quantity to achieve long electric driving ranges represents a major difficulty and limits the value proposition to the customer until today.

This means the analysis demonstrated, as already mentioned, that the battery was consistently the most significant bottleneck of the BEV´s value proposition over the entire study period, but the individual causes for this limitation have changed over the last 20 years. These causes were triggered by various influencing factors, which are summarized in Figure 30. At the beginning of the study period, this battery bottleneck was caused primarily by the performance and, to some extent, by the quality (lifetime) of the battery. The change to the lithium-ion battery technology has improved the performance significantly. However, it has resulted in new challenges, bringing the quality issue to the foreground, and these quality issues are remaining until today. The performance of the batteries still has a detrimental effect today, but its extent has lowered compared to the beginning of the 2010s. However, the battery costs are still a major issue today, having a huge negative impact on customer acceptance.

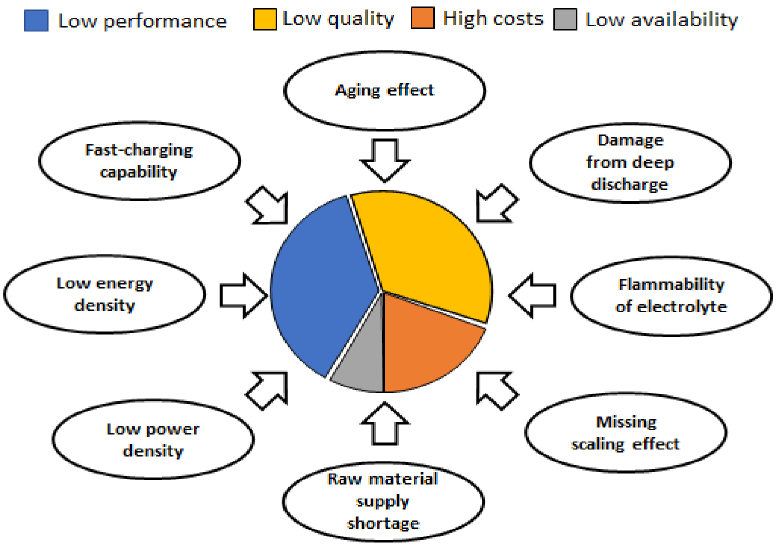


Figure 30: Trigger for identified battery bottlenecks in the innovation ecosystem of battery electric vehicles

4.1.2 Electric charging infrastructure

From the beginning of the study period until today, the electric charging infrastructure represented one of the key bottlenecks in the ecosystem of battery electric vehicles, besides the battery and the thermal management (from the late 2000s), which can be seen in Figure 27. In the early 2000s, the limitations were mainly related to the long charging times required (charging station performance), which was also influenced by the battery's non-fast charging capability, and the lack of public charging stations.

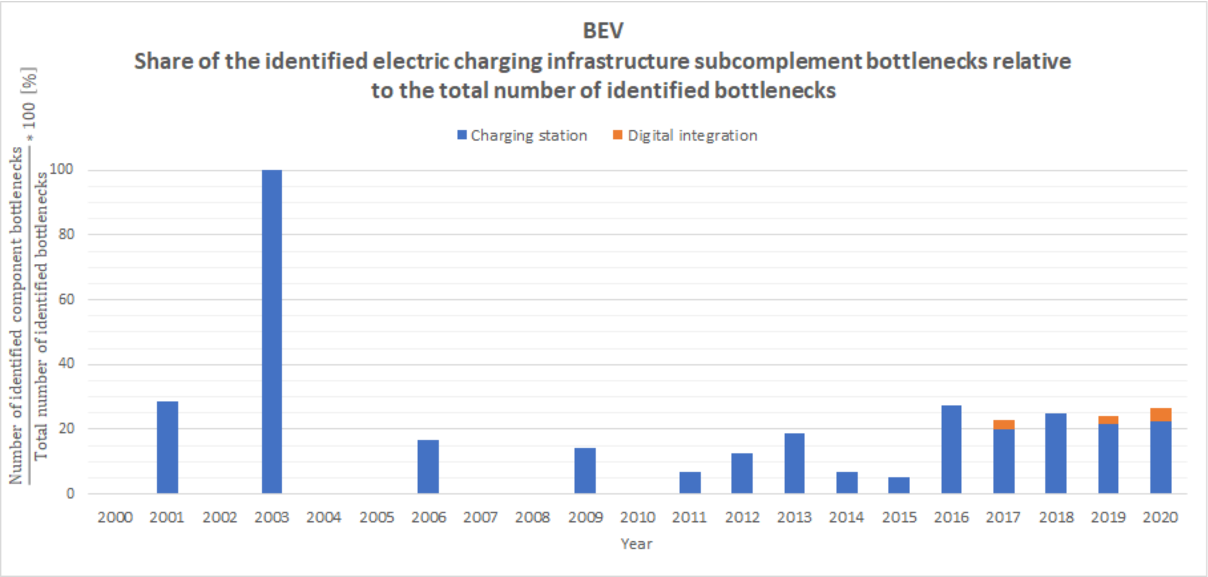


Figure 31: Share of the identified electric charging infrastructure bottlenecks in the innovation ecosystem of BEVs relative to the total number of identified bottlenecks

The fact that this complementary product was the only limiting component/complement in the ecosystem of battery electric vehicles in 2003 (see Figure 31) must be seen in relative terms because of the small number of articles dealing with BEVs and FCEVs in this year.

An interesting aspect is that the electric charging infrastructure began to have a continuous limiting effect on the ecosystem's growth from 2009 onwards.
Especially in the early 2010s (2011 and 2012), it became apparent that the variety of different charging plugs and their compatibility with the charging stations (missing interoperability) was a major problem. However, this standardization issue was not detected anymore in the further course of the analysis.

Another noticeable fact is that the missing public electric charging infrastructure has been mentioned repeatedly as one of the main issues, and since the year 2011, this availability issue is consistently seen as a crucial limiting factor. The analysis revealed that the main reason for the lack of charging infrastructure is the high expansion cost. Due to these high costs, it is often not very lucrative for the stakeholders to build new public charging stations, and thus they hesitate to expand the charging infrastructure further.

In addition to this availability problem, the charging stations' performance (long charging time) was becoming more limiting from 2015 onwards, as the charging process still takes a long time. The reason why the charging station performance became more and more limiting can be attributable to the development of the fast charging capability of lithium-ion batteries. This means that fast charging is no longer limited only by the battery but also by the charging station's power.

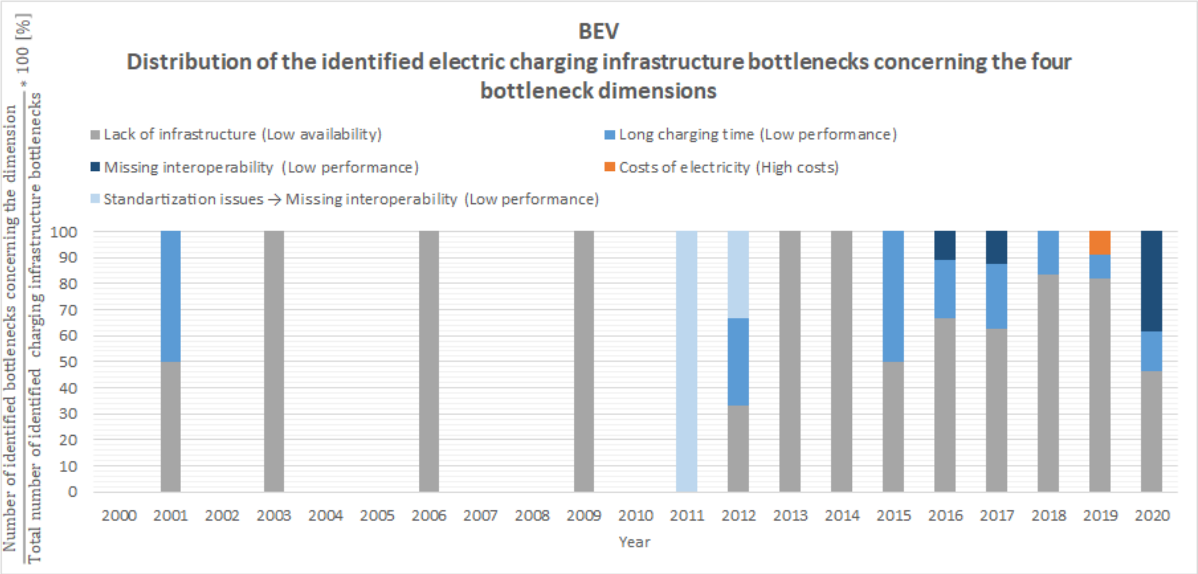


Figure 32: Distribution of the identified electric charging infrastructure bottlenecks concerning the four bottleneck dimensions in the innovation ecosystem of BEVs

In the last years of the analysis period (from 2017 onwards), the digital integration of the electric charging infrastructure became an additional issue (see Figure 31). This digital integration concerns the billing process and the compatibility of charging stations with various apps supporting the charging process. In this context, the communication interruption during the charging process or even the possibility to start the charging process represents a major issue since different providers use different apps for their charging stations. This lack of an overarching charging network usually causes a major obstacle for the end customer.

This means the analysis demonstrated, as already mentioned, that the electric charging infrastructure was consistently one of the key bottlenecks of the BEV´s value proposition over the entire study period, but the individual causes for this limitation have partly changed over the last 20 years. These causes were triggered by various influencing factors, which are summarized in Figure 33. The issue regarding the standardization of the charging plugs was solved during the study period, but new challenges regarding the billing process or the communication between the vehicle and the charging station arose. Other reasons why the electric charging infrastructure is still a bottleneck today are the lack of electric charging infrastructure, which was consistently seen as a limitation, and the low performance of the charging stations, which has been frequently mentioned as a limiting factor, especially since 2015.

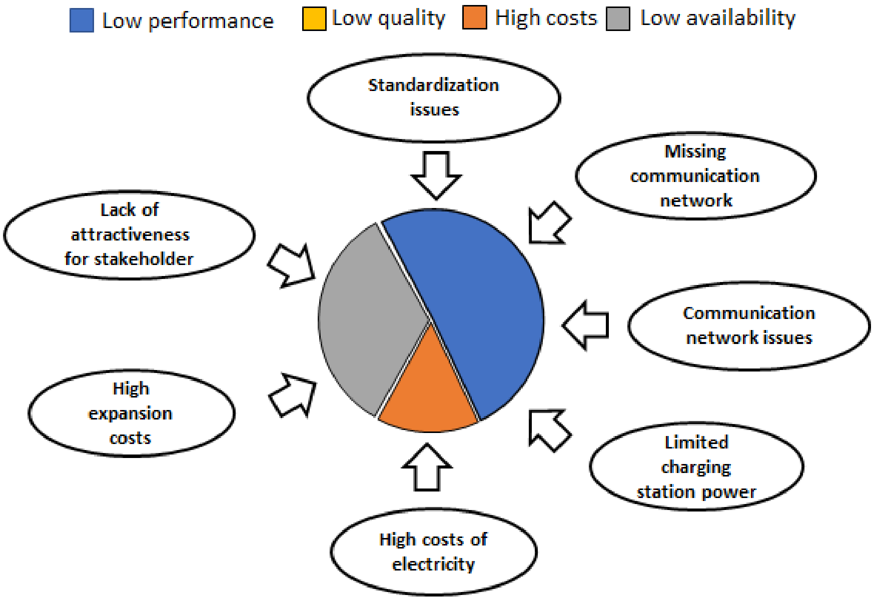


Figure 33: Trigger for identified electric charging infrastructure bottleneck in the innovation ecosystem of battery electric vehicles

4.1.3 Thermal management

Starting in 2009 the thermal management with its subcomponents was one of the key bottlenecks within the ecosystem because of its low performance. This can be seen in Figure 34.

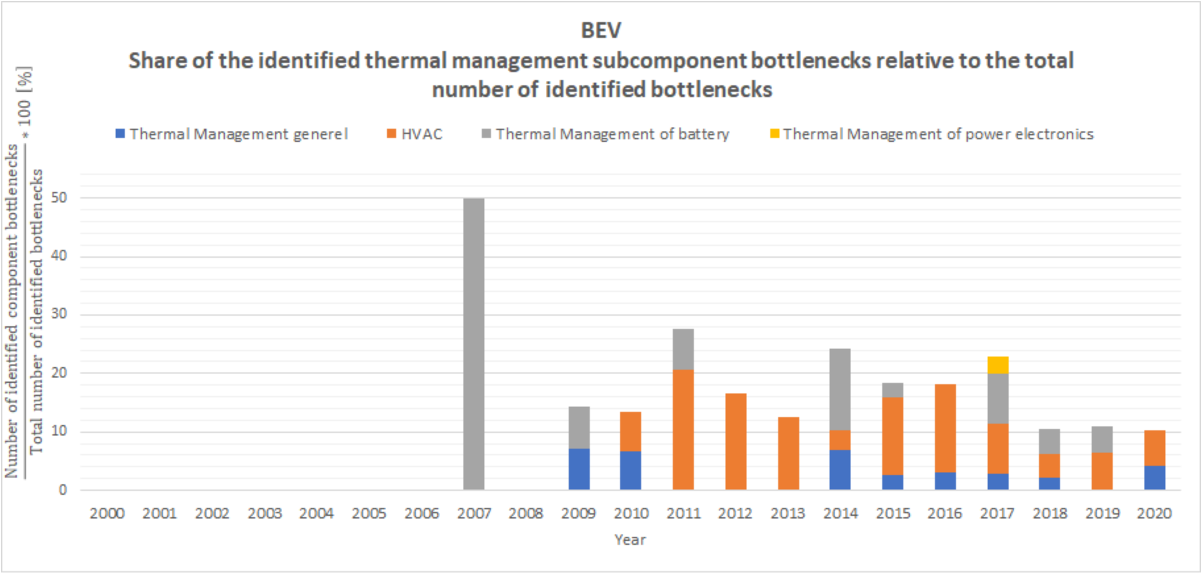


Figure 34: Share of the identified thermal management bottlenecks in the innovation ecosystem of BEVs relative to the total number of identified bottlenecks

The subcomponent thermal management of the battery was very often mentioned as a bottleneck, which can also be seen in Figure 34. From 2009 onwards, it became visible in the analysis that the heating and cooling procedure of the battery has a decisive influence on the performance, in terms of efficiency and charging speed, and additionally on the safety aspects (thermal runaway) of the battery. For these reasons, the thermal management of the batteries turned out to be very complex and represents a bottleneck until today.

In the early 2010s, when batteries had a very low energy density, HVAC was also a key bottleneck. This can be traced back to the fact that the required energy for air conditioning and heating the passenger compartment in a BEV had to be provided by the battery. Consequently, this energy is no longer available for propulsion, and the overall driving range of the BEV is getting reduced. However, in the last years of the analysis period (2018 to 2020), the extent of the limitation decreased significantly. Nevertheless, thermal management is still one of the key bottlenecks besides the battery and the electric charging infrastructure since the thermal management, as already mentioned, influences the entire vehicle's performance.

4.1.4 Electric grid

The electric grid played no role in limiting the value proposition to the customer until 2016. However, in the last years of the analysis period, this complementary product/service was increasingly identified as a bottleneck. This can also be seen in Figure 35, which shows that although the share is small compared to other detected bottlenecks, the electric grid represents in those years one of the key bottlenecks in the innovation ecosystem of BEVs, along with the battery, electric charging infrastructure and thermal management.

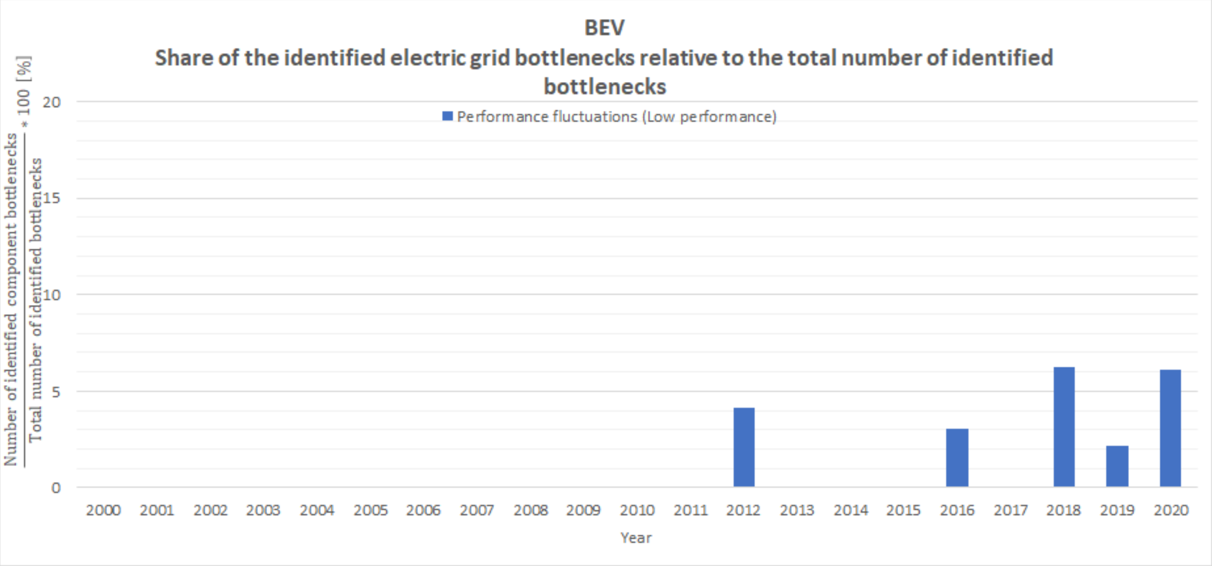


Figure 35: Share of the identified electric grid bottlenecks in the innovation ecosystem of BEVs relative to the total number of identified bottlenecks

An interesting finding of the analysis was that the amount of energy required for a complete transition to e-mobility would not be a problem, but the simultaneous charging of many vehicles would bring the electrical power grid to its limits, especially in rural areas. The resulting peak loads can cause interruptions of the charging process and thus represent an obstacle to the widespread use of BEVs.

4.1.5 E-Motor and Power electronics

In terms of limiting effects to the BEV´s value proposition, relatively little importance was attributed to the e-motor and power electronics in articles of the two journals. However, it was noticeable that until 2013, the e-motor and power electronics had not been identified as a bottleneck in any of the two journals' articles, which can also be seen in Figure 36.

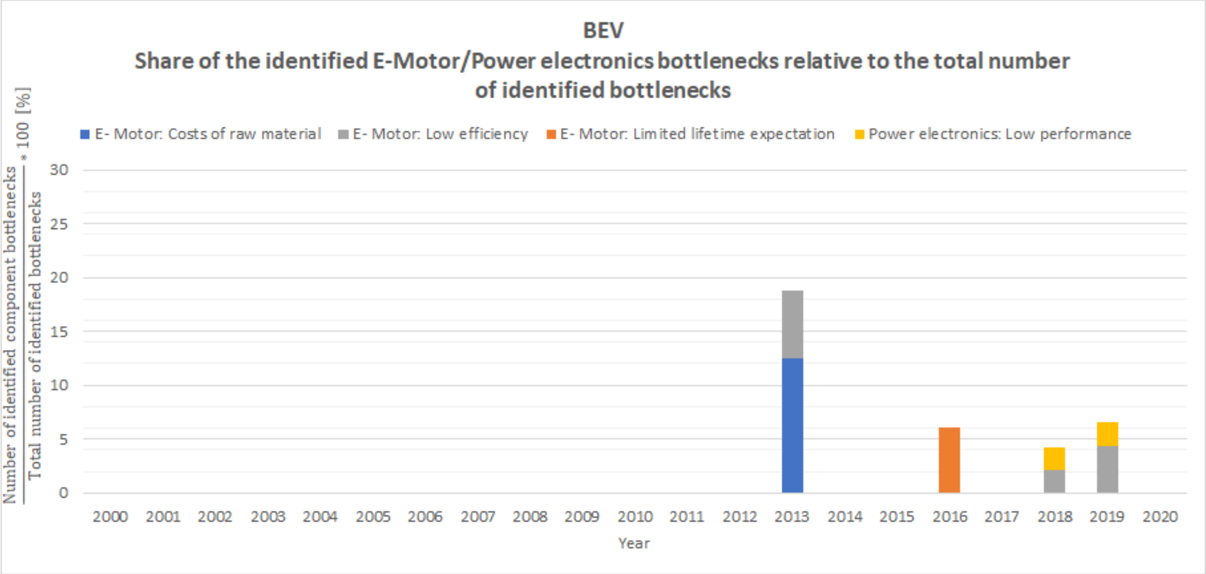


Figure 36: Share of the identified e-motor/power electronics bottlenecks in the innovation ecosystem of BEVs relative to the total number of identified bottlenecks

In general, all the text passages that described the e-motor as a bottleneck concerned the permanently excited machine. Thus, the limitations in 2013 were mainly related to the high cost of the raw materials, particularly neodymium, needed for permanent magnets of the electric machines. In addition to the cost issue of electric machines, the performance, or more precisely the efficiency of these machines, was also partly identified as the reason why the e-motor was a bottleneck. The insufficient quality in terms of the lifetime of the e-motors was only described as a limiting factor in one article.

The component power electronics was not identified as a bottleneck in any of the two journals until 2018. Even after that, this component was only seen in a very few text passages as limiting for the value proposition to the customer.

The analysis has shown that due to the minimal number of text passages, which declare the e-motor and the power electronics as a bottleneck, the two components have only a small limiting effect on the BEV´s value proposition to the customer. Nevertheless, in 2013, the e-motor had a comparatively high share relative to all detected bottlenecks in the innovation ecosystem of BEVs.

4.1.6 Dealer/workshop and disposal/recycling

The workshops responsible for repairing electric vehicles and the dealers hardly played a role in the articles of the two journals, as shown in Figure 37. This complementary service was already considered to be a bottleneck in 2006 but was only identified as a bottleneck once afterward. The triggers for these bottlenecks concerned missing qualification in repairing and selling vehicles with electric powertrains (BEVs, HEVs, FCEVs).

The complementary service of disposal and recycling has also been addressed very rarely. While the “disposal and recycling” was already detected as a bottleneck in 2008, as shown in Figure 37, it was not identified as a bottleneck until 2018. By 2018, this topic came back into the focus of battery manufacturers. The expensive raw materials required for battery production make the recycling process viable to keep the raw materials in the loop and reduce battery costs.

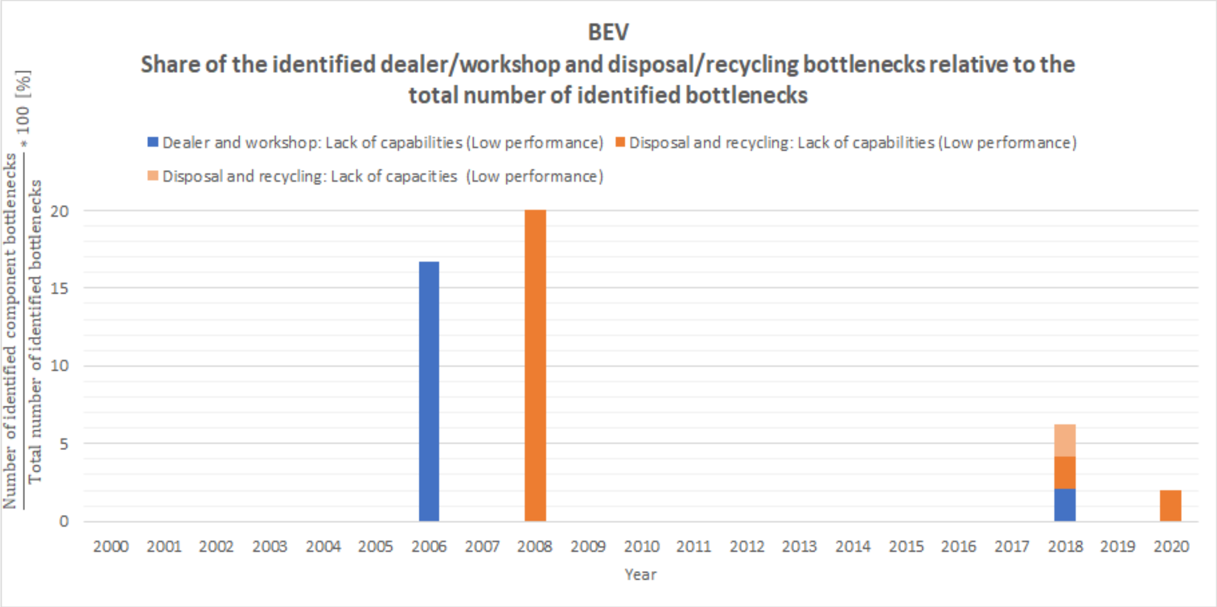


Figure 37: Share of the identified dealer/workshop and disposal/recycling bottlenecks in the innovation ecosystem of BEVs relative to the total number of identified bottlenecks

For this purpose, the topic of "Design for Recycling" was addressed in the articles, which should involve cooperation between battery manufacturers and recycling companies to perform the recycling process as efficiently as possible and thus reduce the costs. This lack of coordination between these two actors in the ecosystem (battery manufacturers and recycling companies) or rather the lack of recycling companies integrated into the ecosystem was therefore seen as an issue.

4.1.7 Summary of findings

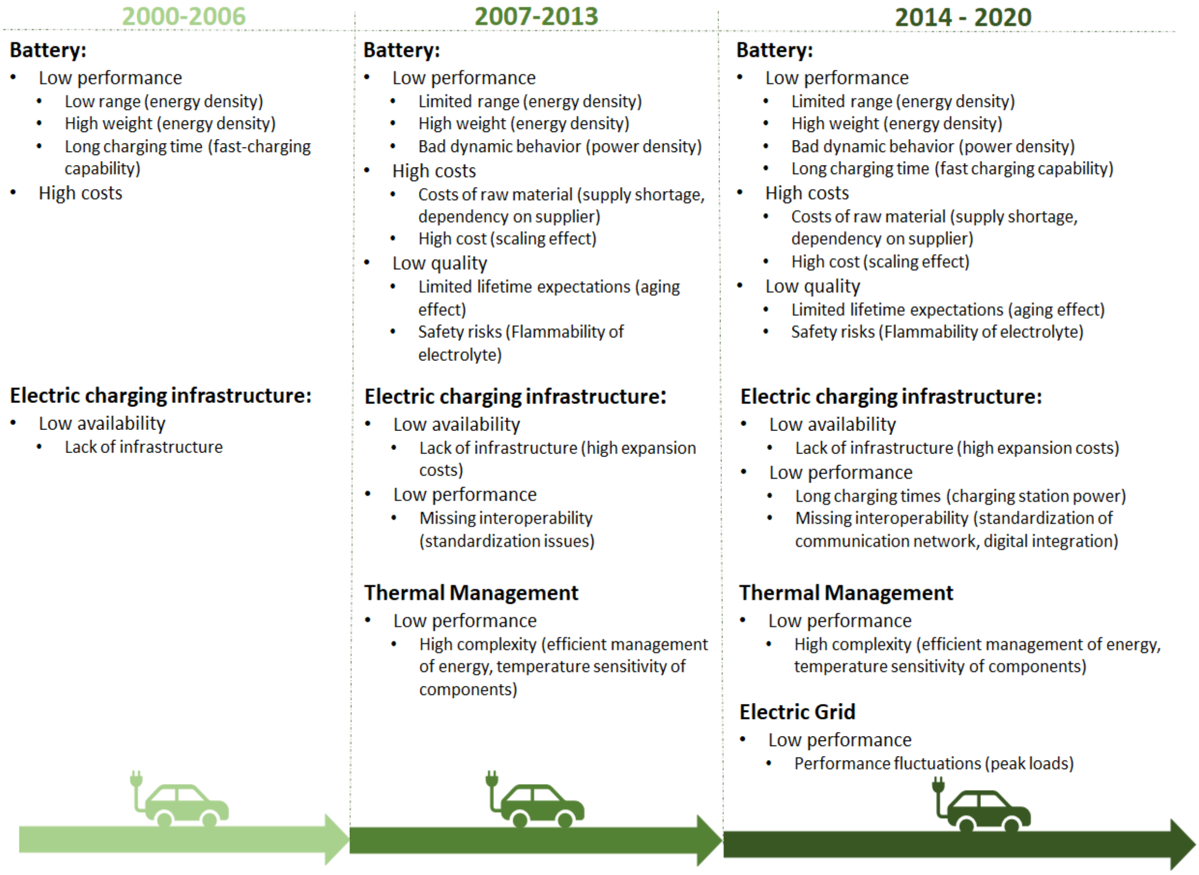
The bottlenecks in the innovation ecosystem of battery electric vehicles have partly changed in recent years, or more precisely, new ones have emerged due to the increased number of vehicles on the roads. Figure 38 shows the change of these identified bottlenecks over the last 20 years, divided into three sections.

In the first period from 2000 to 2006, the value proposition's limitations were mainly related to the batteries and their low energy density and non-existent fast-charging capability. Furthermore, the high costs of batteries were often seen as a significant obstacle. In addition to the battery, the electric charging infrastructure was already seen as a limitation due to the lack of public charging stations.

In the second section, from 2007 to 2013, the battery continued to be the main bottleneck. The main reason for this was still the low achievable range and the high weight due to low energy densities. The cost problem also had a major influence on the fact that the battery was identified as a bottleneck. At this time, battery quality problems were also identified as a limiting factor for the first time. These quality issues can be attributed to the limited lifetime due to the aging effect, and safety risks.
The electrical charging infrastructure continued to be the second key bottleneck in this period, but its low availability was no longer the only limiting factor. Furthermore, the lack of standardization of charging

plugs was a main issue at this time, which made the charging process on public charging stations challenging.

The third bottleneck detected during this period was the thermal management, which represented a major challenge due to the temperature sensitivity of the individual BEV components. In addition, the energy needed to operate the thermal management subcomponents has to be provided by the battery, leading to a tradeoff between comfort and driving range.



2000-2006

Battery:
- Low performance
  - Low range (energy density)
  - High weight (energy density)
  - Long charging time (fast-charging capability)
- High costs

Electric charging infrastructure:
- Low availability
  - Lack of infrastructure

2007-2013

Battery:
- Low performance
  - Limited range (energy density)
  - High weight (energy density)
  - Bad dynamic behavior (power density)
- High costs
  - Costs of raw material (supply shortage, dependency on supplier)
  - High cost (scaling effect)
- Low quality
  - Limited lifetime expectations (aging effect)
  - Safety risks (Flammability of electrolyte)

Electric charging infrastructure:
- Low availability
  - Lack of infrastructure (high expansion costs)
- Low performance
  - Missing interoperability (standardization issues)

Thermal Management
- Low performance
  - High complexity (efficient management of energy, temperature sensitivity of components)

2014 - 2020

Battery:
- Low performance
  - Limited range (energy density)
  - High weight (energy density)
  - Bad dynamic behavior (power density)
  - Long charging time (fast charging capability)
- High costs
  - Costs of raw material (supply shortage, dependency on supplier)
  - High cost (scaling effect)
- Low quality
  - Limited lifetime expectations (aging effect)
  - Safety risks (Flammability of electrolyte)

Electric charging infrastructure:
- Low availability
  - Lack of infrastructure (high expansion costs)
- Low performance
  - Long charging times (charging station power)
  - Missing interoperability (standardization of communication network, digital integration)

Thermal Management
- Low performance
  - High complexity (efficient management of energy, temperature sensitivity of components)

Electric Grid
- Low performance
  - Performance fluctuations (peak loads)

Figure 38: Summary of analysis results for the innovation ecosystem of battery electric vehicles

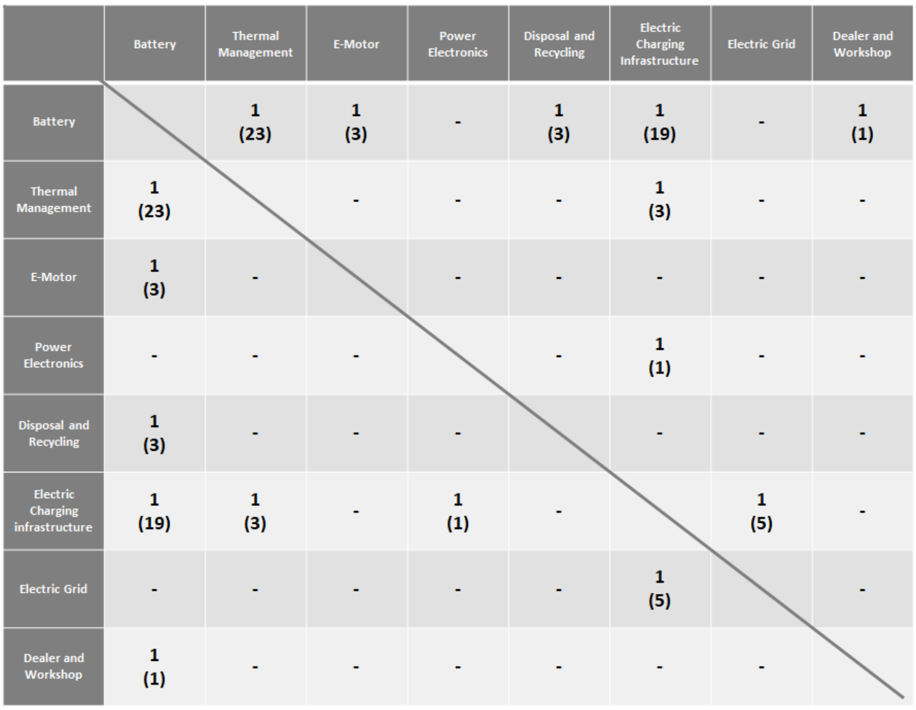
In the third time section from 2014 to 2020, the battery was still detected as the key bottleneck, although the reasons for this were basically the same as before. However, in addition, the long charging times, especially at the beginning of this section (2014 to 2017), were identified as a limiting factor in this period.

Thermal management and electric charging infrastructure were also still seen as limiting the value proposition to the customer. However, in the case of the electric charging infrastructure, the low performance of the charging stations and the missing standardization of the communication network became increasingly limiting in this section.

Finally, the electric grid had increasingly turned into a bottleneck due to the problems in handling peak loads.

4.2 Network of complementarity for BEV

As already described in chapter 3.2, the network of complementarity was constructed from matrices of (co-) occurrences. Interestingly, the three in the qualitative content analysis most frequently mentioned bottleneck categories (battery, thermal management, electric charging infrastructure) play the central role in this network. This fact is illustrated in Figure 40.



	Battery	Thermal Management	E-Motor	Power Electronics	Disposal and Recycling	Electric Charging Infrastructure	Electric Grid	Dealer and Workshop
Battery		1 (23)	1 (3)	-	1 (3)	1 (19)	-	1 (1)
Thermal Management	1 (23)		-	-	-	1 (3)	-	-
E-Motor	1 (3)	-		-	-	-	-	-
Power Electronics	-	-	-		-	1 (1)	-	-
Disposal and Recycling	1 (3)	-	-	-		-	-	-
Electric Charging infrastructure	1 (19)	1 (3)	-	1 (1)	-		1 (5)	-
Electric Grid	-	-	-	-	-	1 (5)		-
Dealer and Workshop	1 (1)	-	-	-	-	-	-	

Figure 39: Complementarity matrix for the innovation ecosystem of battery electric vehicles

The battery shows a degree centrality (number of different components/complements with which a component or complementary product/service was jointly identified as a bottleneck in an article) of 5. For this reason, the battery is the most central part of the network of complementarity.

However, the complementarity strength, which was determined by the number of joint mentions of two components/complementary products or services (see numbers in parentheses of the matrix in Figure 39), is different for the individual components and complementary products/services. The battery and the thermal management were most frequently jointly declared in an article as a bottleneck. The electric charging infrastructure and the battery also showed a very strong complementarity (19 joint bottleneck mentions). The complementary strength of the battery with the e-motor, the disposal/recycling, and the dealer/workshop has turned out to be low in this network due to only a small number of joint mentions.

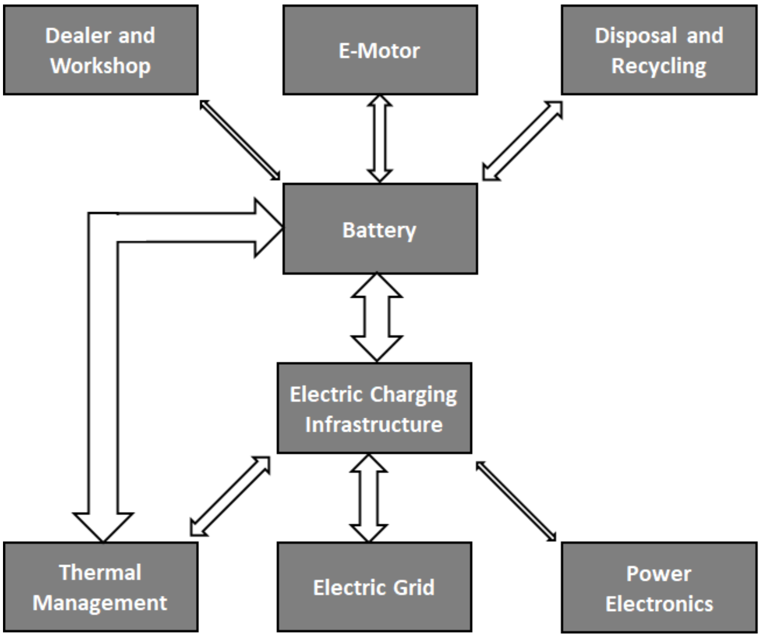


Figure 40: Network of complementarity for the innovation ecosystem of battery electric vehicles

The electric charging infrastructure represents the second central role in the network of complementarity, with a degree centrality of 4. In addition to the frequently joint mentioning of battery and electric charging infrastructure, which was already described above, thermal management was declared as a bottleneck in the same context as the charging infrastructure a few times. The complementarity between the electric grid and the charging infrastructure has also turned out to be strong, with a total number of five joint mentions. The last aspect, the complementarity between power electronics and charging infrastructure, was detected as not very strong. These two components/complements were only once jointly seen as a bottleneck.

This network of complementarity shows that the battery and the electric charging infrastructure impact many other components and complementary products/services and therefore play a central role in the innovation ecosystem of battery electric vehicles and are more likely to represent a bottleneck than peripheral parts of the ecosystem. Thus, the battery and the electric charging infrastructure represent the most critical bottlenecks in the ecosystem of battery electric vehicles

4.3 Results of the qualitative content analysis for the ecosystem of the FCEV

In the analysis of the ecosystem of fuel cell electric vehicles, it was noticeable that significantly fewer articles focused on this technology compared to battery electric vehicles, which is underlined with Figure 41. For this reason, identifying a trend, which should show how bottlenecks change over the period from 2000 to 2020, was sometimes very difficult since only a small number of bottlenecks were detected in a large number of years during the study period. Although especially in the early 2000s, a disproportionately high number of bottlenecks were detected in the two journals. In the year 2000, this was caused by an article in the newly founded IJoAT, which discussed in one of his first published articles the fuel cell electric vehicle with all its advantages and challenges. In that year, two-thirds of all detected bottlenecks for the FCEVs were attributable to this article.

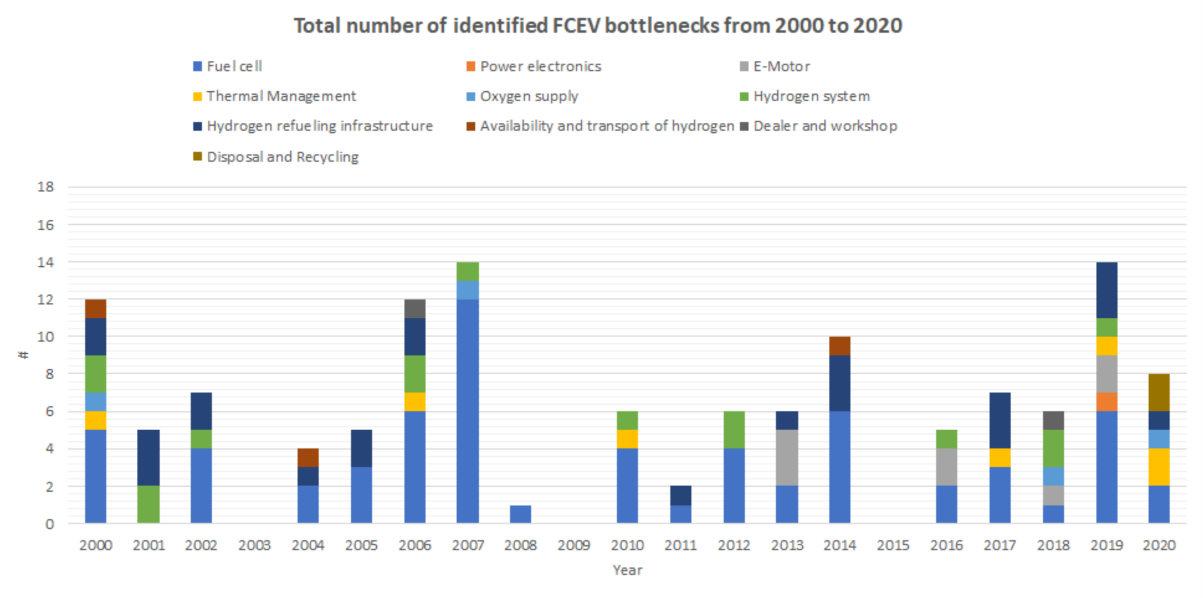


Figure 41: *Total number of identified FCEV bottlenecks in the ATZ and IJoAT in the period from 2000 to 2020*

Nevertheless, it became apparent that during this time up to 2007, a large number of articles focused on FCEVs and their issues, which reflects an opposite picture to the ecosystem of battery electric vehicles. However, the analysis demonstrated that at that time, many questions of this powertrain topology were still unresolved, which also resulted in the identification of a wide variety of different components/complements bottlenecks. This fact is also illustrated in Figure 41. Many questions regarding onboard storage of hydrogen, fuel cell technology, and hydrogen supply infrastructure were still unclear at that time. In fact, it was not even defined which type of fuel cell (PEMFC, DMFC, SOFC) would be used, and the required auxiliary units (Air filter, humidifier, etc.) had not been discussed at that time. Consequently, until 2007, it became apparent that the components “fuel cell” and “hydrogen system”, as well as the complementary product “hydrogen refueling infrastructure”, were the most discussed topics in the ecosystem of fuel cell electric vehicles. Thus, they represented the key bottlenecks, as illustrated in Figure 41 and Figure 42.

Starting in 2008, the picture of fuel cell electric vehicles was in contrast to that of BEVs. From this point on, the fuel cell electric vehicle was only discussed in very little detail compared to the absolute number of pre-filtered articles concerning BEVs and FCEVs. This resulted in a very small number of text passages that represented a bottleneck for FCEVs. Figure 41 underlines this fact by illustrating that even the absolute number of detected bottlenecks has decreased since 2008. Although significantly more articles were analyzed in the later years of the study period than in the early 2000s, fewer of them addressed the topic of fuel cell vehicles. However, the identified bottlenecks from 2008 up to 2020 concerned once more, mainly the fuel cell, the hydrogen refueling infrastructure, and the hydrogen system.

Even though only a few bottlenecks were detected in the last years of the analysis period, the results show that issues such as the thermal management of the vehicles, the peripheral components of the fuel cell (e.g., oxygen supply), or the complementary service of disposal and recycling are slowly gaining importance (see the 2019 and 2020 in Figure 41) beside the three already mentioned components/complements.

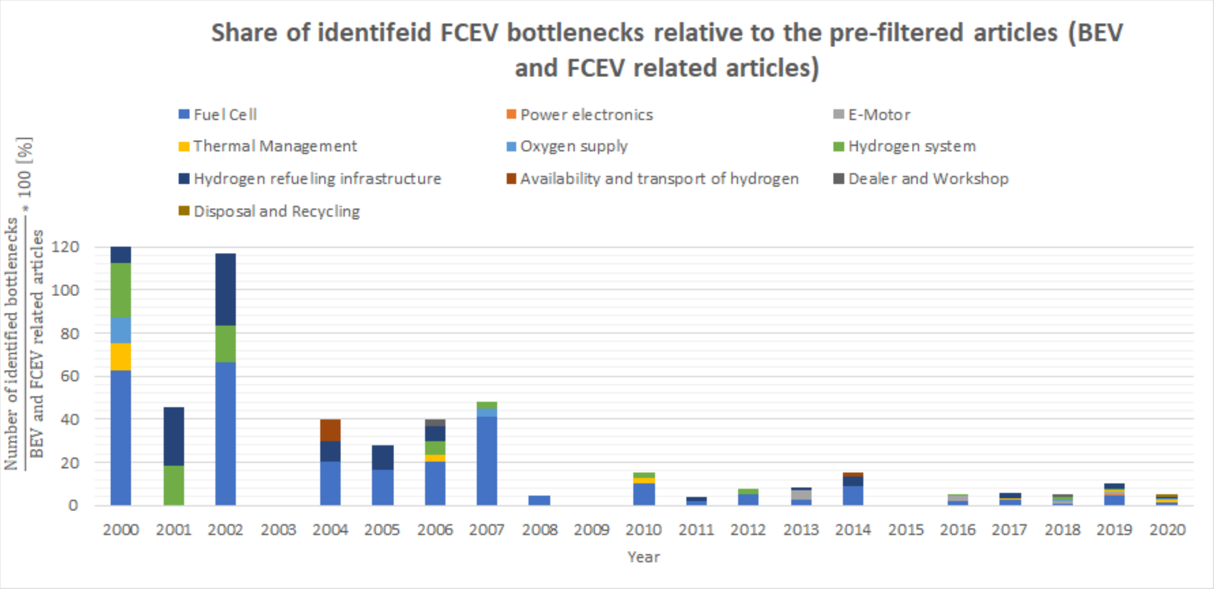


Figure 42: Share of identified FCEV bottlenecks relative to pre-filtered ATZ and IJoAT articles in the period from 2000 to 2020

After this overview of the analysis’ results, the detailed results (subcomponents, type of bottlenecks) for the individual components and complementary products and services in the category system are shown in the following subsections.

4.3.1 Fuel cell

The majority of the identified text passages representing a bottleneck could only be assigned to the main component, the fuel cell, as the assignment to a subcomponent (MEA, bipolar plates, fuel cell management, or fuel cell production) was not possible due to missing information in the articles. Nevertheless, some text passages could be assigned to a subcomponent, as illustrated in Figure 43.

At the beginning of the 2000s, as already mentioned in the previous chapter, it was not even clear to the OEMs which type of fuel cell would finally be used in the automotive sector. For this reason, different articles in the year 2000 referred to different fuel cell types, namely the PEMFC, the SOFC, and the DMFC. However, the consensus for all three technologies was that the costs of fuel cells, mainly because of the expensive raw materials, were far too high. In addition to the high costs, the performance in terms of efficiency and dynamic behavior of the fuel cell was seen as a limiting factor for the customer's value proposition as well.

An interesting fact is that many articles concerning fuel cell electric vehicles were published in 2006 and 2007. This is reflected in a disproportionately high number of detected bottlenecks in those years. The analysis showed that automotive OEMs had laid the foundation for fuel cell electric vehicles to become ready for serial production from this time onwards. Therefore huge progress has been made in fuel cell technology. However, in the time around the year 2007, the already discussed bottleneck dimensions, high costs, and low performance due to cold start-, dynamic-, and efficiency problems were some of the major limiting factors identified in fuel cell electric vehicles. In addition, the quality problem concerning the calendrical and operating lifetime caused by the temperature sensitivity of fuel cells was detected as a limitation for the value proposition at this time.

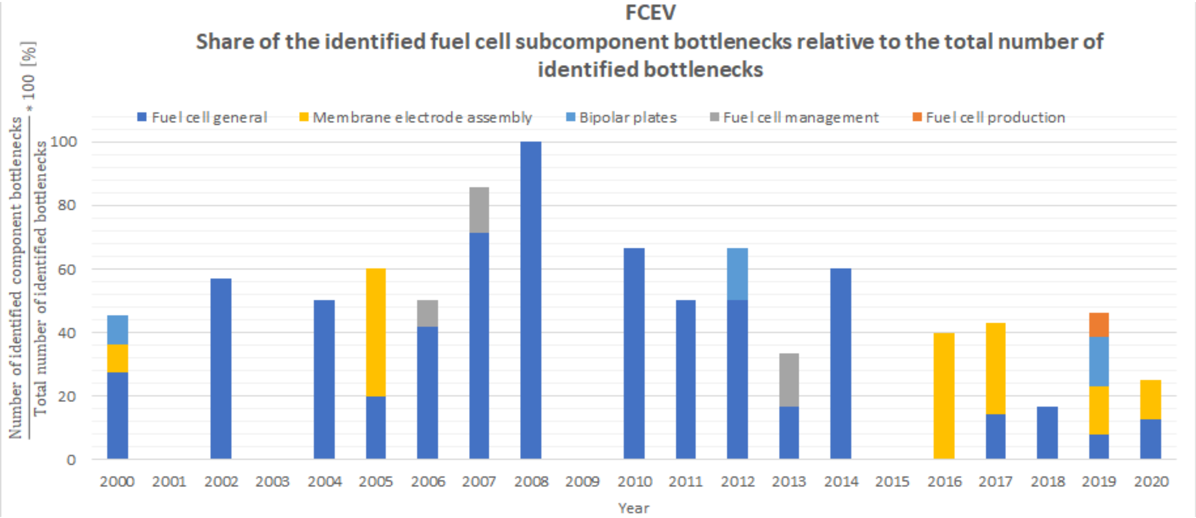


Figure 43: Share of the identified fuel cell subcomponent bottlenecks in the innovation ecosystem of FCEVs relative to the total number of identified bottlenecks

The peripheral components (air filter, compressor, etc.) necessary for the fuel cell operation were hardly considered as a bottleneck at that time. Respectively the analysis showed that the basic issues of the fuel cell stack itself had to be solved first.

In the year 2008, the quality of the fuel cell was the only limitation in the ecosystem of FCEVs, as illustrated in Figure 43. But this must be relativized since only one text passage representing a bottleneck was detected in that year.

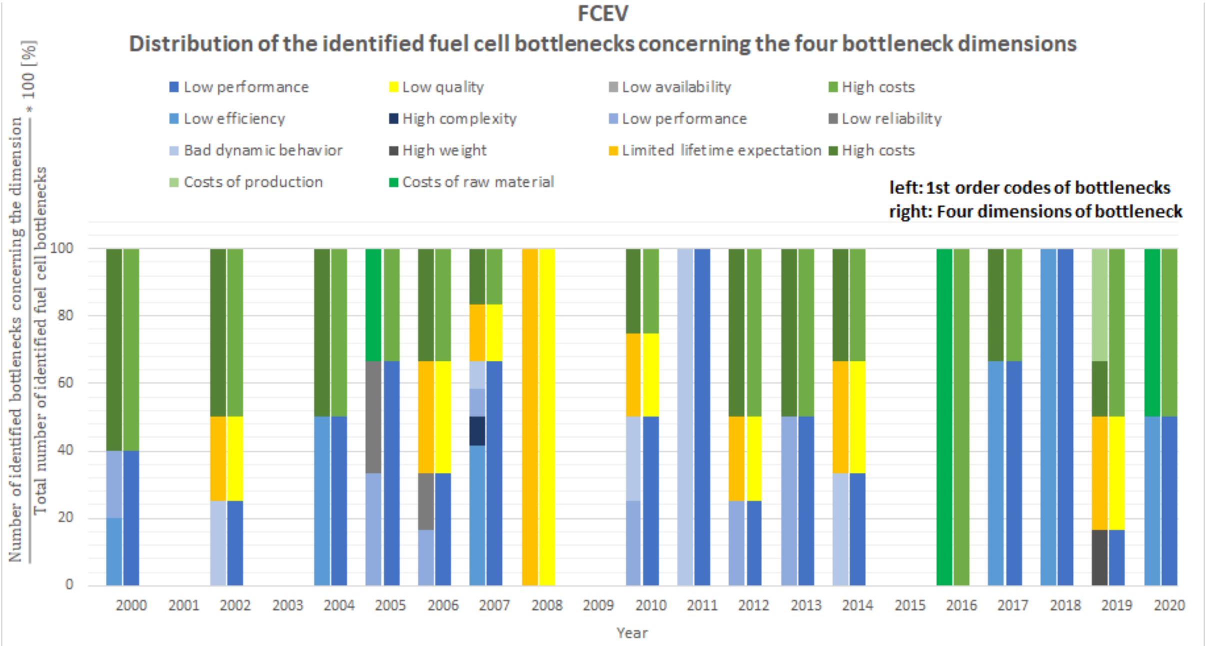


Figure 44: Distribution of the identified fuel cell bottlenecks concerning the four bottleneck dimensions in the innovation ecosystem of FCEVs

From 2010 to 2015, although fuel cells continued to be the key bottleneck in the FCEV ecosystem in percentage terms, as illustrated in Figure 43, the number of bottleneck mentions was limited to a small number, as can be seen in Figure 41.

In the detected text passages, which describe the fuel cell as a bottleneck, the reasons for the limiting effect were the issues already mentioned around the year 2007. In addition, it was also noticeable during this period that the bad dynamic behavior of the fuel cell, meaning that the fuel cell has slow response times, was seen as a limitation too.

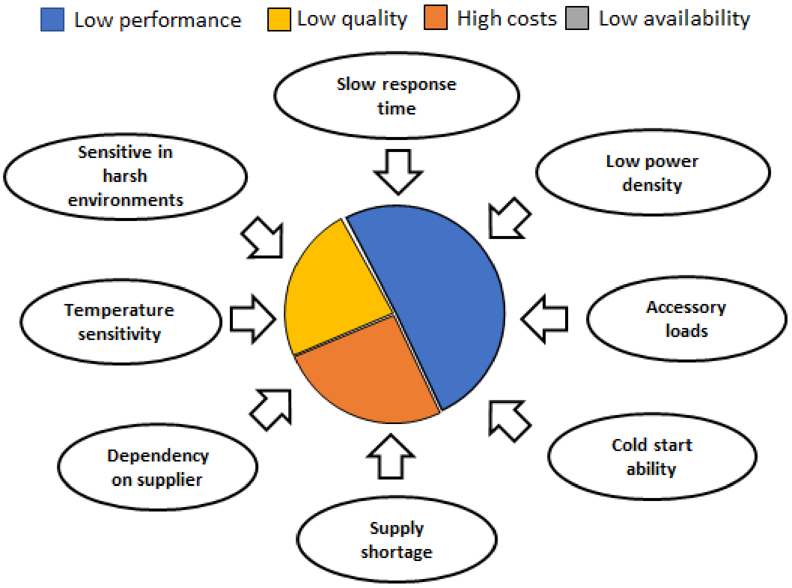


Figure 45: Trigger for identified fuel cell bottlenecks in the innovation ecosystem of fuel cell electric vehicles

The fact that enormous progress has been made in the development of the fuel cell since 2010 became apparent in the analysis from 2015 onwards since only one text passage described the lifetime of the fuel cell as an issue in the period from 2015 to 2020 anymore.

The fuel cell's costs and performance in terms of efficiency were still identified as limiting in the analysis for the year 2020, even though the platinum required for the fuel cell catalyst was reduced and the power density has been improved. However, especially the results obtained from 2010 onwards must be taken into the perspective of a very small number of detected bottlenecks.

Nevertheless, the analysis showed that the component fuel cell had a limiting effect on FCEVs' ecosystem consistently over the whole study period, but the individual causes for this limitation have changed over the last 20 years. These causes were triggered by various influencing factors, which are summarized in Figure 45. The quality of the fuel cell, more precisely the lifetime, has improved so significantly in recent years that this bottleneck dimension is no longer a limiting factor. In contrast to that, the fuel cell costs are still too high due to a missing scaling effect (small production figures) and the high price of platinum. Furthermore, the performance of the fuel cell remains a limiting factor related to efficiency problems.

4.3.2 Hydrogen refueling infrastructure

The third key bottleneck in the ecosystem of fuel cell electric vehicles, besides the fuel cell technology and the hydrogen system, is the hydrogen refueling infrastructure, where its availability was a limitation throughout the entire study period. It was interesting to observe that the hydrogen refueling infrastructure was already seen as a bottleneck at the beginning of the 2000s, even though it was not even clear how hydrogen could be stored most efficiently. Nevertheless, the infrastructure was repeatedly mentioned in the articles, especially up to 2006, as a key limiting factor for the expansion of fuel cell electric vehicles.

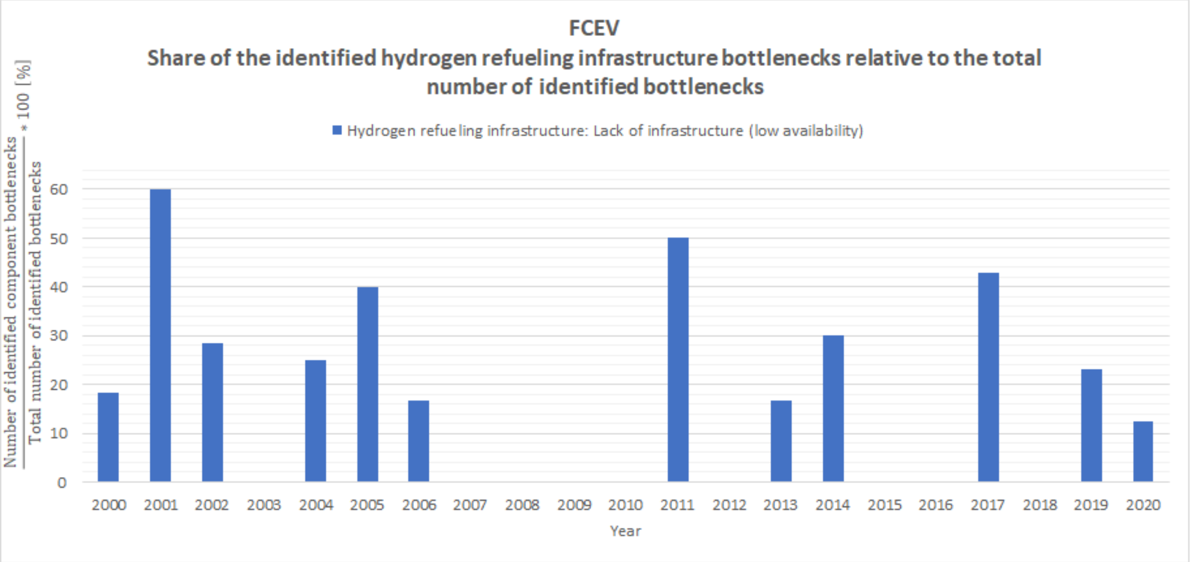


Figure 46: Share of the identified hydrogen refueling infrastructure bottlenecks in the innovation ecosystem of FCEVs relative to the total number of identified bottlenecks

As the number of articles dealing with fuel cell vehicles decreased from 2009 onwards, this complementary product was correspondingly less frequently detected as a bottleneck. Nevertheless, from 2009 onwards, the availability of public hydrogen filling stations was the biggest bottleneck in the innovation ecosystem of fuel cell electric vehicles, in addition to the fuel cell and the hydrogen system. The reasons for the lack of infrastructure can be traced back to the high costs of building a large-scale hydrogen filling station network.

The analysis showed that, despite the very small number of text passages representing a bottleneck, this complement was a limitation over the entire study period and remains until today a critical constraint in the ecosystem of FCEVs, which significantly limits the widespread adoption of fuel cell electric vehicles

4.3.3 Hydrogen system

The detected text passages, which declare the component “hydrogen system” as a bottleneck, can in most cases be assigned to the subcomponent “hydrogen tank”. From the beginning of the study period, hydrogen storage was a key issue, as illustrated in Figure 47. The analysis showed that in the early 2000s, the automotive manufacturers were not sure in which form hydrogen could be stored most efficiently for mobile applications.

In addition, the onboard hydrogen supply process was also an issue detected in the analysis in the year 2000. This bottleneck is caused by the low efficiency resulting from the hydrogen stored in a chemically bonded form, because in this case, a reformer would be required. In other words, the analysis showed that the storage of hydrogen was the big unknown in the 2000s, which was also directly related to the used fuel cell type.

Unfortunately, due to the small number of detected bottlenecks in the later years (2010 onwards), it was very difficult to derive a trend indicating to what extent the component “hydrogen system” has improved over the study period. However, what could be concluded from the analysis is that due to the complexity in storing hydrogen (small molecular size, explosion risk) and the associated high weight of the hydrogen storage system, this component still represents a bottleneck today.

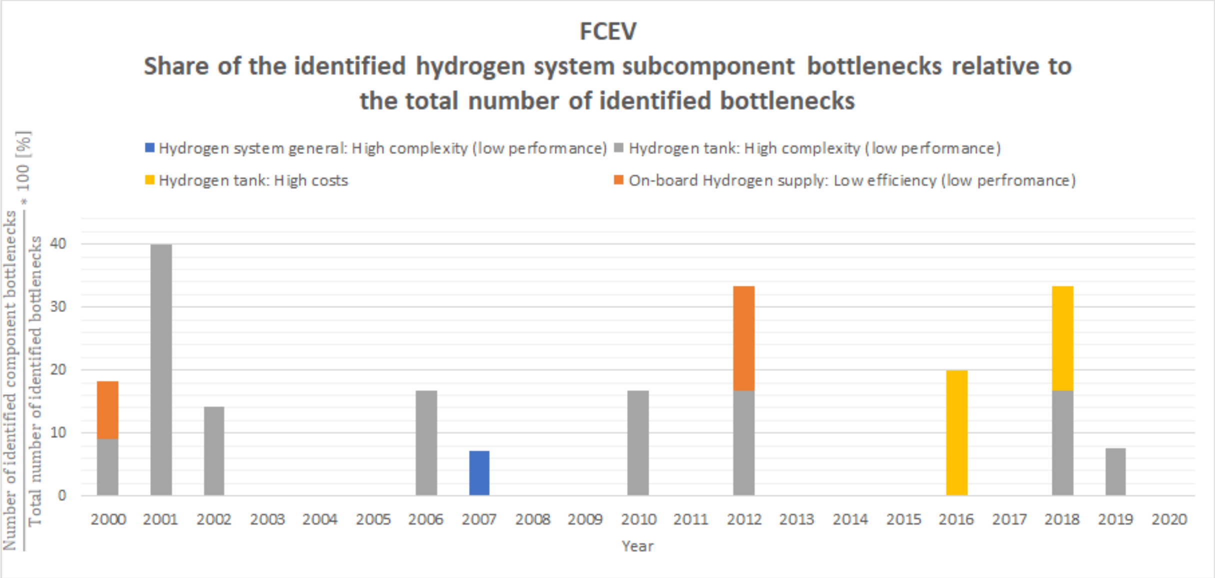


Figure 47: Share of the identified hydrogen system subcomponent bottlenecks in the innovation ecosystem of FCEVs relative to the total number of identified bottlenecks

The analysis showed that, despite the very small number of text passages representing a bottleneck, this component was a bottleneck over the entire study period. Besides the fuel cell and the hydrogen refueling infrastructure, it was the most frequently mentioned bottleneck in the ecosystem of FCEVs.

4.3.4 Thermal management

The thermal management in fuel cell electric vehicles is a component whose limiting effect is difficult to determine over the entire study period based on the analysis results. While it was already discussed in the year 2000 that, due to the temperature sensitivity of the fuel cell, oversized and heavy radiators are required for temperature control and thus have a limiting effect on the overall system, the topic of thermal management was only very rarely seen as a bottleneck in the further course of time (see Figure 48).

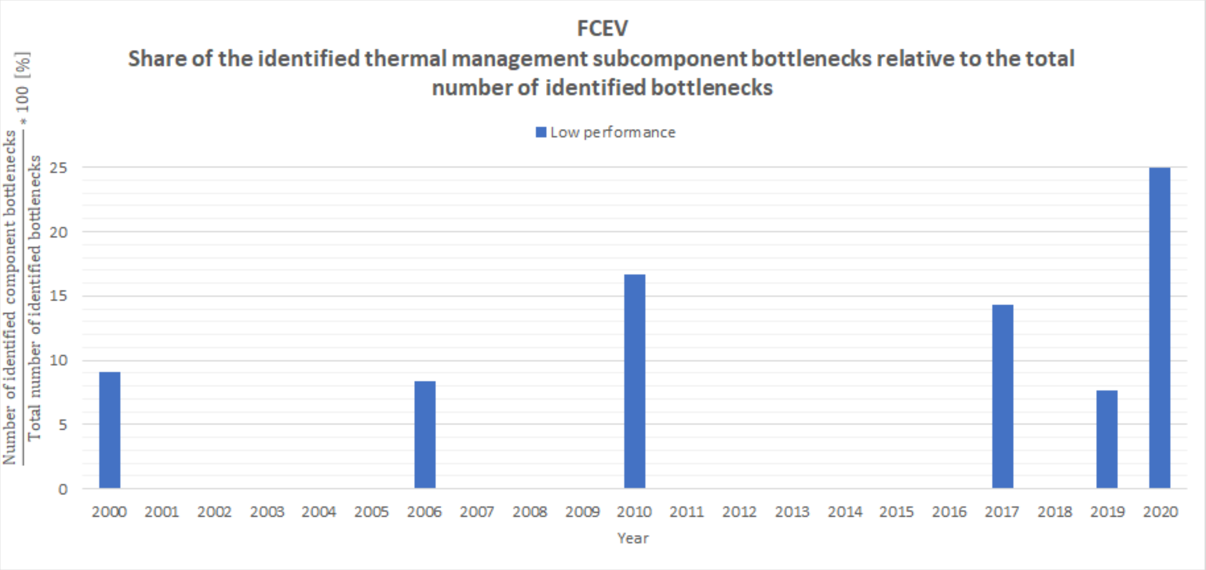


Figure 48: Share of the identified thermal management subcomponent bottlenecks in the innovation ecosystem of FCEVs relative to the total number of identified bottlenecks

Overall, thermal management in the FCEV ecosystem was identified only six times as a bottleneck during the entire analysis period, and for this reason, it is considered to be of secondary importance. Nevertheless, it was interesting to observe that thermal management has become increasingly important in the last two years, with the performance and the high complexity of tempering the fuel cell being the limiting factor.

4.3.5 E-Motor and Power electronics

In terms of limiting effects to the FCEV´s value proposition, relatively little importance was attributed to the e-motor and power electronics in articles of the two journals.

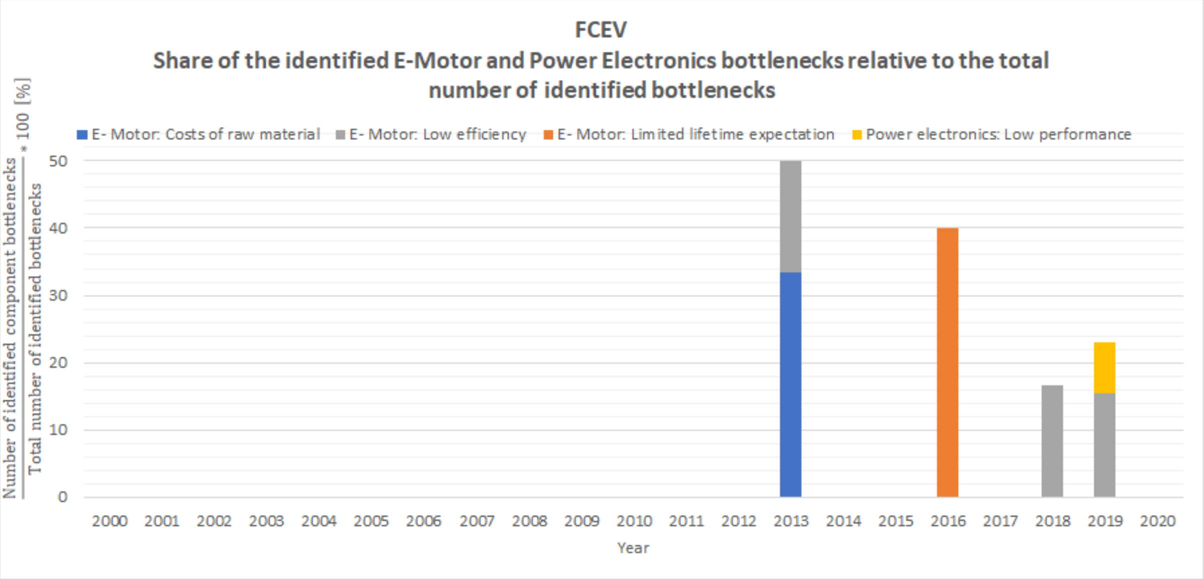


Figure 49: Share of the identified e-motor/power electronics bottlenecks in the innovation ecosystem of FCEVs relative to the total number of identified bottlenecks

For these two components, the synergy effects between BEV and FCEV were used, and thus the bottleneck text passages were the same as in the analysis of the ecosystem of the BEV. This means the results were already discussed in chapter 4.1.5. An exception was the bottleneck regarding the onboard charger identified in the BEV ecosystem. This bottleneck could not be included in the analysis results of the ecosystem of FCEVs because this component is needed for the external charging of the HV battery (Hohmann et al., 2017, p. 39), and therefore, it is not part of the FCEV.

Nevertheless, as shown in Figure 49, the identified text passages representing a bottleneck of these two components have a much larger share on the total number of detected bottlenecks than in the ecosystem of BEVs. This indicates once more the very low number of identified bottlenecks in the ecosystem of FCEVs.

Moreover, all the limitations concerning these two components were detected in articles that dealt with battery electric vehicles, which led to the high share in 2013, since only six text passages were detected in total that represents a bottleneck in the ecosystem of FCEVs.

Due to these reasons, the e-motor and the power electronics have only a very small limiting effect on the FCEV´s value proposition to the customer.

4.3.6 Oxygen supply

The component oxygen supply was rarely considered as a bottleneck in the analysis material, as shown in Figure 50. Although the compressor, which is responsible for compressing the air for the fuel cell stack, was already seen as a bottleneck in the year 2000 due to its high weight, it was not mentioned in any of the subsequent articles.

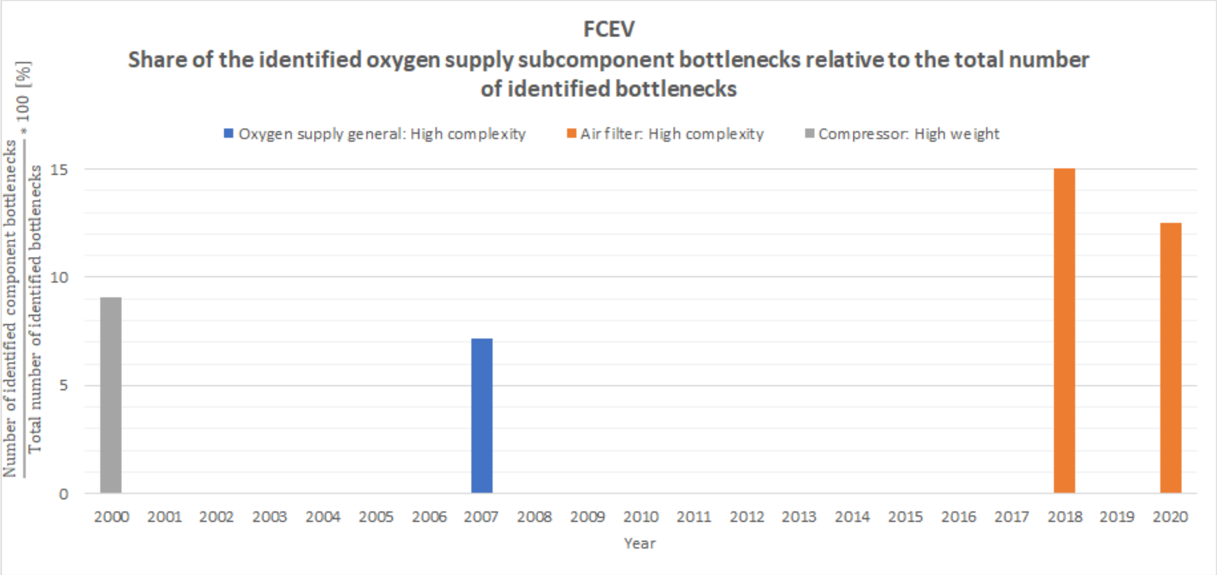


Figure 50: Share of the identified oxygen supply subcomponent bottlenecks in the innovation ecosystem of FCEVs relative to the total number of identified bottlenecks

One thing which was noticeable in the analysis is that the air filtration as a peripheral component of the fuel cell was only seen as a bottleneck from the year 2018 onwards, i.e., after the quality issues of the fuel cell had been solved. In this context, it was mentioned that due to the sensitivity of the fuel cell concerning dirty air, air filtration is a very complex issue. But again, these results must be put into perspective since only two text passages, in the articles of the ATZ and the IJoAT, identified air filtration as a limiting factor, which makes it difficult to assess these results. Nevertheless, compared to other components/complements, issues concerning oxygen supply turned out to be of secondary importance.

4.3.7 Availability/transport of hydrogen, dealer/workshop, and disposal/ recycling

The workshops responsible for repairing the fuel cell electric vehicles and the dealers hardly played a role in the articles of the two journals, as shown in Figure 51. For this complementary service, the synergies with the BEV were used again, which means that the same text passages were considered as a bottleneck as in the ecosystem of battery electric vehicles. This synergy effect is based on the fact that the detected dealer and workshop bottlenecks all generally referred to electrified vehicles and thus did not have to be explicitly assigned to BEVs or FCEVs. Therefore, these limitations have already been discussed in chapter 4.1.6.

The complementary service of disposal and recycling has also been addressed very rarely in the analysis. Nevertheless, it was interesting to observe that disposal/recycling has become increasingly important in the last year (2020), focusing on the recycling process to keep the raw materials of the fuel cell in the loop.

The complementary service/product of availability/transport of hydrogen was only identified in the context of the whole “hydrogen supply infrastructure” as a bottleneck in the analysis, i.e., from hydrogen production to the refuel stations. In this case, the availability of hydrogen supply infrastructure was the cause of the bottleneck. This was especially the case in the early 2000s when stakeholders were not even aware of how hydrogen can be stored most effectively. One fact important to mention is that it was not considered in the analysis if the produced hydrogen is “green”.

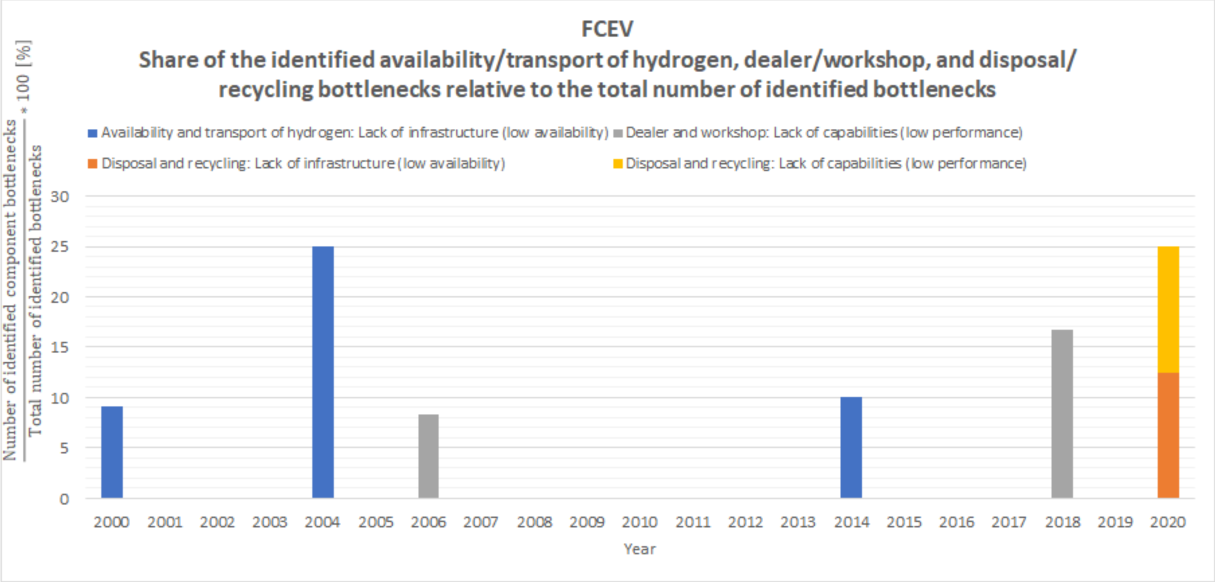


Figure 51: Share of the identified availability/transport of hydrogen, dealer/workshop, and disposal/recycling bottlenecks in the innovation ecosystem of FCEVs relative to the total number of identified bottlenecks

4.3.8 Summary of findings

The bottlenecks in the innovation ecosystem of fuel cell electric vehicles have not changed over the entire study period. However, what has partly changed is the underlying issue of why a component/complement is a bottleneck. Figure 52 shows these identified bottlenecks over the last 20 years, divided into three sections.

In the first period from 2000 to 2006, the limitation of the value proposition to the customer was mainly related to the fuel cell and its performance. The low efficiency of the used fuel cells and the bad dynamic behavior due to low power densities were the main limitations. Furthermore, the high costs of the fuel cells were often seen as a major obstacle.

The second bottleneck identified in this period concerned the hydrogen system and its performance. At this time, it was not entirely clear how hydrogen could be stored most efficiently, as this storage is highly complex due to the small molecular size of hydrogen.

In addition to the fuel cell and the hydrogen system, the hydrogen refueling infrastructure was already seen as a bottleneck due to the lack of hydrogen refueling stations.

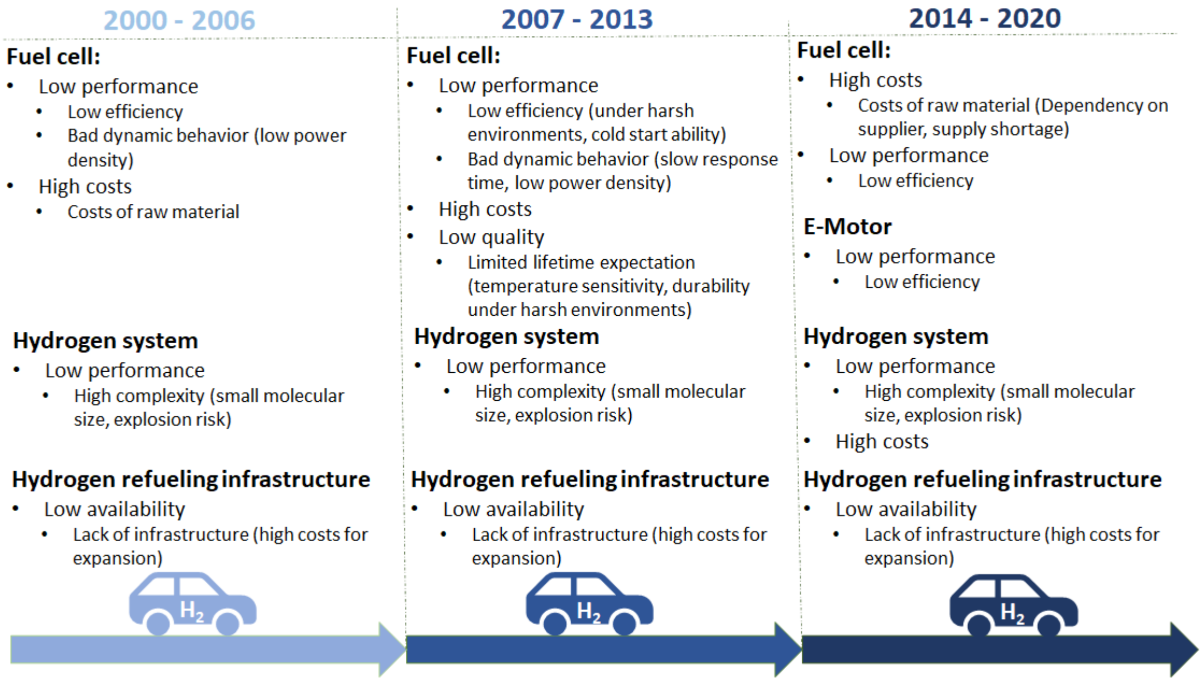


Figure 52: Summary of analysis results for the innovation ecosystem of fuel cell electric vehicles

In the second section, from 2007 to 2013, the fuel cell continued to be the key bottleneck. The main reason for this was still the low efficiency of the used fuel cells, especially in harsh environments, and the bad dynamic behavior caused by low power densities, resulting in slow response times. The cost issue also had a major influence on the fact that the fuel cell was declared as a bottleneck. At this time, quality problems of the fuel cell were identified as limiting for the first time. These problems can be attributed to the limited lifetime of the fuel cell. This lifetime is getting shortened if the fuel cell is not sufficiently temperature-controlled or the fuel cell is operated in harsh environments.

The hydrogen system and the hydrogen refueling infrastructure were also again identified as bottlenecks in this period, for the same reasons as described in the first section.

In the third time section from 2014 to 2020, the fuel cell was still detected as the key bottleneck. This can be attributed to the low performance due to low efficiencies of fuel cells and the high costs of raw materials due to supplier dependencies. The quality problem of the fuel cell, on the other hand, was no longer seen as a limiting factor during this section.

The hydrogen system was once again identified as a bottleneck in this period, with the complexity of storage continuing to be the reason for this. In addition, the high costs of hydrogen tanks were also a reason for the hydrogen system to be declared as a bottleneck. These high costs can also be traced back to the complexity of storing hydrogen.

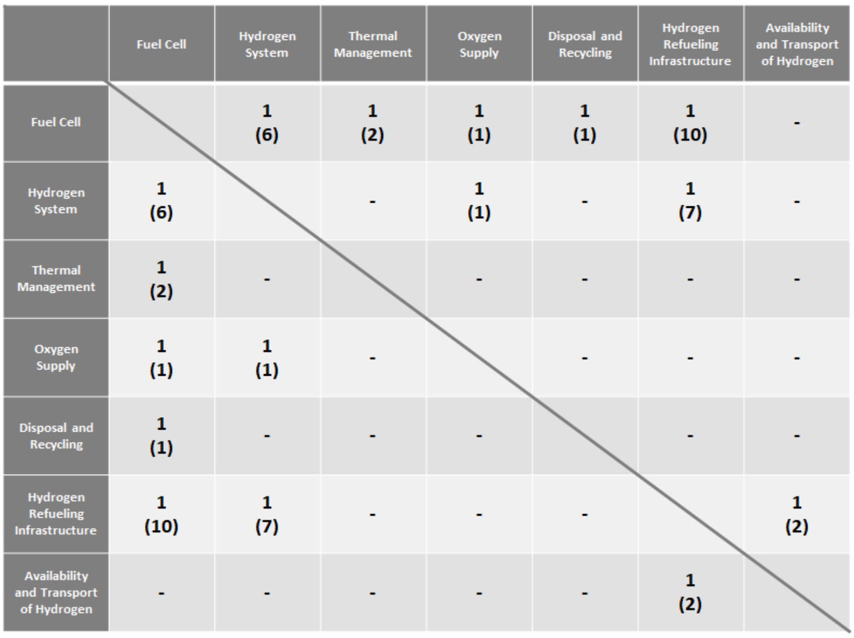
The third bottleneck identified in this period, as in the previous two sections, is the hydrogen refueling infrastructure due to its lack of availability.

Finally, the e-motor was detected as a bottleneck due to efficiency issues.

4.4 Network of complementarity for FCEV

As already described in chapter 3.2, the network of complementarity was constructed from matrices of (co-) occurrences. An interesting fact is, similar to the BEV ecosystem that the three in the qualitative content analysis most frequently mentioned bottleneck categories (fuel cell, hydrogen system, and hydrogen refueling infrastructure) play the central role in this network. This can be seen in Figure 54.
But it is important to mention that one article respectively its matrix of (co-) occurrence was not considered in this framework since all components and complementary products/services, which can be seen in the complementarity matrix in Figure 53, were described as a bottleneck in this article. For this reason, the inclusion of this article would distort the results.

In the network of complementarity, the fuel cell represents the most central element with a degree centrality of 5. However, the complementarity strength, which was determined by the number of joint mentions of two components/complementary products or services (see numbers in parentheses of the matrix in Figure 53), is different for the individual components and complementary products and services. The fuel cell combined with the hydrogen refueling infrastructure was most frequently declared as a bottleneck in an article with a total number of joint mentioning of ten. Furthermore, the fuel cell was frequently seen as a bottleneck together with the hydrogen system.
The complementary strength of the fuel cell with the oxygen supply, the disposal/recycling, and the thermal management has turned out to be low in this network due to only a small number of joint mentions.



	Fuel Cell	Hydrogen System	Thermal Management	Oxygen Supply	Disposal and Recycling	Hydrogen Refueling Infrastructure	Availability and Transport of Hydrogen
Fuel Cell		**1 (6)**	**1 (2)**	**1 (1)**	**1 (1)**	**1 (10)**	-
Hydrogen System	**1 (6)**		-	**1 (1)**	-	**1 (7)**	-
Thermal Management	**1 (2)**	-		-	-	-	-
Oxygen Supply	**1 (1)**	**1 (1)**	-		-	-	-
Disposal and Recycling	**1 (1)**	-	-	-		-	-
Hydrogen Refueling Infrastructure	**1 (10)**	**1 (7)**	-	-	-		**1 (2)**
Availability and Transport of Hydrogen	-	-	-	-	-	**1 (2)**	

Figure 53: Complementarity matrix for the innovation ecosystem of fuel cell electric vehicles

The hydrogen refueling infrastructure represents the second central role in the network of complementarity, with a degree centrality of 3. In addition to the frequent joint mention of fuel cell and hydrogen refueling infrastructure, the hydrogen system was also declared several times as a bottleneck in combination with the refueling station infrastructure.
The last aspect, the complementarity between hydrogen refueling infrastructure and availability and transport of hydrogen, was detected as not very strong. These two components/complements were only two times jointly seen as a bottleneck.
The third central role in the complementarity network is played by the hydrogen system, which also shows a degree centrality of 3. The complementarity strengths to the other components/complements have already been explained in the paragraphs above.

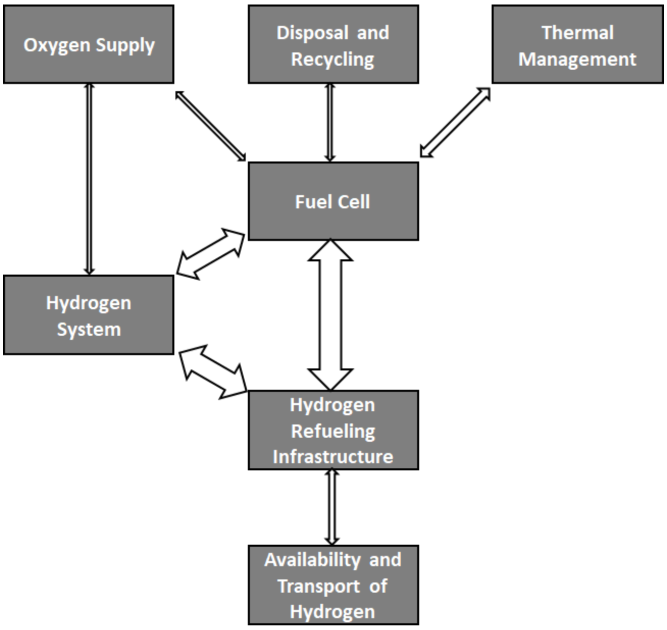


Figure 54: Network of complementarity for the innovation ecosystem of fuel cell electric vehicles

This network of complementarity shows that the fuel cell, the hydrogen system, and the hydrogen refueling infrastructure have an impact on many other components and complementary products and services and therefore play a central role in the innovation ecosystem of fuel cell electric vehicles and are more likely to represent a bottleneck than peripheral parts of the ecosystem. Thus, the fuel cell, the hydrogen system, and the hydrogen refueling infrastructure represent the most critical bottlenecks in the ecosystem of fuel cell electric vehicles.

5 Validation of the results from the qualitative content analysis

In this chapter, the results from the validation interviews with the three experts are presented. For this purpose, as already discussed in chapters 4.1.7 and 4.3.8, the analysis period from 2000 to 2020 is divided into three time sections, i.e., 2000 to 2006, 2007 to 2013, and 2014 to 2020. Within these sections, the results of the qualitative content analysis are compared with the results from the qualitative evaluation of the expert interviews, and the validated results are presented at the end. The first section of this chapter deals with results validation for the battery electric vehicles, and the second one with the validation of the results for the fuel cell vehicles.

5.1 Validation of the results for the ecosystem of the battery electric vehicle

The analysis results basically matched the results of the validation interviews, which can be seen in Appendix Q. Nevertheless, there were some differences between the analysis results and the expert interviews, which will now be presented.

5.1.1 Time period from 2000 to 2006

Especially at the beginning of the study period, the analysis indicates that the battery was the key bottleneck due to its low energy density and non-fast charging capability. The interviewees confirmed this result. The high battery costs, which were also detected from the analysis as limiting in this period, were not seen as a hindrance by all experts. While all experts agreed that the costs of batteries were extremely high at that time, one expert considered this to be of secondary importance. Regarding the quality aspect of batteries, the interviewees contradicted each other. The problem was that the experts were sometimes talking about different battery technologies (NiMH and Li-ion), which also indicated that some experts were talking about the beginning of the first section (2000) and the others were talking about the end of this section (2006). While everyone agreed that the battery lifetime, in hindsight, was not good at that time, some of the experts did not see this as a limiting factor for the BEV. They emphasized that it was not even possible to assess the lifetime of the batteries at that time due to a lack of practical experience. Due to that fact and because only one article was detected in the qualitative content analysis during this period that identified the lifetime of the batteries as a constraint, the quality of the battery is not rated as a limitation in this period.

The second issue detected in the analysis and confirmed by two experts as limiting was the not existing public electric charging infrastructure. In addition to the lack of availability of this public charging infrastructure, two experts also mentioned that the lack of fast charging capability due to low charging power also had a limiting effect. However, at the same time, one of them remarked that the battery was not able to handle higher charging currents at all, thus putting his statement into perspective. The third expert outlined that public electric charging infrastructure was not required at that time due to the small number of vehicles on the roads.

Since the analysis results and two experts identified the electric charging infrastructure as a bottleneck due to the lack of public charging stations, it is considered as the second bottleneck in this period. The insufficient charging power of the charging stations could not be derived from the analysis material as a limitation in this period, and, as already mentioned above, one of the experts put his statement regarding this topic into perspective.

The two components that were identified as a bottleneck in only a few articles within the entire analysis, namely the e-motor and the power electronics, were evaluated as bottlenecks by two experts at this time, but for different reasons. One expert noted that the efficiency of the e-motor and the power density of the power electronics had been improved tremendously since that time, and the other expert noted that there had been issues with the rare earths of the permanently excited motor. Nevertheless, both agreed that these issues were not too limiting compared to the problems with the battery. For this reason, these two components are not seen to be limiting for the value proposition to the customer in this period.

Another issue identified as a challenge by one expert was the vehicle architecture or the integration of the components into the overall vehicle. This could not be included in the results because this issue cannot be assigned to one single component or complementary product or service.

5.1.2 Time period from 2007 to 2013

In the next period discussed in the interviews, the battery remained the key bottleneck according to the qualitative content analysis due to performance, quality, and cost issues, as already discussed in chapter 4.1.7. The experts agreed with these limitations in the interviews, especially with the performance issue addressed by each of the three interviewees. However, one expert only mentioned the improvements in the performance, the reduction of costs, and the quality improvement, which indirectly indicated a limitation but could not be coded accordingly by the qualitative evaluation. The performance issue raised by the experts was again mainly related to the limited energy density. Another point that the experts confirmed was the fact that the batteries had quality issues related to safety and lifetime. This resulted in a limitation during this period as well. Additionally, to the performance and the quality of the batteries, the costs remained high. For these reasons, the component battery was detected as the key bottleneck in this period due to its low performance, low quality, and high cost.

The electric charging infrastructure, which was already a bottleneck in the previous section, continued to be a limitation, as discussed in chapter 4.1.7. The expert interviews also confirmed this result. The limitation reason was still the low availability of public charging stations. In addition, the standardization of charging plugs, which also emerged as a limiting factor in the analysis, was also mentioned by two experts. The third expert mentioned the low charging power as a limitation, but this fact could neither be deduced from the analysis nor from the other expert interviews. For these reasons, the electric charging infrastructure has been considered as the second key bottleneck due to the low availability of public charging stations and the non-standardization of charging plugs.

The thermal management, which was identified as the third key bottleneck in the analysis, could not be validated by the expert interviews. However, this is because thermal management is sometimes not defined as an external component, and therefore it is often associated as part of the battery. But the thermal management includes much more than just the temperature control of the battery. Other components such as the e-motor and the power electronics have to be heated and cooled as well, and the entire HVAC is also part of this component. Therefore, the consideration of thermal management as a separate component is essential. The experts repeatedly mentioned battery management, more precisely the efficient management of the energy, in the interviews and the fact that the battery must be tempered, but this could not be directly assigned to the topic of thermal management during the qualitative evaluation. However, since this topic was indirectly addressed by all the experts (in the context of safety, lifetime, and battery management), thermal management is nevertheless seen as a limiting factor of the BEV ecosystem from 2007 to 2013.

5.1.3 Time period from 2014 to 2020

In the last time section of the analysis, the validation interviews confirmed the results. Despite significant improvements, the battery still represents the key bottleneck of battery electric vehicles for the value proposition to the customer. All experts agreed on the fact that the performance, which was also detected in the analysis, or more precisely the achievable driving range, and the costs of the battery, are still broad hurdles for the widespread usage of battery electric vehicles.

The third bottleneck dimension, which was limited in the previous period, the quality of the batteries, was also identified in the analysis of this time section as a limiting factor due to a limited lifetime and safety risks, but the interviews could only validate this result to a limited extent. The experts definitely saw problems in the lifetime of batteries, especially at the beginning of this time section in the year 2014, but according to the experts, these issues have been solved today, or rather, they described the lifetime issues as very manufacturer-specific. For this reason, the quality of the battery is no longer seen as a limiting factor today, but in 2014 it was definitely a key issue.

The electric charging infrastructure, or rather the availability of public charging stations, is still a huge issue today, as shown in the analysis and confirmed by the experts. However, the missing standardization of charging plugs was not detected as a limitation either in the analysis nor by the experts during this period. In contrast, the issue regarding the low charging power of the charging stations identified during this period was confirmed by the experts. The new challenges of the charging infrastructure in terms of digital integration detected in the analysis were not mentioned by any expert and could not be validated.

The thermal management issue, which was detected in the analysis to become an increasingly important topic, was not explicitly mentioned by the experts, but this component is again rated as a bottleneck.

The reason for considering this component as a bottleneck is that, as in the previous section, the complexity of energy management and battery tempering was discussed by all of the experts also in this section, but this topic could not be directly assigned to thermal management during the qualitative evaluation.

The electric grid, which in recent years, according to the analysis, had increasingly turned into a bottleneck due to the problems in handling peak loads, could only be validated to a limited extent, but one expert explicitly pointed out that peak loads are a significant problem for energy suppliers. This statement, combined with the analysis results, made it necessary to see this complementary product as a limiting factor in 2020.

5.1.4 Summary of the validated results

The summary of the identified and validated bottlenecks in the innovation ecosystem of battery electric vehicles in the period from 2000 to 2020, divided into the three discussed time sections, can be seen in Figure 55. In this figure, the third section (2014-2020) was further divided because the experts mentioned several times in the interviews that the quality of the battery is no longer a limiting factor in 2020, but it was in 2014. On the other hand, the electric grid has become a bottleneck in 2020.

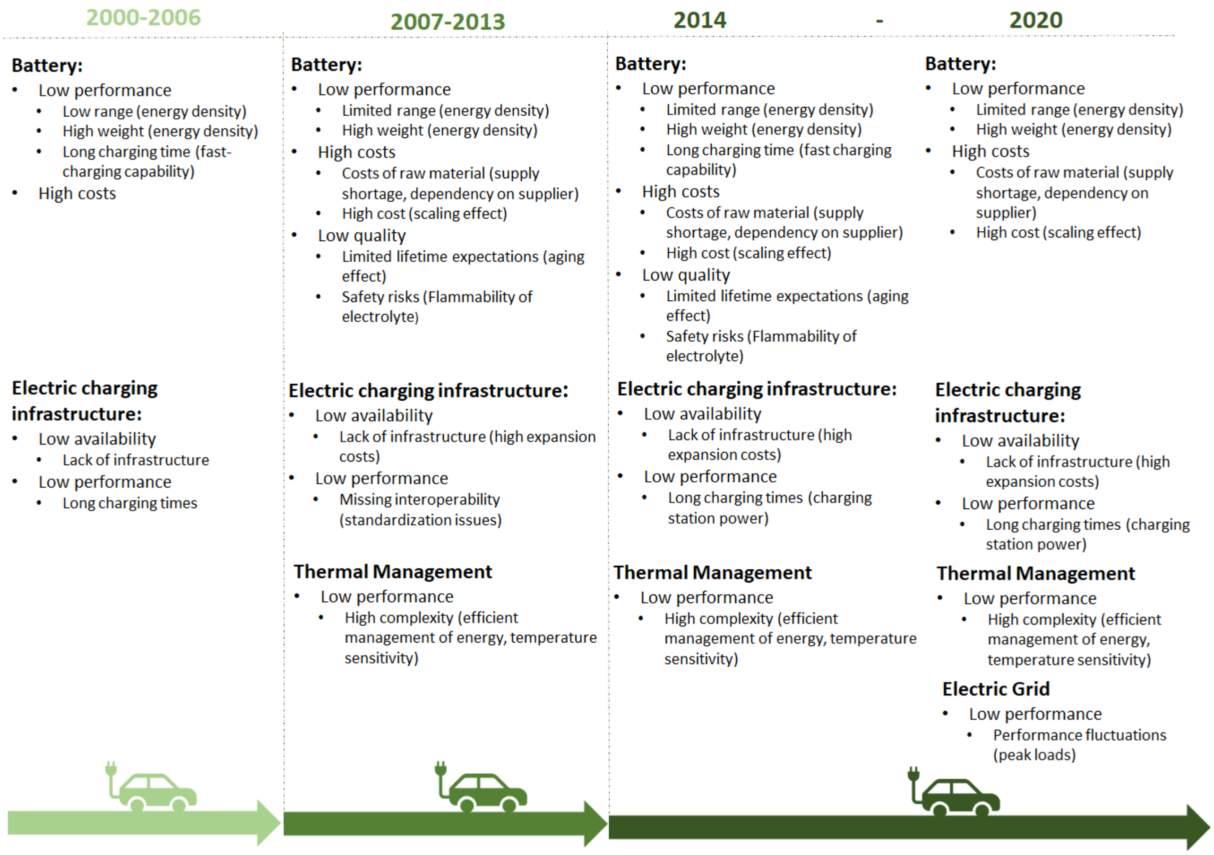


Figure 55: Validated bottlenecks for the ecosystem of BEV divided into three time periods

5.2 Validation of the results for the ecosystem of the fuel cell electric vehicle

The analysis results basically matched the results of the validation interviews, which can be seen in Appendix R. Nevertheless, there were some differences between the analysis results and the expert interviews, which will now be presented.

5.2.1 Time period from 2000 to 2006

In the first section of the analysis period, it was confirmed that the fuel cell, the hydrogen tank, and the hydrogen refueling infrastructure had a limiting effect on the FCEV ecosystem.
All experts agreed that the performance of the fuel cell stacks, more precisely the dynamic behavior and efficiency, which was also detected as a constraint in the analysis, was a limiting factor. The high costs of the fuel cell were also seen as a constraint for the ecosystem growth, and therefore the analysis results were confirmed as well. In addition, one expert mentioned that there was a lifetime limitation for the fuel cells due to problems with the materials, but this quality issue was not addressed at all by the other two experts. This quality problem of the fuel cell was also not detected as an issue in the analysis in this period. For this reason, the quality of the fuel cell is not seen as a limitational aspect in this period.

The hydrogen system, or more precisely the hydrogen tank, which was detected as a bottleneck in the analysis, was validated by the expert interviews. The low performance due to the high complexity in hydrogen storage was a crucial reason for this limitation. In addition, all experts agreed that the high cost of the storage tanks also had a limiting effect on the ecosystem. However, this was not identified in the analysis as a limiting reason for the hydrogen tank. This difference in the analysis results and the interviews with the experts can be attributed to the fact that, as already mentioned several times, the

number of articles dealing with fuel cells was unfortunately very low in the analysis. Moreover, the high costs can also be seen as a consequence of the high complexity of hydrogen storage.
Additionally, one expert identified the quality of the storage tanks as an issue in the interview, stating that safety risks in hydrogen storage were existing. However, since this safety issue was only addressed by one expert during this time section and was not detected in the analysis, the hydrogen tank's quality is not considered a limiting factor.

The low availability of the hydrogen refueling infrastructure was also one of the key limitations detected in the analysis during this period. Two experts confirmed this result. The third one also mentioned the refueling infrastructure but pointed out that the problems in the construction of this infrastructure were detected in a later time section. As a result of these facts, the low availability of the hydrogen refueling infrastructure is considered as the third bottleneck in this time section.

Furthermore, the periphery necessary for the function of the fuel cell stack (e.g., oxygen supply) was mentioned in the interviews, but the experts agreed that the players in the ecosystem were not even aware of what the periphery should look like at this point in time.

The two components that were detected as a bottleneck in only a few articles in the analysis, namely the e-motor and the power electronics, were identified as a bottleneck by one expert in this time section. Nevertheless, the expert pointed out that the issues of these two components were not too limiting compared to the problems with the fuel cell, hydrogen tank, and the hydrogen refueling infrastructure. For this reason, these two components are not considered to be a bottleneck in this time section.

Another topic that was identified as a significant challenge by one expert, similar to the BEVs, is the vehicle architecture and the integration of the components into the overall vehicle. However, this issue was not included in the results for the same reasons as mentioned in chapter 5.1

5.2.2 Time period from 2007 to 2013

In the next period discussed in the interviews, the fuel cell remained the key bottleneck in the qualitative content analysis due to performance, quality, and cost issues, as already discussed in chapter 4.3.8. In the interviews, the high costs of the fuel cell were seen as a limiting factor by all the experts. The other two bottleneck dimensions (low performance and low quality) could only be validated to a limited extent. One expert only mentioned the improvements in the performance (efficiency) and the lifetime, which indirectly indicated a limitation but could not be coded accordingly by the qualitative evaluation. The performance issue of the fuel cells, which was identified as the most limiting factor in the qualitative content analysis, was addressed by all the experts, but only one of them explicitly assessed the fuel cell performance (dynamic behavior and efficiency) as a limitation. However, since the other two experts also indirectly discussed the performance issue, even though this was not directly visible in the results for the reasons mentioned above, the performance of the fuel cell is also rated as a limiting factor in this period. The same applies to the quality issue in terms of lifetime, and therefore the component fuel cell remained the key bottleneck in this period due to its low performance, low quality, and high costs.

The hydrogen refueling infrastructure, which already had a limiting effect in the previous section, continued to be a bottleneck, as discussed in chapter 4.3.8 and confirmed by the expert interviews. The reason was the still low availability of hydrogen refueling stations.

The analysis results for the hydrogen system, or more precisely for the hydrogen tank, were not the same as those of the expert interviews. All three experts identified the hydrogen tank’s high costs as one of the key limitations in this period, but the analysis did not reflect this. In the analysis, the poor performance of the hydrogen tanks was detected as a constraint attributed to the high complexity in storing hydrogen. Although the results did not show the high costs of the hydrogen tank as a limitation, the high complexity in hydrogen storage can be traced back to high requirements on the hydrogen tanks. Therefore a connection to the high costs becomes apparent. For this reason, the hydrogen tank, respectively its higher category, the hydrogen system, is rated as a bottleneck due to high costs.

The e-motor and the power electronics were again identified as a bottleneck by one expert, but in comparison with the other challenges in the ecosystem of fuel cell electric vehicles, these limitations were seen as secondary by the expert. For this reason, these two components were not considered as a bottleneck in this period.

5.2.3 Time period from 2014 to 2020

The last section showed the most significant differences between the analysis results and the validation interviews. However, this can be attributed to the fact that the topic of fuel cell electric vehicles was hardly mentioned in the analysis articles during this period. Therefore only a small number of text passages that represent a bottleneck were detected.

Nevertheless, the fuel cell was once again the most frequently mentioned bottleneck in the analysis. The identified text passages referred to the high costs and the low performance (efficiency) of the fuel cells in this time section. But, similar to the BEVs, it was again observed that enormous developments in the technology happened between the years 2014 and 2020. In the case of the FCEVs, it was not possible to split up the time section again as it was done for the BEVs because the experts always referred to the period as a whole (made no differences between 2014 and 2020). Nevertheless, all the experts agreed on the fact that the costs of the fuel cell remain a key issue until today.

On the other hand, all the experts pointed out that the performance of the fuel cell in 2020 is very good and is no longer a limiting factor. This is in contrast to the analysis results. As a result of these expert opinions and the already mentioned fact of the small number of detected bottleneck text passages, the performance of the fuel cell is no longer seen as a limiting factor in this period.

The experts' opinions and the analysis results showed that, due to the low availability, the hydrogen refueling infrastructure remains a bottleneck in the year 2020, which was already discussed in chapter 4.3.8.

The same can be said for the hydrogen system, respectively, the hydrogen tank, which still has comparatively high costs. Furthermore, the performance of the hydrogen system was also detected as a limiting factor in the analysis. This can be traced back to the high complexity in hydrogen storage and can, as already described above, indirectly be transferred to the cost factor.

The low number of detected bottlenecks for FCEVs in this time section is illustrated by the fact that the electric motor represents one of the main limitations in the analysis, with three bottleneck mentions. However, this disproportionately high number is attributable to the in chapter 4.3.5 (synergy with BEVs), mentioned reasons, and therefore the e-motor is not rated as a bottleneck.

The same applies to the peripheral component oxygen supply, which was only seen by one expert as limiting due to its high cost, but this expert also mentioned that in comparison, the hydrogen tank and the fuel cell are significantly more expensive.

5.2.4 Summary of the validated results

The summary of the identified and validated bottlenecks in the innovation ecosystem for fuel cell electric vehicles in the period from 2000 to 2020, divided into the three discussed time sections, can be seen in Figure 56.

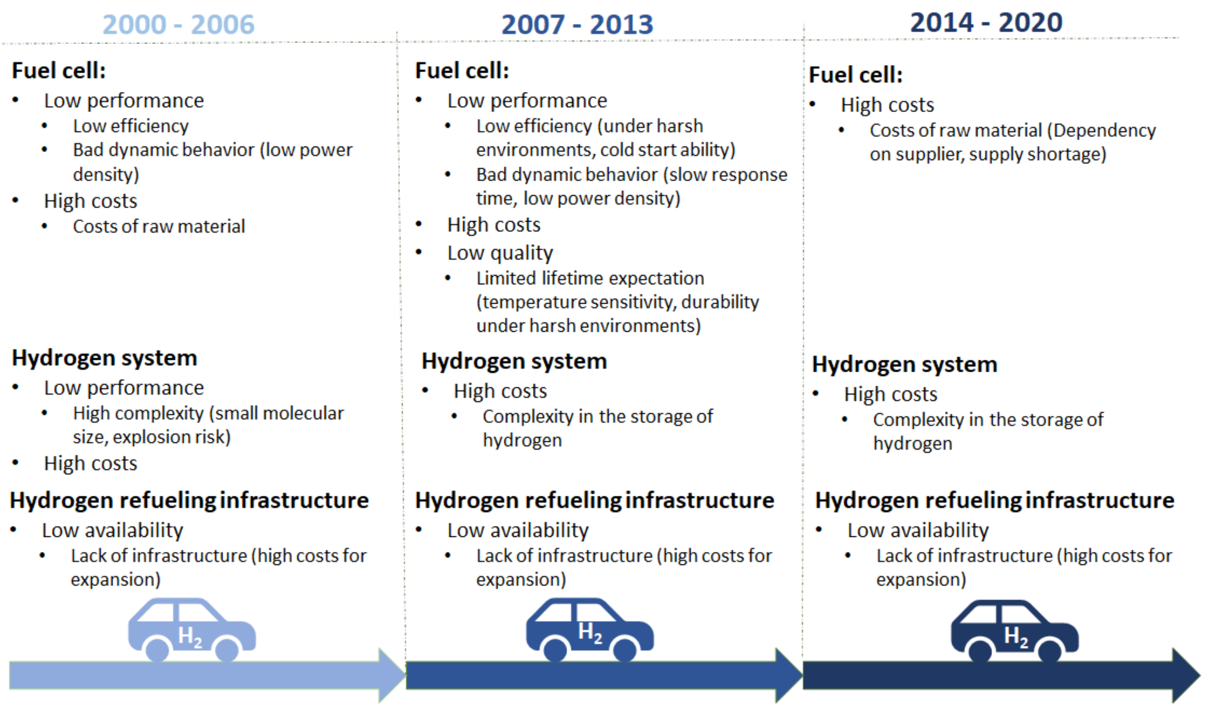


Figure 56: Validated bottlenecks for the ecosystem of FCEV divided into three time periods

6 Discussion

In this chapter of the thesis, the empirical results are discussed, interpreted, and linked to the theory presented. Since the analysis material also showed some anomalies over the study period and consequently influenced the results of the bottlenecks for BEVs and FCEVs, these anomalies will be discussed first. Afterwards, the results of the two powertrain technologies are discussed separately. Finally, the analysis results are linked to the theory.

6.1 Discussion of the analysis material

During the analysis, it was noticeable that the sum of published articles in the journals ATZ and IJoAT, which address the topic of battery electric vehicles and fuel cell electric vehicles, has significantly increased over the period from 2000 to 2020. One explanation for this trend could be that the two described journals published more articles in the later years than in the early 2000s and thus covered a broader range of topics, such as alternative powertrains. The trend curves in Figure 57 for the total number of published articles compared to the number of articles dealing with BEVs and FCEVs show a very similar pattern, which confirms the claim from above.

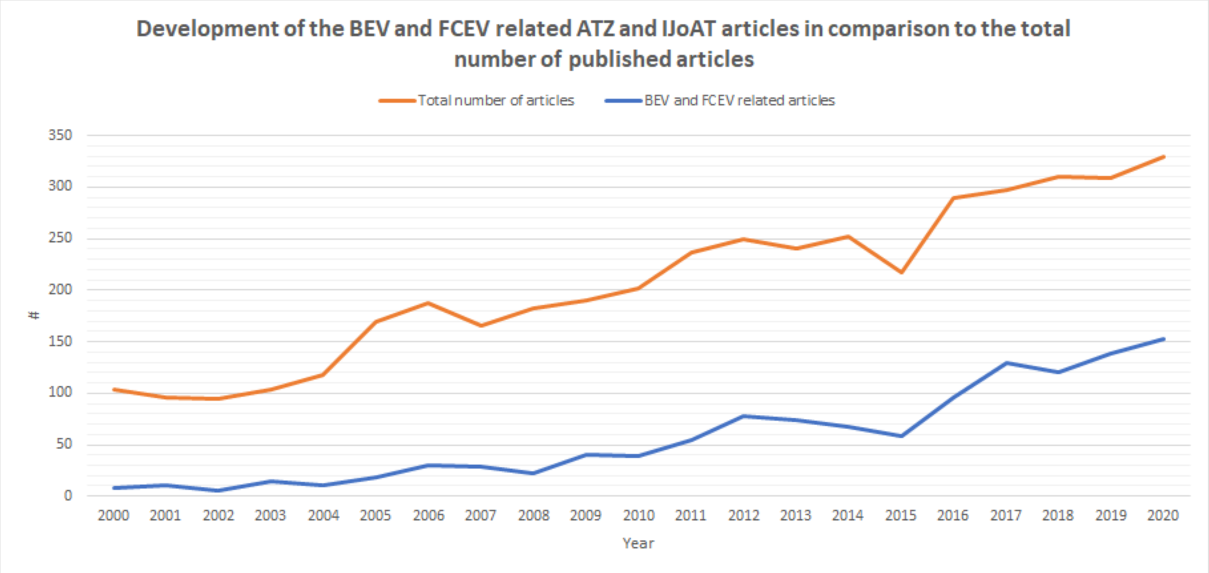


Figure 57: Development of the BEV and FCEV related ATZ and IJoAT articles in comparison to the total number of published articles in the time period from 2000 to 2020

Another explanation for the increasing number of articles in the journals dealing with alternative powertrain systems might be the legislation concerning CO_2 emissions, which was introduced during the study period and forced car manufacturers to focus on these powertrain topologies

In terms of CO_2 emission legislation, a pioneer was California, which had already been working on ZEV regulation since 1990 and announced for 1998 the first mandatory ZEV quota for car manufacturers. However, this quota was amended and postponed several times due to various technical hurdles (e.g., battery maturity) and was finally introduced in 2003 in a weakened form of partial zero-emission vehicles (PZEV). PZEVs refer to gasoline vehicles that meet the highest existing emission standards, with additional higher requirements concerning evaporative emissions, and have a 150,000-mile warranty on the emission system. (McConnell et al., 2019, p. 6; Fischer et al., 2020, p. 344)

However, the introduction of this U.S. legislation did not show a disproportionate increase in the number of articles dealing with BEVs and FCEVs in the two selected journals. In contrast to that, with the EU-legislation, whose first target (130 g/km CO_2 -fleet-emissions) was announced in the late 2000s and became mandatory in 2012 respectively in 2015, the BEV and FCEV related articles in the two journals increased by a factor of four during this period (2008-2012). (Fischer et al., 2020, p. 428; Europäische Union, 2009) This fact can be seen in Figure 57.

The huge increase in the number of BEV and FCEV related articles from 2015 to 2017 can possibly be attributed to the 2014 tightening of measures to a CO_2-fleet target of 95 g/km in 2020 respectively 2021, which put even more pressure on the OEMs to address the topic of alternative powertrains. (Fischer et al., 2020, p. 428; Europäische Union, 2009, p, 5)

As already mentioned, this increase in the number of analyzed articles has also influenced the results. These results for the innovation ecosystem of BEVs and FCEVs are now discussed in the following two sub-chapters.

6.2 Discussion of the results for battery electric vehicles

The discussion of the analysis results for the battery electric vehicles is again divided into three time sections, as already practiced in other chapters of this thesis. This subdivision makes it easier to address individual issues in different periods and interpret the underlying reasons for the bottlenecks' changes.

6.2.1 Time period from 2000 to 2006

In this section of the analysis period, relatively few bottlenecks could be identified in the BEV ecosystem because almost no articles in the selected journals dealt with the topic of BEVs.

This is because the technology was still in the applied basic research process, and therefore only a few prototypes from different car manufacturers were on the roads. The technology, in general, worked reasonably well at that time, but the low battery maturity level still caused significant issues. (Kampker et al., 2018, p. 12) These big issues concerning the battery indicate that the customer's value proposition was not yet defined in this phase.

For this reason, it was interesting to observe that the electric charging infrastructure was already detected as a bottleneck in the early 2000s, even though there were only very few BEVs on the market. This shows that already at this time, it was clear to the participants in the ecosystem that the chicken-and-egg principle had to be overcome. Consequently, the BEVs can only achieve a market break-through if the complementary products are built, developed, and coordinated simultaneously with the vehicles. The fact that the component battery and the complementary product electric charging infrastructure were identified as bottlenecks in this period can be explained by the necessary interaction during the charging process and the resulting specific complementarity. This means that the knowledge of the actors' interdependence to jointly deliver an attractive product to the customer has already existed at that time. These facts also indicate that the ecosystem around the innovation of battery electric vehicles was just starting to emerge at that time and thus was still in the birth phase of Moore's (1993) ecosystem lifecycle. Furthermore, the emergence of the complementary service “dealer and workshop” as a bottleneck (2006, according to Figure 26) due to new challenges in repairing electrified vehicles shows the impact that the innovation “BEV” had on activities that had previously remained unchanged for decades.

6.2.2 Time period from 2007 to 2013

As already mentioned in chapter 4.1, more and more articles in the two journals have dealt with BEVs, especially since 2008. This can be attributed to two reasons.

Firstly, the above-mentioned CO_2 emission limits in Europa were announced, which became mandatory from 2012 onwards (Europäische Union, 2009, p. 5; Fischer et al., 2020, p. 428). They indirectly forced car manufacturers to develop (zero-) low-emission vehicles to avoid penalties, and thus, it also became apparent how much governmental institutions can promote such innovations.

Secondly, significant progress regarding the battery technology was achieved at that time. In 2006, the start-up Tesla Inc. presented the Tesla Roadster, which was produced in small series from 2008 onwards and was the first serial-produced vehicle using the innovative lithium-ion battery technology (Kampker et al., 2018, p. 12), which achieved significantly higher energy densities than the previously used nickel-metal hydride battery (Fischer and Neunteufel, 2018, p. 339). The difference in the energy densities between NiMH batteries and Li-ion batteries can be seen in Figure 58. This diagram illustrates the increase in energy densities of these two battery technologies in recent years.

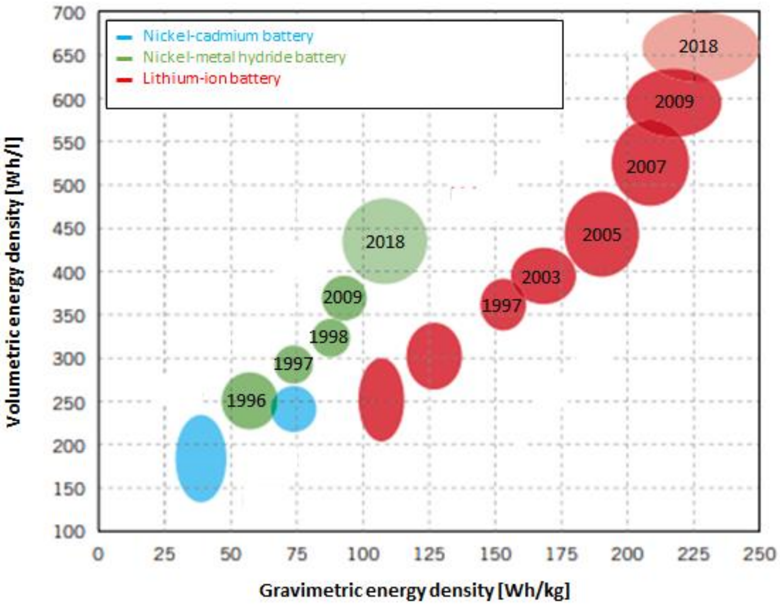


Figure 58: Gravimetric and volumetric energy density increase over the years for Li-ion and NiMH batteries (Birke, 2018, p. 22)

However, according to the analysis, the energy densities of the batteries around 2010 were still too low to achieve driving ranges that were acceptable for the end customers. The VW E-Golf's maximum driving range of 190km at this time underlines this claim (Pudenz, 2013), and therefore this performance problem was still a limitation for the value proposition to the customer. Nevertheless, this technological leap made the product BEV more attractive for the end customer and an increasing number of manufacturers launched vehicles on the market in the following years (Kampker, et al. 2018, p. 13).

The switch to lithium-ion batteries led automotive manufacturers to focus on other issues besides the battery too. From 2010 onwards, thermal management was increasingly detected in the analysis as a bottleneck. This can be attributed to two factors. On the one hand, lithium-ion batteries need to be cooled since a thermal runaway of the battery cells occurs at a battery temperature beyond 70°C (Fischer and Neunteufel, 2018, p. 329).

On the other hand, the HVAC, which is part of the thermal management component, requires energy from the battery for air conditioning and heating the passenger compartment. Consequently, this energy is no longer available for propulsion, and the overall driving range of the BEV is getting reduced. (Wirth et al., 2013, p. 46) This means that the comfort issue for the end customer also became acute during this time and indicates that bottlenecks in the ecosystem of BEVs were partially processed sequentially.

Another interesting aspect is that the electric charging infrastructure, which was already detected as a bottleneck in the previous section, had a consistently limiting effect on the value proposition to the customer from 2011 onwards. This indicates a connection to the introduction of lithium-ion battery technology and the associated increase in the attractiveness of BEVs again.

Since an increasing number of BEVs could be found on the roads at the end of this period (see Figure 59), the lack of standardization of charging plugs also became an issue. This lack of standardization and, consequently, the limited possibility for the end-customer to use public charging stations offered an insight into the necessity of coordination between the actors within the ecosystem. As a result of a lack of cooperation in developing customer-friendly charging solutions between the vehicle manufacturers and the charging station providers, the value proposition to the customer was significantly limited. This standardization, which was necessary due to the specific complementarity of the two products (BEV and electric charging infrastructure), was resolved by the EU in 2013 (Doppelbauer, 2020b, p. 295).

Furthermore, the lack of availability of public charging stations became an increasing issue due to the higher number of new BEV registrations at the end of this period. This means that the comprehensive installation of a charging infrastructure could not keep pace with the increasing number of BEVs on the road. This fact can be seen in Figure 61.

Figure 59: New registered BEVs in Germany from 2006 to 2020 (Kraftfahrt-Bundesamt, 2019, 2018, 2008, 2007, 2006)

The analysis results show that the battery maturity level was the decisive factor for the market introduction of BEVs. Once an acceptable battery maturity level was reached, manufacturers also increasingly focused on other components and complementary products and services. As a result, the innovation challenges within the ecosystem were redistributed. While the challenges in battery development overshadowed everything else in the previous period, significant improvements with the switch to lithium-ion batteries also brought challenges concerning thermal management in the spotlight. The interdependence of these two components also became apparent, as the battery must be managed within a small temperature range in order to work efficiently (Stephens et al., 2017, p. 2.14). The electric charging infrastructure also became increasingly critical in terms of bottleneck, especially towards the end of this period, as the number of new registrations of BEVs increased significantly.

The fact that the first BEVs were registered in this phase of the analysis period suggests that the value proposition to the customer was finally defined. But the ecosystem was still in the birth phase based on Moore's (1993) ecosystem lifecycle, as a small number of customers were already operating the first BEVS on the roads, but the expansion to a broader customer group had not yet been completed.

6.2.3 Time period from 2014 to 2020

In the third phase of the analysis period, the number of articles dealing with BEVs increased even more (see Figure 57). This could be the result of the announcement in 2014, for tightening the CO_2 limits in the year 2020, respectively 2021. During this entire period, considerable technological improvements were achieved, which led to an enormous increase in the number of new vehicle registrations (see Figure 59).

The increase in the number of new registrations shows that a broad customer group increasingly accepted the product BEV from 2014 onwards. This means that more and more customers valued the concept behind BEVs, which indicates that the BEV ecosystem has reached the expansion phase in the life cycle described by Moore (1993). During this time, especially the battery was improved enormously in terms of energy density (see Figure 58) and fast-charging capability. This also caused the intensity of the battery bottleneck to decrease in the late 2010s. In contrast, the bottleneck intensity of the electric charging infrastructure increased in recent years, which can be seen in Figure 60.

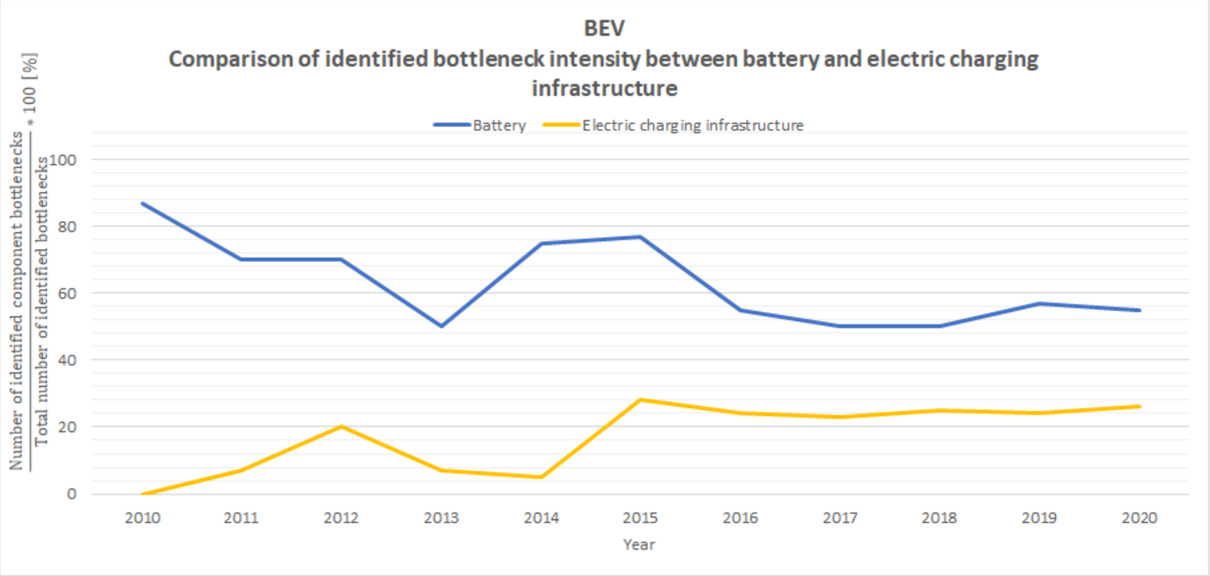


Figure 60: Comparison of identified bottleneck intensity between battery and electric charging infrastructure

Both of these facts can be attributed to several reasons.

On the one hand, starting in the mid-2010s, it was possible to charge the battery with higher charging currents, which means that the battery has reached the fast-charging capability. This resulted in shifting the bottleneck from the battery to the electric charging station, as these charging stations mostly did not have sufficient power to achieve short charging times. This bottleneck shift in the ecosystem is an interesting finding, indicating that the actors within the ecosystem have not been able to solve their innovation challenges at the same pace. Consequently, the development of the fast-charging capability of the batteries did not bring any significant benefit for the end customer, as the complementary product of the charging station was now responsible for the fact that fast charging times could not be achieved. In other words, the attractiveness of the product BEV could not be increased by achieving the battery fast-charging capability. This demonstrates how important it is that all actors in the ecosystem solve their innovation challenges.

As shown in Figure 61, the second reason is that the number of new BEV registrations has increased significantly compared to the number of newly built charging stations. In particular, the still small number of fast-charging stations is one of the main causes that the charging times of BEVs still significantly limit the value proposition to the customer, even though they have already improved considerably.

Thermal management, especially concerning the energy required for heating and cooling the compartment, also continued to be a key bottleneck during this period, although the intensity has decreased significantly. This can mainly be attributed to the fact that battery capacities have increased, and thus, more energy can be stored in the batteries that can be used for heating the compartment. This shows that the improvement of the component battery also led to an improvement of the component thermal management, which again reflects the interdependency between the actors and their contributions in the ecosystem. In addition, heat pumps instead of PTC heaters were increasingly used for heating the compartment, as these heat pumps require less energy (Fischer et al., 2015, p. 131).

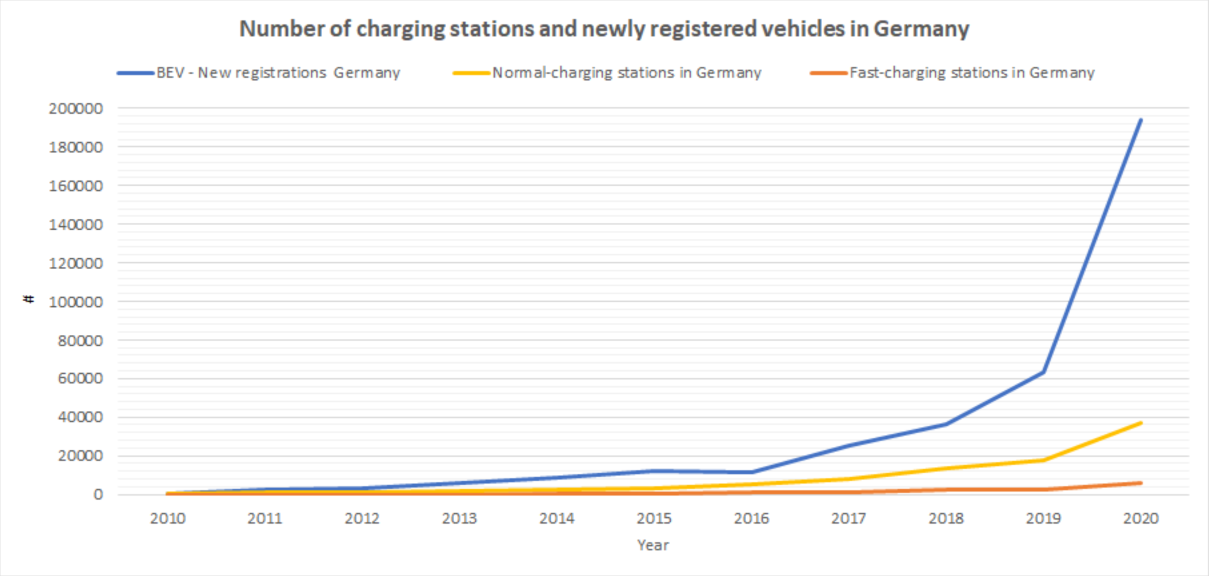


Figure 61: Number of public (fast-)charging stations and newly registered battery electric vehicles in Germany (Kraftfahrt-Bundesamt, 2019; Bundesnetzagentur, 2021; Auf der Maur et al., 2020, p. 16)

At the end of the 2010s, as described in chapter 4.1.4, a new bottleneck emerged in the form of the complementary product of the electric grid. This reflects the dynamics in the environment of ecosystems resulting from solving specific bottlenecks, at least in parts. In other words, the increased attractiveness of BEVs brought a complementary product into the focus of the ecosystem, which had never been seen as limiting before. Thus, a trend towards sequential processing of bottlenecks can be identified in the innovation ecosystem of battery electric vehicles.

All of these facts indicate that the BEV ecosystem is still in Moore's (1993) expansion phase of the ecosystem lifecycle, which is confirmed by the numbers in Figure 59, showing a percentage increase in new BEV registrations of over 200% from 2019 to 2020.

However, to ensure that the BEV ecosystem can grow further, the actors involved must solve the bottlenecks to attract an even broader customer group. While the BEV ecosystem, with the associated actors and their contributions, has grown tremendously throughout the study period and solved many issues, some issues that are responsible for a component/complement to be declared as a bottleneck remained unresolved even in 2020.
The batteries, which despite enormous improvements still represent the key bottleneck, must be further improved, especially concerning their performance and costs. The electric charging infrastructure must be further expanded. In particular, the expansion of public fast-charging stations must be accelerated to achieve short charging times. In addition, it will become increasingly important that the charging infrastructure becomes digitalized in the coming years. Volkswagen demonstrates one approach for solving the battery and electric charging infrastructure bottlenecks. They are planning a drastic cost reduction of the batteries (Volkswagen has a battery joint venture), and they want to cooperate with energy suppliers to improve the charging infrastructure significantly. (Schäfer, 2021)

If no countermeasures concerning the electric grid are taken in the future, the grid may become more and more a bottleneck. Such a countermeasure could be the installation of a smart grid that integrates consumers, generators, and those who do both to ensure a sustainable economic electricity solution while also giving consumers the ability to optimize the operation of the system through bidirectional electricity exchange (Vijayapriya and Kothari, 2011, p. 305).

6.2.4 Network of complementarity

The network of complementarities revealed the most important bottlenecks in the BEV ecosystem, as already described in chapter 4.2. In this context, this network provided interesting insights, especially regarding the connections between the components and complementary products within this network. The most central elements are the battery and the electric charging infrastructure, and thus, they are the key bottlenecks, which can also be seen in Figure 62.

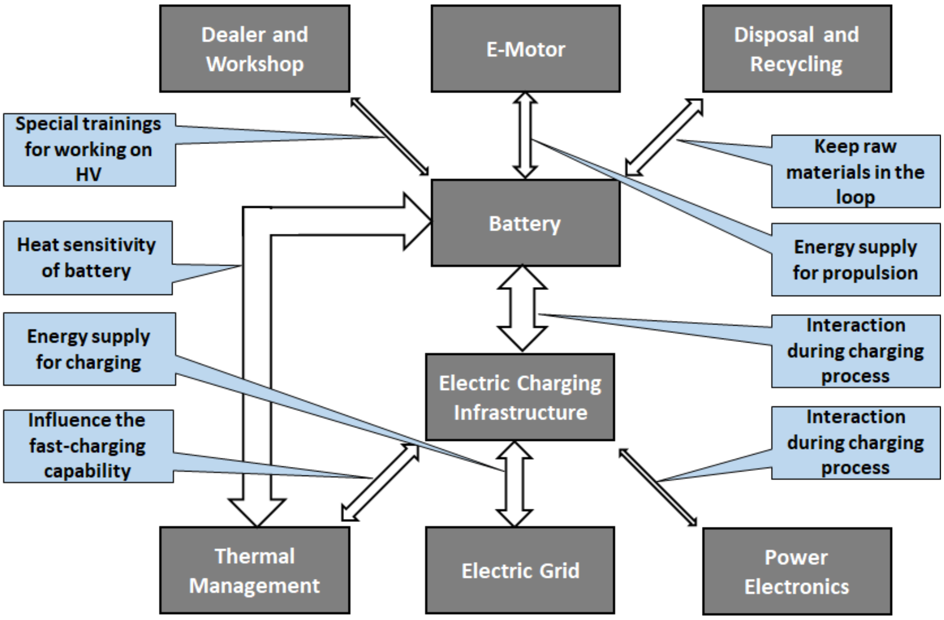


Figure 62: Network of complementarity for BEVs including complementarity background

The fact that the battery and the thermal management have a strong complementarity to each other has already been mentioned several times in the course of this chapter. The necessary interaction between the battery and the charging infrastructure during the charging process has also been mentioned. Interestingly, there is a complementarity between the battery and the complementary service "dealer and workshop". This is probably a result of the fact that the batteries operate with high voltages, and accordingly, the workers have to be trained on these high voltages. That the complement dealer/workshop does not have any complementarity with other components can be traced back to the low number of detected “dealer and workshop” bottlenecks.

Several facts can explain the complementarity between batteries and disposal/recycling. On the one hand, recycling processes are becoming increasingly important to keep raw materials in the loop and reduce the costs of expensive batteries. On the other hand, there are safety risks associated with faulty batteries, making the disposal process challenging.

The complementarity between the electric motor and the battery can be attributed to the fact that the battery must supply the electric motor with energy for propulsion. In other words, this interaction has a significant impact on the efficiency of the drivetrain.

The second central element of this network, the electric charging infrastructure, shows a strong complementarity with thermal management. As a result, it became apparent that the charging time is strongly dependent on the temperature of the components. For this reason, thermal management also plays an important role in the context of the electric charging infrastructure and the associated fast-charging capability. The complementarity between the electric grid and the charging infrastructure seems to be logical since the charging infrastructure receives the required charging power from the electric grid.

The last aspect, the complementarity between power electronics and charging infrastructure, is based on the interactions during the charging process between the onboard charger and the charging station, leading to potential issues.

The fact that components such as the e-motor and power electronics only show complementarity with very few other components/complements in this network can be attributed to the low number of detected power electronics and e-motor bottlenecks. In this context, a complementarity between the battery and the power electronics would be obvious since the OBC is responsible for charging the battery, but this could not be deduced from the analysis material.

This network of complementarity shows how important the concept of the innovation ecosystem is for research on the product BEV since complementarities exist between diverse components and complementary products and services. As a result, innovation progress in one component/complement can also influence other ecosystem components. On the other hand, the analysis also showed that solving one bottleneck can cause another. As a consequence, the value proposition is then limited by the new unresolved bottleneck.

6.3 Discussion of the results for fuel cell electric vehicles

The discussion of the analysis results for the fuel cell electric vehicles is again divided into three time sections, as already practiced in other chapters of this thesis. This subdivision makes it easier to address individual issues in different periods and interpret the underlying reasons for the bottlenecks' changes.

6.3.1 Time period from 2000 to 2006

In contrast to the BEVs, significantly more articles dealt with the FCEVs in the first section of the analysis period. This was interesting to see since there were hardly any prototypes from the OEMs on the roads at this time (Wind, 2019, p. 100).

Many questions concerning the onboard storage of hydrogen and the operation of fuel cells in automotive applications were unsolved at that time. Different possibilities for onboard hydrogen storage were existing, such as high-pressure hydrogen storage, liquid hydrogen storage, or hydrogen storage in chemically bound form. This means that the basic idea of operating a vehicle with a fuel cell was there at this time, but the value proposition to the customer was much less defined than for BEVs. In some cases, not even the basic functions of the drivetrain were available in this period (Wind, 2019, p. 100).
Nevertheless, it was interesting to observe that the fuel cell, the hydrogen system, and the hydrogen refueling infrastructure were the key bottlenecks during this time. This can be explained by the interdependencies between the individual components/complements.
For example, the type of fuel cell depends on the form in which the hydrogen is stored. Also, vice versa, the condition in which hydrogen must be stored depends on the type of fuel cell (Wind, 2019, p. 104). This means it was enormously important that the two components were coordinated with each other to generate the value proposition for the customer.

The hydrogen refueling infrastructure was also detected as a bottleneck in this period because of its limited availability, even though there were hardly any FCEVs on the roads. This reflects the same picture as already presented for the BEVs. In other words, in both ecosystems (BEV and FCEV), a complementary product, in addition to components, was detected as a bottleneck from the beginning of the analysis period. This shows how important the application of the innovation ecosystem concept is for the bottleneck identification of these two innovations (BEV and FCEV). The actors may already have been aware that only through a cooperative development process (supplier, OEM, and complementor) can a product become attractive for the end customer. These facts described and the results obtained in the analysis indicate that at the end of this period, i.e., around 2006, the ecosystem of FCEVs has slowly begun to form and thus entered the birth phase of Moore's (1993) ecosystem lifecycle. The beginning fleet tests under everyday conditions of Daimler (Achleitner et al., 2016, p. 205) also indicate this early phase in the ecosystem lifecycle.

6.3.2 Time period from 2007 to 2013

As already described in chapter 4.3, only a few articles in the two journals dealt with fuel cell electric vehicles, especially from 2008 onward. One reason for this can be that enormous progress was made in battery technology, particularly at the beginning of the 2010s, which resulted in an increased focus on BEVs by car manufacturers, especially in Germany (Burkert, 2019, p. 9). Despite the small number of articles dealing with fuel cell electric vehicles, and thus the small number of bottlenecks identified, these bottlenecks remained the same as in the previous period. This means the fuel cell, the hydrogen system, and the hydrogen refuel infrastructure continued to be the limiting factor throughout this period. Nevertheless, enormous progress in technology must have happened during this period, since from the mid-2010s onward, manufacturers such as Toyota, Hyundai, and Honda launched their first serial produced vehicles (Klell, et al. 2018, p. 180).

In the analysis, it was noticeable that the articles in this period only referred to PEM fuel cells and high-pressure storage tanks and not to other types of fuel cells and storage tanks anymore. This can be attributed to the fact that since 2011 it became possible to store hydrogen in high-pressure storage systems with pressures of up to 700 bar, which means that more energy can be stored (Wind, 2019, p. 111). In addition, OEMs like Toyota have made huge progress in fuel cell technology in terms of cold-start capability and durability (Shinobu and Kojima, 2011). In this period, the component types concerning hydrogen system and fuel cell were finally defined, which led to the fact that the value proposition to the customer was defined at the end of this period. This shows how important it is that innovation challenges in the ecosystem are not just solved for one component or one complementary product but that several component supplier and complementors address their issues simultaneously. Only the development of new hydrogen tanks and the improvement of the fuel cell made it possible for the product FCEV to be ready for the market in the next period. But the analysis also showed that the hydrogen system and fuel cell still had enormous issues in terms of performance, cost, and quality.

The availability of hydrogen refueling infrastructure was also identified in the analysis of this period as a key bottleneck, which also hindered some manufacturers from focusing on developing FCEVs. By looking at the number of twelve public hydrogen refueling stations in Germany in 2012, the analysis result is confirmed (Ramsauer, 2012). Furthermore, this demonstrates how important it is to develop complementary products parallel with an innovation since the technological progress of a product in the ecosystem can only lead to an increase in ecosystem value if the required complementary products also develop further.

As a result, despite the small number of analysis articles dealing with FCEVs, it became clear that although the technology, in general, worked reasonably well at the end of this period, there were still many component-specific issues. All the facts indicate that the ecosystem was still in the birth phase of Moore's (1993) ecosystem lifecycle.

6.3.3 Time period from 2014 to 2020

In the last section, the trend continued that fewer and fewer articles dealt with FCEVs. This can be explained, among other things, by the further improvements in the BEVs. As a result, it was challenging to obtain meaningful results in this period.

Nevertheless, the analysis showed that the bottlenecks have remained unchanged. Thus the fuel cell, the hydrogen system, and the hydrogen refueling infrastructure still represent the most significant limitation for the value proposition to the customer. However, the fact that the issues regarding the quality and performance of the fuel cells have been resolved, as the analysis showed, is also indicated by looking at the trend in the number of new registrations of fuel cell electric vehicles, which can be seen in Figure 63.

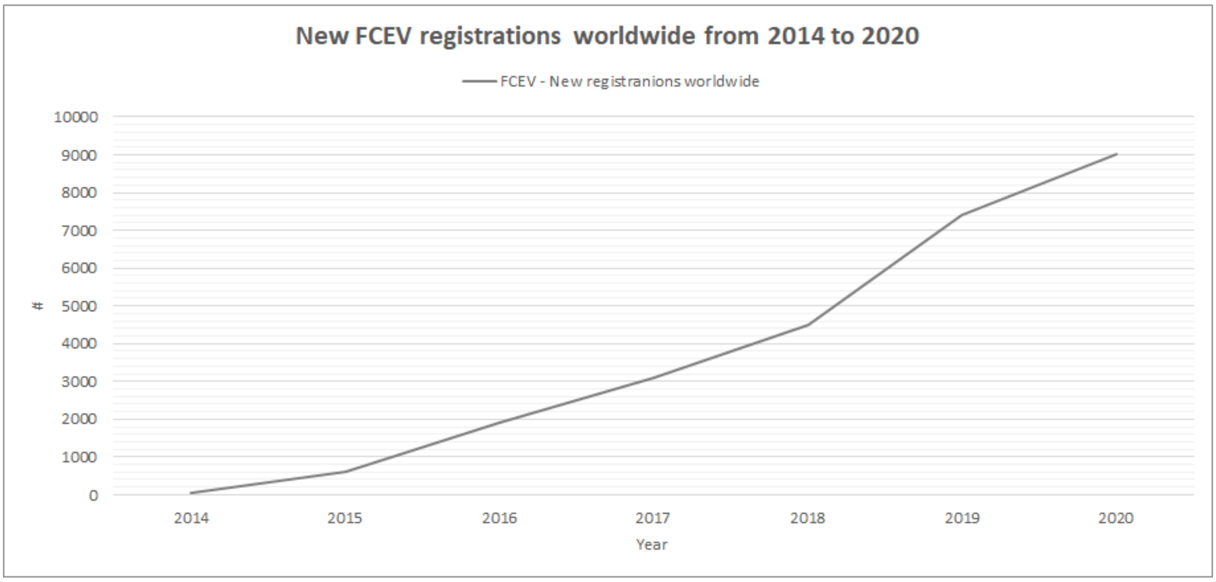


Figure 63: Number of newly registered fuel cell electric vehicles worldwide from 2014 to 2020 (VDI/VDE, 2019; ZSW, 2021)

Although the number of new registrations is still very low, it has been increasing significantly in recent years. This means that the product FCEV has been accepted by a small group of customers. Nevertheless, the fuel cell costs and the hydrogen system costs in 2020 are still significant issues. These high costs of the fuel cell are caused by the missing scaling effect in the production and the platinum needed for the MEA. For the hydrogen system, these high costs are caused by the high complexity of hydrogen storage, which requires high-pressure tanks.

Figure 64 illustrates the reason why the hydrogen refueling infrastructure remained a bottleneck in this period. While there are still not many fuel cell electric vehicles on the road, about 550 hydrogen refueling stations worldwide are not even come close to being sufficient for the broad series production ramp-up of fuel cell electric vehicles. In comparison to that, there are more than 138,000 gasoline and diesel refueling stations just in Europe in the year 2019 (WKO, 2019).

These described facts indicate that the FCEV ecosystem is still in Moore's (1993) birth phase of the ecosystem lifecycle, which is confirmed by the numbers in Figure 63 since the fuel cell vehicles are still not used by a broad customer group. Nevertheless, the number of new registrations is increasing continuously, and, especially in the last year of the study period (2020), components such as thermal management (comfort aspects) and complementary services such as disposal and recycling (cost reduction) were detected as partially limiting. This indicates that the innovation ecosystem could soon enter the expansion phase of the ecosystem lifecycle.

However, to ensure that this expansion phase can be reached, the actors involved must solve the bottlenecks to attract an even broader customer group. Although the FCEV technology developed enormously during the study period, with serial-production vehicles being sold for the first time in the final section (2014 to 2020), many issues still remain unresolved.

The costs of fuel cells and hydrogen tanks must be reduced enormously to make the vehicles competitive and thus become attractive for a broader customer group. The expansion of the hydrogen refueling network must be driven forward because this may represent the biggest bottleneck in the next few years since this expansion will require a great deal of money and time. But this comprehensive hydrogen refueling network is the only way to ensure that the ecosystem can continue to grow because, without this complementary product, the FCEV has no value for the end customer.

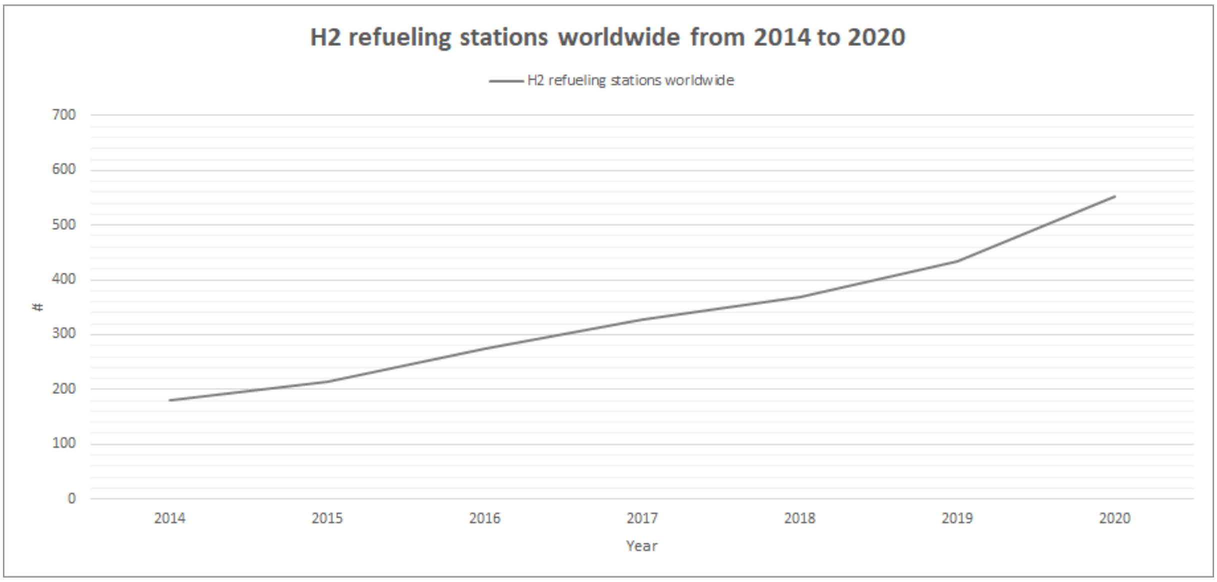


Figure 64: Number of public hydrogen refueling stations worldwide from 2014 to 2020 (Ludwig-Bölkow-Systemtechnik GmbH, 2020)

6.3.4 Network of complementarity

The network of complementarities revealed the most important bottlenecks in the FCEV ecosystem, as already described in chapter 4.4. In this context, this network provided interesting insights, especially regarding the connections between the components and complementary products within this network. The most central elements are the fuel cell and the hydrogen refueling infrastructure and were thus the key bottlenecks, which can also be seen in Figure 65.

The fact that the fuel cell and the hydrogen refueling infrastructure are strongly complementary to each other can be attributed to two reasons: Firstly, just at the beginning of the study period, as already described, it was not even clear in which form the hydrogen could be stored most efficiently, and thus the fuel cell type and the technical concept of the hydrogen refueling infrastructure was not yet defined. Secondly, the high complementarity strength was the fact that these two ecosystem components/complements were mentioned most frequently as bottlenecks in the analysis and are therefore the key bottlenecks.

The strong complementarity between fuel cell and hydrogen system can be attributed to the fact that the hydrogen is supplied from the hydrogen tanks to the fuel cell. In addition, the hydrogen system, fuel cell, and oxygen system are often seen together as the “fuel cell system”, which also explains the complementarity between these three components.

It was also interesting to see that a complementarity between fuel cells and disposal/recycling was identified. The main reason for this is probably the expensive platinum, which is tried to be kept in the loop by recycling in order to reduce the costs. However, since this complementary service was not often detected as a bottleneck, the complementarity strength is correspondingly low.

The second central element of this network, the hydrogen refueling infrastructure, has, in addition to the fuel cell, also a strong complementarity with the hydrogen system. This can be explained by the

fact that interaction of these two components/complements is required during the hydrogen refueling process. In addition, the way the hydrogen is stored in the vehicle also influences the storage of the hydrogen in the refueling station.
The complementarity between the hydrogen refueling infrastructure and the availability/transport of hydrogen seems logical since the refueling stations are supplied with hydrogen from these complementary actors.

The fact that components such as the e-motor or power electronics, which are essential for the propulsion of the vehicles and therefore have to interact with the fuel cell, do not appear in this network of complementarity is a result of the small number of bottlenecks detected in the FCEV ecosystem.

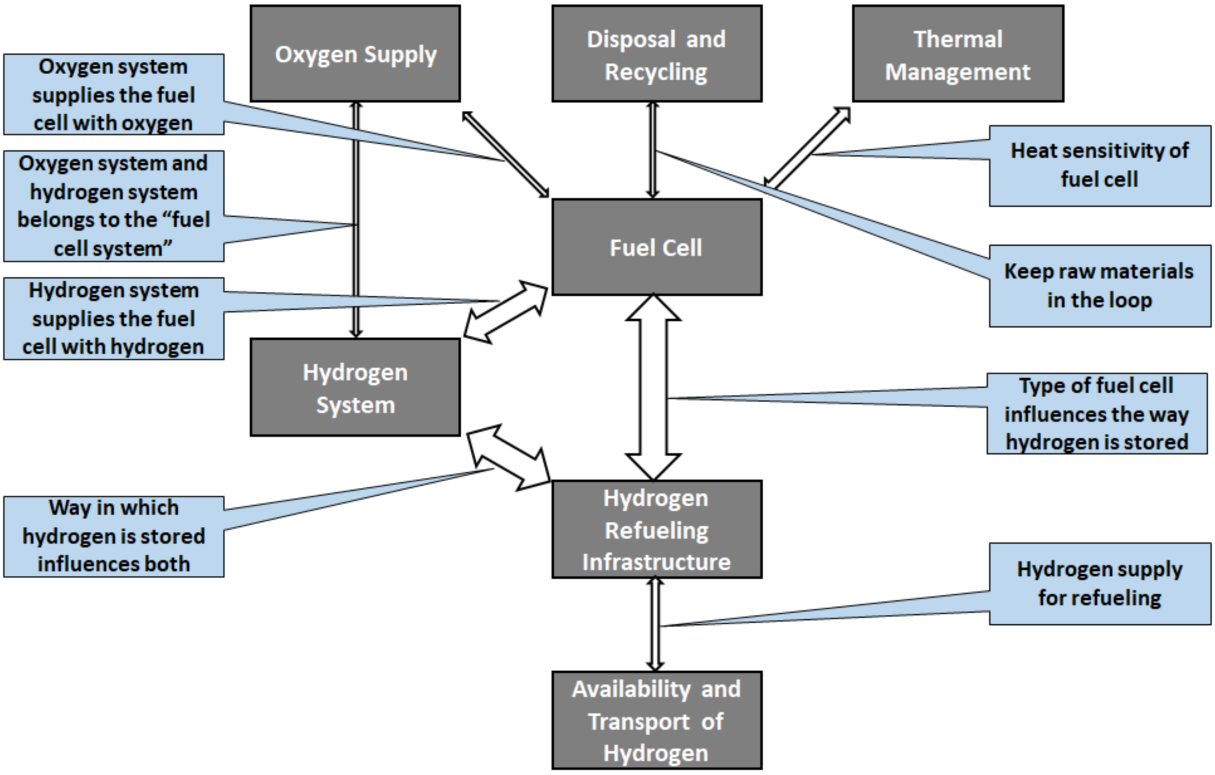


Figure 65: Network of complementarity for FCEVs including complementarity background

This network of complementarity shows how important the concept of the innovation ecosystem is for research on the product FCEV since complementarities exist between diverse components and complementary products and services. As a result, innovation progress in one component/complement can also influence other ecosystem components. On the other hand, solving one bottleneck can cause another. As a consequence, the value proposition is then limited by the new unresolved bottleneck.

6.4 Theoretical integration

One of the key findings of this work is that solving bottlenecks in an innovation ecosystem has an enormous impact on the evolution of this innovation ecosystem. This fact confirms Makinen and Dedehayir's (2012, p. 7) statement that removing bottlenecks promotes the ecosystem's growth. Especially the partly solving of the battery bottleneck with the introduction of the lithium-ion battery was an example for this finding, as the entire innovation ecosystem of BEVs has experienced enormous growth, making the BEV product more attractive for the end customer. Although the analysis showed that this solving of bottlenecks significantly promoted the ecosystem's growth, this does not mean that no bottlenecks existed anymore in the innovation ecosystem. In other words, the solving of bottlenecks led to new bottlenecks that limited the ecosystem´s growth. Jacobides et al. (2006, p. 28f) already recognized this shifting of bottlenecks. However, an additional fact that was interesting to observe was that the bottlenecks were partially solved sequentially. This means that in the example of BEVs, with reaching a higher battery maturity level and thus solving individual bottleneck causes, other components/complements (e.g., thermal management for comfort) came into the focus of the ecosystem. Consequently, it can be concluded that solving certain bottlenecks is the prerequisite for other bottlenecks to occur at all.

Another important finding of this work is that a multiplicity of bottlenecks can co-occur in an innovation ecosystem. Kapoor (2018, p. 6) already recognized this, but the analysis additionally showed that the same influencing factor can cause these bottlenecks. In other words, the underlying causes of co-occurring bottlenecks can be partially traced back to the same factors. The dynamics of these factors (e.g., price fluctuations, dependencies on raw material suppliers) often represent significant issues for the actors, which are hard to solve.

Another interesting link between theory and analysis can be drawn from the interdependency of the individual actors in an innovation ecosystem (Adner and Kapoor, 2010, p. 310). It became apparent that causes for limiting the value proposition to the customer (e.g., long charging time) were solved at different paces by different component suppliers and complementors in the ecosystem. As a result, these bottleneck causes continued to have a limiting effect on the value proposition despite solving a bottleneck. In other words, due to this interdependency between the actors, solving a bottleneck did not lead to an increase in the value proposition to the customer. Furthermore, the fact that in both analyzed innovation ecosystems, components, and complementary products/services simultaneously had a limiting effect on the value proposition to the customer over the entire study period demonstrated how important the innovation ecosystem concept is when looking at innovations.
This was also described by Adner and Kapoor (2010, p. 310), by noting that *"the success of an innovation is very often dependent on the success of other innovations in the focal firm´s external environment."*

7 Conclusion

The objective of this master thesis is to identify the changes of the bottlenecks in the innovation ecosystem of battery electric vehicles and fuel cell electric vehicles in the period from 2000 to 2020. For this purpose, the first step was a literature review on the topics of innovation ecosystems and bottlenecks in ecosystems. Based on this literature review, these two terms were defined for the scope of this work and formed the basis for the empirical analysis. In the following step, already conducted studies concerning the identification of bottlenecks in ecosystems were reviewed. From this literature, a method was selected, using secondary longitudinal data from different sources to meet the thesis's objectives.

The methodology to identify the changes of the bottlenecks in the innovation ecosystem of BEVs and FCEVs in the period from 2000 to 2020 is based on three main steps.

In the first step, a qualitative content analysis was conducted using secondary data. For this purpose, two automotive journals formed the secondary data basis and were selected based on predefined criteria. After this selection process, the qualitative content analysis was performed by using a combined approach of deductive and inductive category formation to ensure the best quality of the analysis results. In order to ensure reliability, an intercoder reliability check was performed by the two supervisors of this work. The results of this check were compared and aligned with the analysis results.

The second main section of this thesis focused on the validation of the qualitative content analysis results with primary data, i.e., with expert interviews. These expert interviews were conducted as semi-structured interviews. For this purpose, an interview guideline was created in advance. The interviews lasted an average of 1 ½ h, and their content was transcribed and analyzed qualitatively.

The qualitative content analysis, together with the validation interviews, resulted in the following findings regarding the change of the bottlenecks in the innovation ecosystem of BEVs: The battery was detected as a key bottleneck in the entire period from 2000 to 2020. While at the beginning of the 2000s, the high costs and the low performance of the battery were primarily responsible for limiting the value proposition to the customer, the quality issue concerning lifetime and safety risk became increasingly critical in the early 2010s. The performance, cost, and quality issues of the battery were identified as bottleneck causes until the late 2010s, but the quality issue was resolved by the year 2020 and does not represent a limitation anymore.

The second identified bottleneck in the innovation ecosystem of BEVs, which poses limits on the value proposition to the customer over the entire period, was the complementary product of the electric charging infrastructure. In this context, the low availability of public charging stations was consistently seen as an issue. In addition, the performance of the electric charging infrastructure had a limiting effect from 2007 onwards. Until the mid-2010s, this was mainly caused by the standardization issue of the charging plugs. From 2014 onwards, the performance issue was related to the charging power of the charging stations.

Furthermore, the analysis showed that certain bottlenecks were processed sequentially, with the battery’s maturity level being the basis for this process. As a result of this sequential processing of the bottlenecks, at the end of the 2000s, the vehicle’s thermal management was increasingly identified as a bottleneck. The limiting effect of the thermal management for the value proposition to the customer was linked to the significant impact the thermal management’s low performance had on the achievable driving range and the charging duration of the BEV. Even today, thermal management is still seen as a bottleneck in the ecosystem of battery electric vehicles.

In recent years, i.e., from 2018 onwards, new complementary products moved into the focus since the increasing number of BEVs on the roads resulted in new issues, such as performance fluctuations of the electric grid.

Thus, for battery electric vehicles, it can be said that new bottlenecks like the thermal management or the electric grid materialized in the last 20 years, but the battery and the electric charging infrastructure have consistently remained the most mentioned bottlenecks concerning the value proposition to the ecosystem's customers over the entire period.

The qualitative content analysis, together with the validation interviews, resulted in the following findings for the change of the bottlenecks in the innovation ecosystem of FCEVs. These results should be treated with caution due to the small number of articles dealing with FCEVs: Fuel cells have been identified as the key bottleneck throughout the entire analysis period. In the early 2000s, the low technical performance and the high cost of the fuel cell stacks were mainly responsible for that. In the late 2000s, the quality issue, more precisely the lifetime of the fuel cells, became increasingly critical and remained a limitation for the value proposition to the customer until the mid-2010s. In the last few years of the analysis period, it became apparent, especially from the expert interviews, that the performance and quality issues of the fuel cell were solved. This means that only the costs had a limiting effect on the value proposition to the customer anymore.

The second bottleneck identified in the innovation ecosystem of FCEVs, which poses limits on the value proposition to the customer over the entire period, was the complementary product of the hydrogen refueling infrastructure. In this context, the low availability of hydrogen refueling stations was consistently seen as an issue over the entire period from 2000 to 2020.

The third detected bottleneck in the ecosystem of FCEVs is the component hydrogen system or, more precisely, the hydrogen tank, which was identified in the qualitative content analysis as a limitation in the early 2000s due to its low performance. In addition, in the interviews, the experts identified the costs of these tanks as having an enormous impact on the overall costs of the vehicles, which also represented a limiting factor. However, according to the interviewed experts, the performance issue was resolved in the early 2010s, which means only the costs of the hydrogen tanks remain a limiting factor today. In contrast to that, the analysis still represents the performance of the hydrogen tank as an issue today. In the analysis, performance is considered in terms of the complexity in the storage of hydrogen, which can be indirectly transferred to the requirements and, furthermore, to the costs of the tanks.

In the third main section of this thesis, a network of complementarity was formed for the innovation ecosystem of BEVs and the innovation ecosystem of FCEVs, which is intended to show which components/complements play a central role in the ecosystem and consequently influence several other components and complementary products/services. Thus, these central components/complements represent the key bottlenecks in the ecosystem.

In this approach, the battery and the electric charging infrastructure were identified as having a central role in the ecosystem of battery electric vehicles and thus represent the key bottlenecks.

In the ecosystem of fuel cell electric vehicles, the fuel cell, the hydrogen refueling infrastructure, and the hydrogen system were detected as the key bottlenecks.

In conclusion, the ecosystems of the two powertrain topologies have evolved tremendously over the past 20 years, and bottlenecks have shifted mainly in the ecosystem of BEVs. This means the analysis has shown that bottlenecks are partially processed sequentially. Nevertheless, the key bottlenecks concerning the value proposition to the customer remained in both ecosystems almost the same. However, what has changed, is the reason for them being a bottleneck. Furthermore, the identified bottlenecks in the ecosystems of BEVs and FCEVs were in all three subdivided periods a component as well as a complementary product/service. In other words, the analysis has shown how important it is that the innovation challenges are solved at both the component level and the level of the complementary products/services simultaneously.

Finally, it was also noticeable that innovation progress in one component/complement can also influence other ecosystem components. On the other hand, solving one bottleneck can also cause another, which leads to the consequence that the new unresolved bottleneck then limits the value proposition.

8 Limitations and future research

In the final chapter of this thesis, the limitations of the conducted empirical study are presented and based on these limitations, an outlook for future research topics is given.

8.1 Limitations of analysis

The empirical results of the bottleneck detection in the innovation ecosystem of the battery electric and fuel cell electric vehicle should be considered, including some limitations.
First of all, it must be noted that only two journals were analyzed in the course of the qualitative content analysis due to time constraints, which represents only a fraction of all available journals dealing with BEVs and FCEVs. Thus, the analysis results, especially for fuel cell electric vehicles, were partially only of limited significance due to the lack of articles dealing with FCEVs. In addition, due to the time constraints, journals were selected that covered different powertrain topologies at the same time, like BEV and FCEV, which led to a limited discussion of individual components in some cases (e.g., battery or fuel cell). Thus, the results only reflect a trend in the change of the bottlenecks over time and include no detailed information on the technological development of the individual components and complements. The selection of discipline and powertrain-specific journals (e.g., journal for BEVs) was discussed, but none could be found that covered the entire analysis period. Furthermore, this powertrain-specific journal selection would have required the analysis of more than two journals (at least two per powertrain topology) and would have been beyond the time scope of the thesis. Nevertheless, these limitations could be minimized due to the journal selection based on predefined specific selection criteria, which resulted in two representative journals.

The selection of a US journal for this analysis was also planned since the USA, with its ZEV legislation, is a pioneer in the field of alternative powertrains (Fischer et al., 2020, p. 402). But unfortunately, no freely accessible peer-reviewed journal covering the entire period of the analysis could be found. For this reason, the analysis results are very European-driven, as most of the detected bottlenecks originated from the ATZ. However, since the European automotive market is seen as very representative and articles from US companies were also published in the ATZ, this limitation should not influence the results too much.

A further limitation of this work became apparent during the analysis of the two journals. Text passages that referred to a limitation (high costs, limited range) but could not be directly assigned to a component or a complementary product/service were not included in the results. However, since this fact occurred in a large number of text passages, the creation of a category for the overall vehicle would have made sense, but this category would have added only limited value since an overall vehicle bottleneck would not help to detect the limiting factors of an ecosystem. Nevertheless, the component or the complementary product/service sometimes could have been identified indirectly from the texts, but this could not be coded and included in the analysis results for objectivity reasons. Since these text passages mostly referred indirectly to the component battery and this component was detected as the key bottleneck over the entire study period, this limitation had only a minor influence on the results.

In addition, due to the Covid-19 pandemic and the associated conditions in the industry (short-time work, etc.), the interview partners were selected exclusively from the academic community, which could have influenced the results since the know-how of automotive companies and the associated knowledge of a direct actor in the ecosystem would have added additional value to the analysis. However, as this academic community mostly works closely with the industry, the lack of industry-specific knowledge is likely to have little impact on the results.

8.2 Outlook for future research

In order to further substantiate the results obtained from the analysis, a broader data basis should be used for further studies. For this purpose, a larger number of expert interviews and a larger number of secondary sources are recommended. This broader data basis would allow determining not only the trend of the bottleneck changes but also to identify the reason why specific components and complementary products and services were no longer limiting for the value proposition to the customer. Consequently, this approach would entail a more detailed view on the individual components and complements and their technological development. For this reason, the experts for the interviews should come from a variety of different positions within the ecosystem (e.g., battery supplier, complementors) to gather data directly from the industry. This would lead to detailed information directly from the ecosystem´s players. Consequently, the quality of the results would be improved. This approach would also address the issue concerning the low number of detected bottlenecks for the ecosystem of fuel cell electric vehicles.

Furthermore, the presented study results can serve as a basis for a follow-up analysis in this area. A further research project can focus on a study concerning how the individual players in the ecosystems dealt with the detected bottlenecks. In other words, what strategies the individual actors pursued to address the bottlenecks and, consequently, what were the results of these strategies. This could allow deriving patterns for how to deal with technological bottlenecks in ecosystems. In this analysis for identifying strategies to solve bottlenecks, it could be examined in detail if there are any moderation or mediation effects between the bottlenecks and the success in forming collaborations with third-party partners.

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Appendix A: List of observed data sources

Data source	Availability (time period)	Type of source	Publisher	Editor-in-Chief	Location
Automobiltechnische Zeitschrift	Available as e-paper from 1998-2020	Journal with focus on the automotive industry	Springer Fachmedien Wiesbaden	Alexander Heintzel	Germany
Motortechnische Zeitschrift	Available as e-paper from 1998-2020	Journal with focus on ICE and E-Motor	Springer Fachmedien Wiesbaden	Alexander Heintzel	Germany
International Journal of Automotive Technology	2000-2020	Journal with focus on the automotive industry	The Korean Society of Automotive Engineers	Choongsik Bae	South Korea
Auto Tech Review	2012-2017	Journal with focus on the automotive industry	Springer India	Deepangshu Dev Sarmah	India
ATZelektronik	2006-2020	Journal with focus on electrical parts of the vehicle	Springer Fachmedien Wiesbaden	Robert Unseld	Germany
ATZproduktion	2008-2020	Journal with focus on production processes in the automotive industry	Springer Fachmedien Wiesbaden	Alexander Heintzel	Germany
IEEE Vehicular Technology Magazine	2006-2020	Journal with focus on mobile radio, automotive electronics, and transportation systems	IEEE Vehicular Technology Society	Javier Gozalvez	Spain
SAE International Journal of Electrified Vehicle (Alternative Powertrains	2012-2020	Journal with focus on e-mobility	SAE International	Simona Onori	USA
SAE International Journal of Passenger Cars-Electronic and Electrical Systems (Connected and autonomous vehicle)	2009-2020	Journal with focus on electronic and electrical systems of the vehicle	SAE International	Daniel Watzenig Terry Fruehling	USA

SAE-Automotive Engineering	< 1980-2020	Journal with focus on the automotive industry	SAE International	Lindsay Brooke	USA
International Journal of Automotive and Mechanical Engineering	2010-2020	Journal with focus on automotive engineering	The Automotive Engineering Centre (AEC), University Malaysia	Syarifah Nur Aqida Syed Ahmad	Malaysia
International Journal of Automotive engineering	2012-2020	Journal with focus on automotive engineering	Society of Automotive Engineers of Japan, Inc. (JSAE)	Shinichiro Horiuchi	Japan
International Journal of Transportation Science and Technology	2012-2020	Journal with focus on the transportation sector	Tongji University and Tongji University Press. Publishing Services by Elsevier B.V.	Ruey Long Cheu Zhongyin Guo	China
International Journal of Automotive Technology and Management	2001-2020	Journal with focus on automotive engineering	Inderscience Enterprises Ltd.	Giuseppe Giulio Calabrese	Italy
International Journal of Electric and Hybrid Vehicles	2008-2020	Journal with focus on electrified vehicles	Inderscience Enterprises Ltd.	Benoît Maïsseu	France
World Electric Vehicle Journal	2007-2020	Journal with focus on electric vehicles	MDPI	Joeri Van Mierlo	Switzerland
Motor Trend	1949-2020	Consumer Magazine	Motor Trend Group	Edward Loh	USA
Car and Driver	1955-2020	Consumer Magazine	Hearst Communications	Sharon Silke Carty	USA
Automotive News	1925-2020	Consumer Magazine	Crain Communications	Keith Crain	USA
Automobile Magazine	1986-2020	Consumer Magazine	Motor Trend Group	Michael Floyd	USA

Appendix B: Description of components in the BEV category system

Battery:

The battery in a BEV serves as electrochemical energy storage, whose task is to store the energy needed at a later point in time (Amann and Beck, 2012, p. 184). Nowadays, the lithium-ion battery is the state-of-the-art in battery electric vehicles, which consists of two electrodes (anode and cathode), the electrolyte, which is responsible for transporting the lithium ions between the two electrodes, and the separator, which separates the two electrodes from each other (Fischer and Neunteufel, 2018, p. 321 f; Hofmann, 2014, p. 226f). The most important indicators for batteries are their energy density, i.e., how much energy content can be stored in space or with regard to the weight, and the power density, i.e., the economy of space in relation to power (Hofmann, 2014, p. 213f).

E-Motor:

The task of the electric motor is to convert the stored electrical energy into mechanical energy. This mechanical energy is then transferred to the wheels via components such as the transmission and subsequently serves as propulsion. The most commonly used motors in today's vehicles are the permanently synchronous machine and the asynchronous machine, both of them operate with alternating current. (Fischer and Neunteufel, 2018, p. 340f)

Transmission:

The task of the transmission is to convert the torque delivered by the e-motor in such a way that different driving situations (uphill, downhill, constant, etc.) are satisfied (Fischer et al., 2016b, p. 2).
In the case of a purely electric drive, gear ratios are required in most cases in order to adapt the torques and speeds of the electric machine to the requirements on the wheel (Fischer et al., 2016a, p. 336).

Power electronics:

The component power electronics contain the subcomponents inverter, onboard charger as well as electronic parts like fuses. One main task of the power electronics in battery electric vehicles is converting the battery direct current into the three-phase alternating current required for the operation of the e-motor, with variable frequency, amplitude, and phase angle to set the target speed and torque. Another task is to convert the AC voltage from the grid into a DC voltage to charge the high-voltage battery externally. The subcomponent of the power electronics which is responsible for this task is the onboard charger. (Fischer and Neunteufel, 2018, p. 348f)

Thermal Management:

Depending on the different outside temperatures, different components within the vehicle, like battery, e-motor, or power electronics, must be cooled or heated to achieve the best power output and operate efficiently. The task of thermal management is to temper the different components and heat and cool the compartment. (Kampker et al., 2018, p. 19)

Vehicle body and chassis:

The individual components are mounted on the body, which is mainly made of steel and is self-supporting. However, alternative body shapes are used for BEVs (alternative materials), as lightweight design concepts have to be used because of the high battery weight. (Kampker et al., 2018, p. 20)

Appendix C: Description of components in the FCEV category system

Fuel Cell:

The fuel cell is not an energy storage device but an electrochemical converter that converts chemical energy (mostly hydrogen) into electrical energy and supplies the electric motor in vehicles with energy. Basically, many different types of fuel cells exist, but the "Proton Exchange Membrane Fuel Cell" is the most relevant for the automotive industry. The most important components within the fuel cell are the “membrane electrode assembly,” where the chemical reaction occurs, and the bipolar plates, which supply the fuel cell with the reaction gases (Hydrogen, Oxygen) and distribute them on the membranes. (Wind, 2019, p. 101f)

Battery:

The battery in a fuel cell electric vehicle cannot be compared with that of a BEV. In FCEVs, the propulsion energy is generated by the fuel cell, and the battery only has the purpose of enabling recuperation (brake energy recovery) or covering power peaks. However, in FCEVs, lithium-ion batteries are used as well (Wind, 2019, p. 110).

Hydrogen tank and supply:

Since fuel cells require chemical energy to generate electrical power and this chemical energy is stored in hydrogen, which is difficult to store due to its property (small molecular size, flammable, etc.), the hydrogen tank and the supply of hydrogen to the fuel cell is an essential and challenging part of the fuel cell system. In principle, nowadays, mostly compressed hydrogen storage tanks are used, in which gaseous hydrogen with up to 700bar is stored. Another possibility is the liquid storing of hydrogen, which requires a great deal of effort in liquefying the hydrogen. That is why the storage temperatures have to be very low (-250°C). (Weber, 2020, p. 46)

Oxygen supply:

The oxygen supply of the fuel cell includes numerous components such as an air filter, compressor, and humidifier. According to the required power, the fuel cell's cathode must be supplied with humidified air to prevent the fuel cell from drying out and thus being damaged. Due to the sensitivity of the fuel cell, air filtration is a major challenge in FCEVs. (Wind, 2019, p. 180f)

E-Motor (Synergy to BEV):

The task of the electric motor is to convert the stored electrical energy into mechanical energy. This mechanical energy is then transferred to the wheels via components such as transmission and subsequently serves as propulsion. The most commonly used motors in today's vehicles are the permanently synchronous machine and the asynchronous machine. Both of them are operated with alternating current. (Fischer and Neunteufel, 2018, p. 340f)

Transmission (Synergy to BEV):

The task of the transmission is to convert the torque delivered by the e-motor in such a way so that different driving situations (uphill, downhill, constant, etc.) are satisfied (Fischer et al., 2016b, p. 2).
In the case of an electric drive, gear ratios are also required in most cases in order to adapt the torques and speeds of the electric machine to the requirements on the wheel (Fischer et al., 2016a, p. 336).

Power electronics (Synergy to BEV):

The power electronics tasks in fuel cell electric vehicles are very similar to the ones of the battery electric vehicles. Examples are the increase of the stack voltage, the torque and speed control of the electric motor, the supply of the high-voltage consumers, the voltage conversion for the onboard network and the charging and discharging function of the traction battery. (Wind, 2019, p. 108)

Thermal Management:

Depending on the different outside temperatures, different components within the vehicle, like fuel cell, battery, e-motor, or power electronics, must be cooled or heated to achieve the best power output and operate efficiently. The task of thermal management is to temper the different components and heat and cool the compartment. (Kampker et al., 2018, p. 19)

Vehicle body and chassis (Synergy to BEV):

The individual components are mounted on the body, which is mainly made of steel and is self-supporting. However, alternative body shapes are used for FCEVs (alternative materials), as lightweight design concepts have to be implemented due to the higher weight of the powertrain. (Kampker et al., 2018, p. 20)

Appendix D: Deductively created coding guideline for BEV

Type of contribution	Category	Category definition	Anchor example	Coding rules
Component	Battery	This category includes all limitations that deal with the component battery from battery electric vehicles. Considered are all topics related to the entire battery packaging, including housing as safety protection, battery cells or cell interconnections, and battery management and production issues.	*“Current available battery systems do not only have a limited range, but they are also pretty expensive, and their lifetime could be improved as well.”* *(Kampker et al., 2018, p. 18)*	Exclusion criteria are topics regarding: - Thermal Management with a focus on the battery cooling and heating system - Battery charging when the charging station is explicit mentioned
	E-Motor	This category includes all limitations on the topic of electric motors. This can concern production processes or production capacities as well as material-specific points such as active or passive materials.	*“The demand estimated for magnets is about 18.500 metric tons for the year 2020 and even higher with 65.500 metric tons for 2025. Considering the limited production capacity of the magnet manufactures, a latent risk for the automotive sector is possible.”* *(Kilper et al., 2019, p. 276)*	Exclusion criteria are topics regarding: - The cooling and heating procedure of the electric motor.
	Transmission	This category includes all limitations regarding one or multi-speed transmissions in electric vehicles.	No anchor example was found in the literature research.	-
	Power Electronics	This category includes all limitations in power electronics, especially the inverter and the onboard charger.	*“Due to these special requirements on power electronics, a relatively high portion of cost is currently being generated in electric vehicles, which would in the future increase without further improvement of the power*	Exclusion criteria are topics regarding:

			electronics due to the cost reduction of the electric vehicles." *(Hohmann et al., 2017, p. 39)*	- Thermal management (cooling/heating) of power electronics
	Thermal Management	This category includes all limitations of the battery electric vehicles, which are caused by thermal management. These may relate either to the battery and its heating and cooling, power electronics, or other electric vehicle components.	*"On the other hand, air conditioning in summer and especially compartment heating in winter set new requirements on the design of these systems. With the increasing vehicle electrification, the required power for heating and cooling must be provided more and more by the battery, which leads to the reduction of the electric range. The thermal management systems must therefore operate as efficiently as possible. However, air conditioning should not only be seen from the comfort aspect and thus customer acceptance; safety issues also play an important role."* *(Thielmann et al., 2015, p. 35)*	Exclusion criteria are topics regarding: - The damaging effects or efficiency limitations of different components due to insufficient thermal management
	Vehicle body and chassis	This category includes all limitations regarding the vehicle body and chassis, their materials, including the lightweight design, operating behavior (NVH) and production processes.	No anchor example was found in the literature research.	-
Complement	Charging station infrastructure	This category deals with the charging station infrastructure, especially with topics regarding the availability and performance of these charging stations. In addition, topics regarding standardization issues, digital integration, etc., are considered as well.	*"Even in charging parks with four CCS quick charging stations, it is not uncommon that one or two chargers are defective or do not function properly."* *(Jahn, 2018)*	Exclusion criteria are topics regarding: - Charging time of battery electric vehicles when the charging station is not explicitly mentioned

	Electrical energy	This category includes emerging limitations in the area of the electrical grid, e.g., grid fluctuations during peak loads or expansion of the power grid.	*“These residential hot spots and other concentration points of EV charging, such as public EV-fast-charging stations and commercial-vehicle depots, will see significant increases in local peak loads […] Unmanaged, substation peak-load increases from EV-charging power demand will eventually push local transformers beyond their capacity, requiring upgrades.”* *(Engel et al., 2018)*	-
	Disposal, Transportation, and Recycling	This category includes limitations regarding the disposal and recycling of components of the battery electric vehicle or the whole vehicle itself.	*“Prior to transportation and further dismantling, a check of the battery condition is highly recommended as several incidents have demonstrated that damaged traction batteries pose an unpredictable fire risk. Checks should include visual assessment (mechanical damages, signs of heat damage, electrolyte leakage) as well as evaluation of diagnosis data from the BMS (voltage, SOC, temperature sensors, etc.).”* *(Elwert et al., 2015, p. 37)*	-
	Workshop and dealership	This category deals with all limitations regarding the sales, service, and repair activities in the field of battery electric vehicles.	No anchor example was found in the literature research.	-

Appendix E: Deductively created coding guideline for FCEV

Type of contribution	Category	Category definition	Anchor example	Coding rules
Component	Battery	This category includes all limitations which deal with the component battery of an FCEV. The battery in these vehicles distinguishes from the battery in BEVs and this means that no synergies in this component of the two powertrain concepts exist. Considered are all topics related to the entire battery packaging, including housing as safety protection, battery cells or cell interconnections, and battery management and production issues.	No anchor example was found in the literature research, which refers to FCEV batteries.	Exclusion criteria are topics regarding: - Thermal Management with a focus on the battery cooling and heating system and their behavior.
	Hydrogen tank and supply	This category includes all limitations associated with the onboard storage and the transport of hydrogen to the fuel cell. Examples can be bottlenecks related to the tank, like materials or safety-related issues, or topics regarding the purge valve.	*“However, the main problem in the development of FCEVs is the transport and storage of hydrogen. There are two main issues: firstly, the fire and explosion risk of hydrogen mixed with oxygen, especially in case of an accident [...].* *Secondly, the chemical properties of hydrogen make the storage very difficult. Due to its small molecular size, hydrogen diffuses through a variety of materials, including steel, and get therefore lost.”* (Weber, 2020, p. 46f)	Exclusion criteria are topics regarding: - General storage and transport of hydrogen (not onboard storage) - Refueling the hydrogen
	Fuel Cell	This category includes limitations within the component fuel cell and all topics regarding their sub-components such as anode, cathode, membrane, catalyst, bi-polar plates, and fuel cells' management.	*„However, assuming that thinner electrolyte membranes will be introduced to improve performance, further technological development is needed as well as cost reduction of the membrane. In addition, the current status of the durability of cell*	Exclusion criteria are topics regarding: - Auxiliary devices like oxygen supply (e.g., compressor or

			performance does not satisfy the targeted 15 years." (Shinobu and Kojima, 2011, p. 5)	humidifier), hydrogen supply, etc. - Thermal management of the fuel cell
	Oxygen supply	This category deals with limitations regarding the air and oxygen supply of the fuel cells. This system consists of the air cleaner, water separator, compressor, air-cooler, and humidifier. (Harenbrock et al., 2020, p. 238)	*"Future generation fuel cell systems will aim to further improve the air compression technology. The demand for weight and volume reduction combined with increased efficiency requirements will probably suggest compression technologies operating at further increased speeds. As this will extend the frequency ranges of the emitted noise this will be one challenge to future noise countermeasures."* *(Sang et al., 2008, p. 265)*	-
	E-Motor	This category includes all limitations on the topic of electric motors. This can concern production processes or production capacities and material-specific points such as active or passive materials. (Synergy to BEV)	*"The demand estimated for magnets is about 18.500 metric tons for the year 2020 and even higher with 65.500 metric tons for 2025. Considering the limited production capacity of the magnet manufactures, a latent risk for the automotive sector is possible."* *(Kilper et al., 2019, p. 276)*	Exclusion criteria are topics regarding: - The cooling and heating procedure of the electric motor.
	Transmission	This category includes all limitations regarding the transmission in fuel cell electric vehicles.	No anchor example was found in the literature research.	-
	Power Electronics	This category includes all limitations in the field of power electronics in fuel cell electric vehicles. The focus is mainly on the inverter and its related materials. (Synergy to BEV)	*"Due to these special requirements on power electronics, a relatively high portion of cost is currently being generated in electric vehicles, which would in the future increase without further improvement of the power electronics due to the cost reduction of the electric vehicles."* *(Hohmann et al., 2017, p. 39)*	Exclusion criteria are topics regarding: - Thermal management (cooling/heating) of power electronics

	Thermal Management	This category includes all limitations of the fuel cell electric vehicle caused by thermal management. These may relate either to the fuel cell itself or to other parts of the powertrain of the FCEV like the battery, the power electronics, etc.	*“High power requirements of PEMFC stacks while limited space at automotive applications are the significant challenges for a cooling system for FCEVs. The problem becomes more severe due to the small temperature difference between the PEMFC stack and the ambient air, and an almost negligible heat removal by the product streams.” (Nöst et al., 2016, p. 110)*	Exclusion criteria are topics regarding: - The damaging effects or efficiency limitations of different components due to insufficient thermal management
	Vehicle body and chassis	This category includes all limitations regarding the vehicle body and chassis, their materials, including the lightweight design, operating behavior (NVH), and production processes.	No anchor example was found in the literature research.	-
Complement	Hydrogen station infrastructure	This category focuses on the limitations in the hydrogen station infrastructure. Included are all topics related to the availability of public hydrogen stations, the costs for expanding the hydrogen station network, and all issues related to the refueling process.	*“The costs of a hydrogen fuel station with one dispenser are around 1 million € […]. Of course, it can be argued that the price for hydrogen fuel stations will significantly decrease if they are built in high quantities. On the other hand, the current fuel stations are not yet able to refuel more than two cars per hour. To increase the fuel speed, additional technology is required, and this means additional costs.” (Doppelbauer, 2020a, p. 405)*	Exclusion criteria are topics regarding: - Availability and transport of hydrogen to the fuel station
	Availability and transport of Hydrogen	This category includes all limitations regarding the production of hydrogen and its subsequent transport to the individual public hydrogen stations. This consists of all issues regarding the costs of the production of hydrogen, the production capacity of the plants, and the availability of transport facilities such as pipelines or trucks.	*“The cost of building or expanding a hydrogen infrastructure, from industrial production to distribution through pipelines or tank trucks until delivery to filling stations, is under the given conditions such as safety requirements, hydrogen diffusion, compression work or low temperature keeping is immense.”*	Exclusion criteria are topics regarding: - Availability of hydrogen station infrastructure

			(Weber, 2020, p. 47)	
	Disposal and Recycling	This category includes limitations regarding the disposal and recycling of components of the fuel cell electric vehicle or the whole vehicle itself.	*“The recycling rate of the fuel cell must be further improved, especially for the polymer membrane is a big research need to develop an economically advantageous process. Therefore, the materials have to be separated to such an extent that they can be introduced into standardized existing recycling processes.”* *(Ahlfs et al., 2020, p. 12f)*	-
	Workshop and dealership	This category deals with all limitations regarding the sales, service and repair activities in the field of fuel cell electric vehicles.	No anchor example was found in the literature research.	-

Appendix F: Deductively created keyword catalog for BEV

Component / Complement	Keyword	
Battery	- Energy density - Specific energy - Charging rate - Traction battery - Cycle lifetime - Thermal runaway	- Electrolyte - Battery management system - Cell manufacturing - Battery hazard level - Battery disposal
E-Motor	- Electric motor	- Rare earth elements
Transmission	- One speed electric transmission	- Two-speed electric transmission
Power electronics	- Power Electronics	- Semiconductor material
Thermal management	- Battery cooling - Battery heating	- Thermal management - Derating
Vehicle body and chassis	- Multi-material body	- Lightweight design
Charging station infrastructure	- Charging speed - Charging time - Charging plug	- Charging power - Charging station - Charging infrastructure
Electrical energy	- Smart Grid - Power Grid	- Electric Grid - Load peaks
Disposal, transportation, and recycling	- Recycling	- Disposal
Workshop and dealership	- Workshop	- Dealership

Appendix G: Deductively created keyword catalog for FCEV

Component / Complement	Keyword	
Battery	- Traction battery	- Battery management system
Hydrogen tank and supply	- Hydrogen tank	- Hydrogen supply
Fuel cell	- Fuel Cell - Solid oxide fuel cell (SOFC) - Stack - Bipolar plate - Membrane Electrode Assembly (MEA)	- Proton exchange membrane fuel cell (PEMFC) - Cold start ability - Gas diffusion layer (GDL) - Catalyst - Platinum
Oxygen supply	- Air compressor	- Humidifier
E-Motor	- Electric motor	- Rare earth elements
Transmission	- One speed electric transmission	- Two-speed electric transmission
Power electronics	- Power Electronics	- Semiconductor material
Thermal management	- Fuel cell cooling - Fuel cell heating	- Thermal management
Vehicle body and chassis	- Multi-material body	- Lightweight design
Hydrogen station infrastructure	- Hydrogen infrastructure	- Hydrogen stations
Availability and transport of hydrogen	- Hydrogen production	- Hydrogen transport
Disposal and recycling	- Recycling	- Disposal
Workshop and dealership	- Workshop	- Dealership

Appendix H: Total number of articles published in the “ATZ” and “IJoAT”

Year	ATZ articles [#]	IJoAT articles [#]	Articles in total [#]
2000	90	13	103
2001	76	20	96
2002	71	24	95
2003	80	24	104
2004	82	36	118
2005	89	81	170
2006	77	110	188
2007	75	90	165
2008	91	91	182
2009	100	90	190
2010	95	107	202
2011	128	108	236
2012	128	121	249
2013	133	108	241
2014	127	125	252
2015	109	108	217
2016	182	108	290
2017	189	108	297
2018	202	108	310
2019	189	120	309
2020	180	150	330
Total	**2493**	**1850**	**4343**

Appendix I: Final keyword catalog for BEV and FCEV

Battery electric vehicle		**Fuel cell electric vehicle**	
Component / Complement	**Keywords**	**Component / Complement**	**Keywords**
Battery	- Battery - Capacity - Safety issue - Range - Cell chemistry - Energy density - Power density - Raw material - Lithium, Cobalt, and Nickel - Anode, cathode, and electrolyte - Aging - Charging Rate; C-Rate - Cell manufacturing - Cycle lifetime - Energy storage - Nickel-Metal hydride (NiMH, Ni-MH)	Fuel cell	- Fuel cell - Bipolar plates; bi-polar plates - Membrane electrolyte assembly (MEA) - Gas diffusion layer (GDL) - Proton exchange membrane - Solid oxide - Anode, cathode, and electrolyte - Catalyst - Raw material; Platinum - Stack - Cold start ability - Direct methanol fuel cell (DMFC)
Power electronics	- Inverter - On-board charger (OBC) - Fuses - High voltage protection - Power electronics	Power electronics	- Inverter - Fuses - High voltage protection - Power electronics
E-Motor	- Rare earth - Traction machine - Electric motor; E-Motor	E-Motor	- Rare earth - Traction machine - Electric motor; E-Motor
Transmission	- Transmission - Two-speed electric drive - One-speed electric drive	Transmission	- Transmission
		Oxygen supply	- Air filtration - Compressor
Thermal management	- Thermal management - Thermal behavior - Derating - Positive temperature coefficient (PTC) - Cabin climatization - Air conditioning - Thermal runaway - Thermal issue - HVAC	Thermal Management	- Cabin climatization - Air conditioning - HVAC - Thermal management - Thermal behavior
		Hydrogen system	- Hydrogen - Tank
		Battery	- Anode, cathode, and electrolyte - Capacity - Battery - Power density - Lithium, Cobalt, and Nickel

			- Raw material - Cell manufacturing - Safety issue
Vehicle body and chassis	- Lightweight design - Vehicle body	Vehicle Body and Chassis	- Lightweight design - Vehicle body
Electric charging infrastructure	- Charging - Fast-charging - Communication problems - Billing - Power ordering system	Hydrogen refueling infrastructure	- Hydrogen - Supply infrastructure
Electric Grid	- Load peaks - Grid - Distribution system operator - Load management - Voltage fluctuations - Frequency fluctuations	Availability of Hydrogen	- Hydrogen
Dealer and workshop	- Dealer - Workshop - Maintenance	Dealer and workshop	- Dealer - Workshop - Maintenance
Disposal and recycling	- Disposal - Recycling	Disposal and recycling	- Disposal - Recycling

Appendix J: Final coding guideline for BEV

Components	Category definition	Anchor example	Coding rules
Battery	This category includes all limitations that are related to the component battery. The direct assignment to this main category will only be performed if the text passage cannot be assigned to one of the subcategories battery cell, battery production, or battery management system.	*“Current available battery systems do not only have a limited range, but they are also pretty expensive, and their lifetime could be improved as well.”* *(Kampker et al., 2018, p. 18)*	Exclusion criteria are topics regarding: - Charging behavior, if the charging station is explicitly mentioned - If the text passage is related to the thermal management process (complexity, etc.)
Battery cell	This category includes all limitations related to the subcomponent battery cell, which means the term battery cell must be mentioned explicitly in the text passage. The direct assignment to this subcategory will only be performed if the text passage cannot be assigned to one of the subcategories' 2nd order battery anode, battery cathode, or battery electrolyte.	*“The range achievable in real-word operation [2], in contrast, is a factor that truly affects purchasing decisions. Range, however, results in a conflict for developers dealing with today’s battery technology and its low energy density: the larger the range, the higher the vehicle’s weight due to the battery cell. Higher weight in turn reduces efficiency.”* *(Schmidt, 2020, p. 48)*	Exclusion criteria are topics regarding: - Charging behavior, if the charging station is explicitly mentioned - If the text passage is related to the thermal management process (complexity, etc.) - Battery limitations, if these limitations are related to BMS or battery production.
Battery anode	This category includes all limitations related to the subcomponent 2nd order battery anode, which means the term battery anode must be mentioned explicitly in the text passage.	*“One of well-known cause of capacity fade is film formation on the surface of active materials especially in the anode. The film grows due to the side reactions, a phenomenon which is not clearly known yet.” (Baek et al., 2015, p. 312)*	Exclusion criteria are topics regarding: - Charging behavior, if the charging station is explicitly mentioned

				- If the text passage is related to the thermal management process (complexity, etc.) - Battery cathode and electrolyte
	Battery cathode	This category includes all limitations related to the subcomponent 2nd order battery cathode, which means the term battery cathode must be mentioned explicitly in the text passage.	*“The Center Automotive Research (CAR) at the University of Duisburg-Essen has identified that the production process represents only 5 % of the cost of a lithium-ion battery [3].The cathode and the materials needed to manufacture it make up the majority of the cost at 70 %, while the anode and other materials contribute 25 %. For battery manufacturers these are transitory items that involve a high level of dependency on the suppliers of raw materials.” (Backhaus, 2020, p. 10)*	Exclusion criteria are topics regarding: - Charging behavior, if the charging station is explicitly mentioned - If the text passage is related to the thermal management process (complexity, etc.) - Battery anode and electrolyte
	Battery electrolyte	This category includes all limitations related to the subcomponent 2nd order battery electrolyte, which means the term battery electrolyte must be mentioned explicitly in the text passage.	*“EVs and HEVs have potential safety problems under the circumstances of a crash or a rollover event. The occupants could be exposed to a hazard due to electrolyte spillage and/or electric shock during and after these crash events.” (Lim and Kim, 2010, p. 825)*	Exclusion criteria are topics regarding: - Charging behavior, if the charging station is explicitly mentioned - If the text passage is related to the thermal management process (complexity, etc.) - Battery anode and cathode
	Battery management system	This category includes all limitations related to the subcomponent battery management system, which means the software manages the efficient usage of a battery.	*“But how to avoid the adverse effect of cell inconsistency on battery pack performance and prolong the service life of both the pack and the cells are posing tremendous technological challenges to*	Exclusion criteria are topics regarding: - Charging behavior, if the charging station is explicitly mentioned

			battery State-of-Charge (SoC) estimation techniques." (Xiong et al., 2014, p. 89)	- If the text passage is related to the thermal management process (complexity, etc.) - Hardware like battery cell or value chain activities like battery production
	Battery production	This category includes all limitations related to the subcategory battery production, which means this subcategory is not a component but an activity in the value chain. Especially, the focus on this category should be on the production process and the associated capacities of the battery manufacturer.	*"As far as battery production is concerned, it is clear that we need to significantly expand our capacity to meet the growing demand for electric vehicles. In Germany in particular, we have very few battery manufacturing plants, but work has already begun on constructing factories in locations close to the market to reduce the amount of transport needed and to keep one-sided supply chain dependencies to a minimum." (Heintzel and Eisenkrämer, 2020, p. 66)*	Exclusion criteria are topics regarding: - Production process of other components or complements
Power electronics		This category includes all limitations that are related to the component power electronics. The direct assignment to this main category will only be performed if the text passage cannot be assigned to one of the subcategories HV protection system or on-board charger.	*"Due to these special requirements on power electronics, a relatively high portion of cost is currently being generated in electric vehicles, which would in the future increase without further improvement of the power electronics due to the cost reduction of the electric vehicles." (Hohmann et al., 2017, p. 39)*	Exclusion criteria are topics regarding: - Thermal management of the power electronics, if the text passage is related to the thermal management process (complexity, etc.)
	HV protection system	This category includes all limitations related to the subcomponent HV protection system, such as fuses. The assignment to this subcategory will only be performed if the HV protection	*"The range of electric vehicles is constantly growing and, in order to make this possible, batteries with an increasingly large capacity are needed. As a result, short circuits in the vehicle*	Exclusion criteria are topics regarding: - Thermal management of the power electronics, if the text

		system is mentioned explicitly in the text passage.	*electrical system caused by accidents can lead to short circuit currents of up to 20,000 A. As the capacity of the batteries grows in the future, so too will this figure. Fuses and automotive high voltage protection mechanisms have in many cases reached the limits of their potential.”* *(TU Vienna, 2019, p. 66)*	passage is clearly related to the thermal management process (complexity, etc.) - Other power electronics components like on-board charger, inverter, etc.
	On-board charger	This category includes all limitations that are related to the subcomponent on-board charger. The assignment to this subcategory will only be performed if the onboard charger is mentioned explicitly in the text passage.	*“Rapid DC charging covers a large range requirement, but the network of charging stations is sparse. Often, it is only possible to charge these DC-capable vehicles on a single-phase basis at an AC station, because in many cases the On-board Charger (OBC) permanently installed within the vehicle often no longer supports charging.”* *(Brüll and Graf, 2018, p. 63)*	Exclusion criteria are topics regarding: - Thermal management of the power electronics, if the text passage is clearly related to the thermal management process (complexity, etc.) - Other power electronics components like HV protection system, inverter, etc.
Transmission		This category includes all limitations regarding one or multi-speed transmissions in electric vehicles.	No text passage was detected in the literature research and the analysis that describes the component “transmission” as a bottleneck in a battery electric vehicle.	-
E-Motor		This category includes all limitations that are related to the component E-Motor. This can concern production processes or production capacities as well as material-specific topics such as active or passive materials.	*“The demand estimated for magnets is about 18.500 metric tons for the year 2020 and even higher with 65.500 metric tons for 2025. Considering the limited production capacity of the magnet manufactures a latent risk for the automotive sector is possible.”* *(Kilper et al., 2019, p. 276)*	Exclusion criteria are topics regarding: - Thermal management of the e-motor, if the text passage is clearly related to the thermal management process (complexity, etc.)

Thermal management		This category includes all limitations that are related to the component thermal management. The direct assignment to this main category will only be performed if the text passage cannot be assigned to one of the subcategories thermal management of battery, power electronics, or HVAC.	*“Current EVs have the problem of a strongly varying driving range depending on the ambient conditions. At winter conditions and the use of resistance heating the driving range can drop by 50 %.” (Steiner et al., 2018, p. 62)*	Exclusion criteria are topics regarding: - The damaging effects or efficiency limitations of different components due to insufficient thermal management
	Thermal management of battery	This category includes all limitations that are related to the subcomponent thermal management of the battery. The assignment to this subcategory will only be performed if the thermal management of the battery is mentioned explicitly in the text passage.	*“Preconditioning the battery system while driving is essential to achieve maximum charging speed, but leads to range restrictions and, in turn, to a quickly decreasing range on the dashboard.” (Teuschl et al., 2018, p. 61)*	Exclusion criteria are topics regarding: - The damaging effects or efficiency limitations of different components due to insufficient thermal management
	Thermal management of power electronics	This category includes all limitations that are related to the subcomponent thermal management of power electronics. The assignment to this subcategory will only be performed if the thermal management of the power electronics is mentioned explicitly in the text passage.	*“Furthermore, specific components of electric vehicles, like the traction battery or power electronics, have to be conditioned within certain temperature limits in order to ensure functionality and extend their life span.”* *(Rabl et al., 2017, p. 27)*	Exclusion criteria are topics regarding: - The damaging effects or efficiency limitations of different components due to insufficient thermal management
	Heating, ventilation, and air conditioning	This category includes all limitations that are related to the subcomponent HVAC. The assignment to this subcategory will only be performed if the cabin climatization/air conditioning is mentioned explicitly in the text passage.	*“Activating the air conditioning brings thermal management into play. This push of a button signifies a reduction in range of 25 to 45% in today’s electric vehicles.” (Teuschl et al., 2018, p. 61)*	-

Vehicle body and chassis	This category includes all limitations related to the component vehicle body and chassis, their materials, including the lightweight design, operating behavior (NVH) and production processes.	No text passage was detected in the literature research and the analysis that describes the component "vehicle body and chassis" as a bottleneck in a battery electric vehicle.	-
Complements	**Category definition**	**Anchor example**	**Coding rules**
Electric charging infrastructure	This category includes all limitations that are related to the complement electric charging infrastructure. The direct assignment to this main category will only be performed if the text passage cannot be assigned to one of the subcategories charging station and digital integration.	Assignment performed only on subcategories, i.e., no direct assignment made to the main category	Exclusion criteria are topics regarding: - Charging time of battery electric vehicles when the battery is the limiting factor - Thermal behavior during the charging procedure
Charging station	This category includes all limitations related to the subcomponent charging station, like standardization issues, charging station power, or availability.	*"A decisive acceptance factor in e-mobility is trouble-free and fast charging. In addition to large-scale charging parks at high-performance grid connections, decentralized fast chargers will also be needed in the distribution grids." (Ads-Tec, 2017, p. 34)*	Exclusion criteria are topics regarding: - Charging time of battery electric vehicles when the battery is the limiting factor - Thermal behavior during the charging procedure - Digital Integration like apps, billing process with apps, and interconnectivity
Digital integration	This category includes all limitations of the subcomponent digital integration of the charging station infrastructure, like the interconnectivity, apps, etc.	*"Electric vehicles are able to support the mobility and energy transition if cooperative charging is possible, that means the demand for energy and its availability are balanced. The prerequisite is an overarching communication network*	Exclusion criteria are topics regarding: - Charging station and their charging power, standardization issues, etc.

		to control the various functions: authorization, charge control, load management, billing process and value-added services.” (Willrett, 2020, p. 64)	
Electric grid	This category includes all limitations that are related to the complement electric grid. Examples, therefore, can be topics regarding the expansion of the grid or fluctuations of the grid due to peak loads.	*“These residential hot spots and other concentration points of EV charging, such as public EV-fast-charging stations and commercial-vehicle depots, will see significant increases in local peak loads […]. Unmanaged, substation peak-load increases from EV-charging power demand will eventually push local transformers beyond their capacity, requiring upgrades.”* (Engel et al., 2018)	Exclusion criteria are topics regarding: - Availability of the electric energy
Dealer and workshop	This category includes all limitations that are related to the complement dealer and workshop. Examples, therefore, can be topics regarding sales, service, and repair activities in the field of battery electric vehicles.	*“The sales staff in the dealerships are not fully informed and have to spend a lot of time encouraging customers to take an interest in the technology. In a study published in the journal “Nature Energy,” the University of Aarhus came to the conclusion that “car dealerships represent a significant barrier to the market launch of electric cars.”* (Liebl, 2018a, p. 9)	-
Disposal and recycling	This category includes all limitations that are related to the complement disposal and recycling. Examples, therefore, can be topics regarding the recycling process of components or difficulties in the disposal of components.	*“With 10 million batteries from electrical vehicles alone, weighing anywhere between 10 and 100 kg. [..] If the recycling requirements from other applicable fields are also included, recycling capacities will be needed in 20 to 30 years’ time that we ought to be establishing now.”* (Burkert, 2018a, p. 13)	-

Appendix K: Final coding guideline for FCEV

Components	Category definition	Anchor example	Coding rules
Fuel cell	This category includes all limitations, that are related to the component fuel cell. The direct assignment to this main category will only be performed if the text passage cannot be assigned to one of the subcategories MEA, bipolar plates, fuel cell management, or fuel cell production.	*"Similar to the automotive engine, fuel cells have some problems, such as a slow response, difficulty starting cold, and braking energy that cannot be recycled." (Yun et al., 2010, p. 223)*	Exclusion criteria are topics regarding: - Thermal management of fuel cells, if the text passage is clearly related to the thermal management process (complexity, etc.) If the text passage refers to the fuel cell system, the fuel cell, the oxygen supply, and the hydrogen system will be coded.
Membrane electrolyte assembly	This category includes all limitations related to the subcomponent membrane electrolyte assembly, which means the MEA must be mentioned explicitly in the text passage. The direct assignment to this subcategory will only be performed if the text passage cannot be assigned to the subcategory 2nd order fuel cell catalyst.	*"In particular, where the membrane is used in vehicles the specific operating conditions always have to be taken into account. Constant load changes and changes in the environmental conditions provide the biggest challenges to the stability of the fuel cells compared to other applications." (Hertel, 2005, p. 23)*	Exclusion criteria are topics regarding: - Thermal management of fuel cells, if the text passage is clearly related to the thermal management process (complexity, etc.) - Fuel cell limitations, if these limitations are related to bipolar plates, fuel cell management, or fuel cell production,
Fuel cell catalyst	This category includes all limitations related to the subcomponent 2nd order fuel cell catalyst, which means the	*"Conventional fuel cells with platinum catalysts are too expensive for large-scale use, but cheaper systems are*	Exclusion criteria are topics regarding:

		term fuel cell catalyst must be mentioned explicitly in the text passage.	*considerably less efficient." (Jacobs University Bremen, 2016, p. 69)*	- Thermal management of fuel cells, if the text passage is clearly related to the thermal management process (complexity, etc.)
	Bipolar plates	This category includes all limitations related to the subcomponent bipolar plates, which means the bipolar plate must be mentioned explicitly in the text passage.	*"The Fraunhofer Institute for Production Technology (IPT) aims to enable bi-polar plates for fuel cells to be produced more cost-effectively and on a large scale. Researchers at the institute are concentrating on developing a hot forming process for the plates, which account for a large proportion of the weight of the fuel cells and for almost half the production costs." (Fraunhofer IPT, 2019, p. 40)*	Exclusion criteria are topics regarding: - Thermal management of fuel cells, if the text passage is clearly related to the thermal management process (complexity, etc.)
	Fuel cell management	This category includes all limitations related to the subcomponent fuel cell management, which means the management for efficient fuel cell usage.	*"Therefore, water management is an important operation issue in a PEM fuel cell because the liquid water in the fuel cell causes electrode flooding that can lower the cell performance under high current density conditions." (Ha et al., 2007, p. 119)*	Exclusion criteria are topics regarding: - Thermal management of fuel cells, if the text passage is clearly related to the thermal management process (complexity, etc.)
	Fuel cell production	This category includes all limitations related to the subcategory fuel cell production, which means this subcategory is not a component but an activity in the value chain. Especially, the focus on this category should be on the production process and the associated capacities of fuel cell manufacturers.	*"Together with the mass production process, this is the most important means of reducing the costs per kWh. The direct manufacturing costs could level out at 36 euros per kWh if 30,000 assemblies are produced in one year. That is the goal of the AutoStack Industry project, which aims to develop a high-performance*	Exclusion criteria are topics regarding: - Production process of other components or complements

		automotive stack and prepare it for production." (Burkert, 2019, p. 11)	
Oxygen supply	This category includes all limitations related to the oxygen supply in the fuel cell system. The direct assignment to this main category will only be performed if the text passage cannot be assigned to one of the subcategories air filter or compressor.	Assignment performed only on subcategories, i.e., no direct assignment made to main category (Exception: text passages referencing fuel cell system)	Exclusion criteria are topics regarding: - Thermal management, if the text passage is related to the thermal management process (complexity, etc.) If the text passage refers to the fuel cell system, the fuel cell, the oxygen supply, and the hydrogen system will be coded.
Air filter	This category includes all limitations related to the subcomponent air filter, which means limitations in the air filtration must be mentioned explicitly in the text passage.	*"One major challenge in the intake system lies in rating the air filter. This needs to protect the fuel cell system from contamination. Solid and gaseous components must be kept away from compressor, heat exchanger and, above all, the MEA." (Pundt et al., 2018, p. 40)*	Exclusion criteria are topics regarding: - Compression and humidification of the air
Compressor	This category includes all limitations related to the subcomponent compressor, which means the compressor must be mentioned explicitly in the text passage.	*"This requires an air supercharging mechanism at a cost of parasitic loads. Current superchargers used in fuel cell power systems have excessive parasitic loads, approaching 10 - 15 kW at a peak power of 50 kW net, and are heavy and big." (Yang, 2000, p. 14)*	Exclusion criteria are topics regarding: - Air filtration and humidification of the air
Hydrogen system	This category includes all limitations, that are related to the hydrogen system in the fuel cell system. The direct assignment to this main category	Assignment performed only on subcategories, i.e., no direct assignment made to main category (Exception: text passages referencing fuel cell system)	Exclusion criteria are topics regarding:

		will only be performed if the text passage cannot be assigned to one of the subcategories hydrogen tank or on-board hydrogen supply.		- Thermal management, if the text passage is clearly related to the thermal management process (complexity, etc.) If the text passage refers to the fuel cell system, the fuel cell, the oxygen supply, and the hydrogen system will be coded.
	Hydrogen tank	This category includes all limitations related to the subcomponent hydrogen tank, which means the onboard hydrogen storage. These problems in the onboard hydrogen storage must be mentioned explicitly in the text passage to be assigned to this subcategory.	*“The hydrogen storage tanks in the vehicle can be filled just as quickly as fuel tanks in conventional gasoline or diesel cars. However, the hydrogen tanks are currently very heavy and expensive to manufacture.”* (BAM, 2018, p. 65)	Exclusion criteria are topics regarding: - Thermal management, if the text passage is clearly related to the thermal management process (complexity, etc.) - On-board hydrogen supply (pumps, etc.)
	On-board hydrogen supply	This category includes all limitations related to the subcomponent on-board hydrogen supply, which means the transport/reformation, including components, from the hydrogen tank to the fuel cell. These problems in the onboard hydrogen supply must be mentioned explicitly in the text passage to be assigned to this subcategory.	*“Therefore, the development of an efficient and realistic hydrogen production device may accelerate fuel cell technology by resolving a primary roadblock, which is the need for an on-board hydrogen supply system.”* (Lee et al., 2012b, p. 23)	Exclusion criteria are topics regarding: - Thermal management, if the text passage is clearly related to the thermal management process (complexity, etc.) - Hydrogen tank and general hydrogen supply (outside the vehicle)
Battery		This category includes all limitations, that are related to the component battery in fuel cell electric vehicles. The assignment to this category will	No text passage was detected in the literature research and the analysis that describes the component “battery” as a bottleneck in a fuel cell electric vehicle.	Exclusion criteria are topics regarding:

		only be performed if the text passage mentions the battery in correlation to the fuel cell electric vehicle.		- Thermal management of batteries, if the text passage is clearly related to the thermal management process (complexity, etc.) - Batteries in BEVs - Batteries in HEVs
Power electronics		This category includes all limitations, that are related to the component power electronics. The direct assignment to this main category will only be performed if the text passage cannot be assigned to the subcategory HV protection system.	*“Due to these special requirements on power electronics, a relatively high portion of cost is currently being generated in electric vehicles, which would in the future increase without further improvement of the power electronics due to the cost reduction of the electric vehicles.” (Hohmann et al., 2017, p. 39)*	Exclusion criteria are topics regarding: - Thermal management of the power electronics, if the text passage is clearly related to the thermal management process (complexity, etc.)
	HV protection system	This category includes all limitations related to the subcomponent HV protection system, for example, fuses. The assignment to this subcategory will only be performed if the HV protection system is mentioned explicitly in the text passage.	*“The range of electric vehicles is constantly growing and, in order to make this possible, batteries with an increasingly large capacity are needed. As a result, short circuits in the vehicle electrical system caused by accidents can lead to short circuit currents of up to 20,000 A. As the capacity of the batteries grows in the future, so too will this figure. Fuses and automotive high voltage protection mechanisms have in many cases reached the limits of their potential.” (TU Vienna, 2019, p. 66)*	Exclusion criteria are topics regarding: - Thermal management of the power electronics, if the text passage is clearly related to the thermal management process (complexity, etc.) - Other power electronics components like on-board charger, inverter, etc.
Transmission		This category includes all limitations regarding transmissions in electric vehicles.	No text passage was detected in the literature research and the analysis that describes the component “transmission”	-

		as a bottleneck in a fuel cell electric vehicle.	
E-Motor	This category includes all limitations related to the component E-Motor. This can concern production processes or production capacities as well as material-specific topics such as active or passive materials.	*"The demand estimated for magnets is about 18.500 metric tons for the year 2020 and even higher with 65.500 metric tons for 2025. Considering the limited production capacity of the magnet manufactures a latent risk for the automotive sector is possible."* *(Kilper et al., 2019, p. 276)*	Exclusion criteria are topics regarding: - Thermal management of the e-motor, if the text passage is clearly related to the thermal management process (complexity, etc.)
Thermal management	This category includes all limitations, that are related to the component thermal management. The direct assignment to this main category will only be performed if the text passage cannot be assigned to one of the subcategories thermal management of powertrain or HVAC.	Assignment performed only on subcategories, i.e., no direct assignment made to the main category	Exclusion criteria are topics regarding: - The damaging effects or efficiency limitations of different components due to insufficient thermal management
Thermal management of powertrain	This category includes all limitations, that are related to the subcomponent thermal management of the powertrain. The assignment to this subcategory will only be performed if the thermal management of different powertrain components (fuel cell, battery, hydrogen system, oxygen supply, etc.) is mentioned explicitly in the text passage.	*"Thermal management plays an important role in vehicles powered by fuel cells as well. While the requirements for the battery, electric motor, and electronics remain the same, heating the hydrogen is yet another task. Compared with a combustion engine, about 30 % more specific cooling capacity must be provided for the powertrain." (Wawzyniak et al., 2017, p. 50)*	Exclusion criteria are topics regarding: - The damaging effects or efficiency limitations of different components due to insufficient thermal management
Heating, ventilation, and air conditioning	This category includes all limitations, that are related to the subcomponent HVAC. The assignment to this subcategory will only be performed if	*"Thermal management and cabin climatization are crucial factors influencing the driving range of battery and fuel cell electric vehicles. Currently mostly*	-

	the cabin climatization/air conditioning is mentioned explicitly in the text passage.	*electrically powered components are used for this purpose, for example, Positive Temperature Coefficient (PTC) heaters or electrical compressors, which lead to a driving range reduction of up to 50 % during hot or cold weather conditions." (Hegner and Weckerle, 2020, p. 79)*	
Vehicle body and chassis	This category includes all limitations related to the component vehicle body and chassis, their materials, including the lightweight design, operating behavior (NVH) and production processes.	No text passage was detected in the literature research and the analysis that describes the component "vehicle body and chassis" as a bottleneck in a fuel cell electric vehicle.	-

Complements	Category definition	Anchor example	Coding rules
Hydrogen refueling infrastructure	This category includes all limitations related to the complement hydrogen refueling infrastructure, which means all topics related to the availability of public hydrogen stations, the costs for expanding the hydrogen station network, and all issues related to the refueling process.	*"The costs of a hydrogen fuel station with one dispenser are around 1 million € […]. Of course, it can be argued that the price for hydrogen fuel stations will significantly decrease if they are built in high quantities. On the other hand, the current fuel stations are not yet able to refuel more than two cars per hour. To increase the fuel speed, additional technology is required, and this means additional costs." (Doppelbauer, 2020a, p. 405)*	Exclusion criteria are topics regarding: - Production and transport of the hydrogen to the fuel stations If the text passage refers to the hydrogen supply infrastructure, the hydrogen refueling infrastructure and the availability and transport of hydrogen will be coded.
Availability and transport of hydrogen	This category includes all limitations related to the complement availability and transport of hydrogen, which means all topics associated with the production of hydrogen and its subsequent transportation to the individual public hydrogen stations.	*"The cost of building or expanding a hydrogen infrastructure, from industrial production to distribution through pipelines or tank trucks until delivery to filling stations, is under the given conditions such as safety requirements,*	Exclusion criteria are topics regarding: - Availability of hydrogen station infrastructure

	This includes all issues regarding the costs of the production of hydrogen, the production capacity of the plants, and the availability of transport facilities such as pipelines or trucks.	*hydrogen diffusion, compression work or low temperature keeping is immense." (Weber, 2020, p. 47)*	If the text passage refers to the hydrogen supply infrastructure, the hydrogen refueling infrastructure and the availability and transport of hydrogen will be coded.
Dealer and workshop	This category includes all limitations, that are related to the complement dealer and workshop. Therefore, examples can be topics regarding sales, service, and repair activities in fuel cell electric vehicles.	*The sales staff in the dealerships are not fully informed and have to spend a lot of time encouraging customers to take an interest in the technology. In a study published in the journal "Nature Energy," the University of Aarhus came to the conclusion that "car dealerships represent a significant barrier to the market launch of electric cars." (Liebl, 2018a, p. 9)*	-
Disposal and recycling	This category includes all limitations, that are related to the complement disposal and recycling. Examples, therefore, can be topics regarding the recycling process of components or difficulties in the disposal of components.	*"The recycling rate of the fuel cell must be further improved, especially for the polymer membrane is a big research need to develop an economically advantageous process. Therefore, the materials have to be separated to such an extent that they can be introduced into standardized existing recycling processes."* *(Ahlfs et al., 2020, p. 12f)*	-

Appendix L: Text passages that declare a bottleneck for BEVs

Journal	Text passage	(Sub) - component / complement	Component or Complement	Type of bottleneck	Trigger / Comment
ATZ Volume 122 Issue 12 Article 15	*“At the same time, electric vehicles connected to the power grid pose a challenge for Distribution System Operators (DSOs). The high demand for simultaneously charging PEVs can occasionally lead to overload and bottlenecks in low-voltage networks, if no countermeasures are taken.” (Dreisbusch et al., 2020, p. 69)*	Electric grid	Complement	Performance fluctuations → Low performance	Peak loads due to simultaneously charging
ATZ Volume 122 Issue 12 Article 14	*“Electric vehicles are able to support the mobility and energy transition if cooperative charging is possible, that means the demand for energy and its availability are balanced. The prerequisite is an overarching communication network to control the various functions: authorization, charge control, load management, billing process and value-added services.” (Willrett, 2020, p. 64)*	Digital integration → Electric charging infrastructure	Complement	Missing interoperability → Low performance	Missing overarching communication network
ATZ Volume 122 Issue 12 Article 13	*“Generally, the following applies: The comparatively high and long-term power consumption of a charging process is a challenge for the distribution grid. FIGURE 1 shows the common load profile of a household in connection with the power required to charge an electric vehicle. If we look at an entire electrical circuit, this effect accumulates intermittently. The number of vehicles charging simultaneously is therefore decisive.” (Wunsch, 2020, p. 61)*	Electric grid	Complement	Performance fluctuations → Low performance	Peak loads due to simultaneously charging

ATZ Volume 122 Issue 12 Article 09	*“The properties of driving comfort, sense of security, sovereignty, sportiness and precision shape the handling characteristics of a Mercedes-Benz passenger car. Objective parameters for vehicle development are derived from these properties, so that the driver always recognizes their car at first glance. This challenge also needs to be met by vehicles with battery electric drives. However, the lower position of the center of gravity due to batteries, FIGURE 1, that are integrated in the floor area simplifies good ride and handling coordination, but the batteries also lead to a clearly increased vehicle weight.” (Pfister et al., 2020, p. 37)*	Battery	Component	High weight → Low performance	-
ATZ Volume 122 Issue 11 Article 14	*“Weight-intensive high-voltage batteries are required to realize predefined ranges, which makes lightweight design necessary on the one hand, but at the same time limits the available levers for weight reduction.” (Seidel et al., 2020, p. 65)*	Battery	Component	High weight → Low performance	-
ATZ Volume 122 Issue 10 Article 14	*“As far as battery production is concerned, it is clear that we need to significantly expand our capacity to meet the growing demand for electric vehicles. In Germany in particular, we have very few battery manufacturing plants, but work has already begun on constructing factories in locations close to the market to reduce the amount of transport needed and to keep one-sided supply chain dependencies to a minimum.” (Heintzel and Eisenkrämer, 2020, p. 66)*	Battery production → Battery	Component	Lack of capacity → Low availability	Only a few battery manufacturing plants
ATZ Volume 122 Issue 10 Article 14	*“The State of Baden-Württemberg is laying the foundations for the charging infrastructure with its SAFE charging network for electric vehicles. A wide range of different players are currently involved in expanding the network. In addition to providing start-up funding for areas of the infrastructure which are not yet*	Charging stations → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	Legal obstacles

	profitable but play an important role in helping the market to take off, we must continue to focus on the regulatory framework and ensure that the legal obstacles to the introduction of re-fuels are removed.” (Heintzel and Eisenkrämer, 2020, p. 66)				
ATZ Volume 122 Issue 10 Article 13	*“While the capacity of the traction battery determines the driving range of an electric passenger car decisively, it is the heaviest component too.” (List et al., 2020, p. 60)*	Battery	Component	High weight → Low performance	-
ATZ Volume 122 Issue 10 Article 13	*“In terms of a low center of gravity, it is also essential for driving dynamics – because with a mass of up to 700 kg, the traction battery is the heaviest component of a BEV.” (List et al., 2020, p. 60)*	Battery	Component	High weight → Low performance	-
ATZ Volume 122 Issue 10 Article 13	*“Low or high temperatures limit the performance of lithium-ion batteries significantly and have a direct impact on the driving range. If the battery temperature drops from 20 to 0 °C, their efficiency is reduced by approximately 20 %.” (List et al., 2020, p. 61)*	Battery	Component	Limited range → Low performance	Temperature sensitivity of battery
ATZ Volume 122 Issue 10 Article 13	*“Moreover, high temperatures cause the battery materials to age more quickly and reduce the battery capacity in the long term. As a rule, it is also important to avoid a thermal runaway when manufacturer-dependent critical cell temperatures are exceeded.” (List et al., 2020, p. 61)*	Battery	Component	Limited lifetime expectation → Low quality Safety risk → Low quality	Temperature sensitivity of battery (aging, thermal runaway)
ATZ Volume 122 Issue 09 Article 03	*“Of the many new testing tasks, Reuss mentions the case of the thermal behavior of electric powertrains, for instance, in heavy-load and continuous-duty conditions. In addition to cooling, new operating strategies are necessary to better control derating, that is, a kind of intelligent, incremental reduction in output. After all,*	Thermal management	Component	Low reliability → Low performance	-

	electric vehicle owners will naturally want to avoid sudden losses of power.” (Goppelt, 2020, p. 12)				
ATZ Volume 122 Issue 09 Article 03	*“While there is a clear opportunity to target simplification at a mechanical level, batteries naturally remain challenging when it comes to acceptable cost.” (Goppelt, 2020, p. 11)*	Battery	Component	High costs	-
ATZ Volume 122 Issue 06 Article 11	*“The range achievable in real-word operation [2], in contrast, is a factor that truly affects purchasing decisions. Range, however, results in a conflict for developers dealing with today’s battery technology and its low energy density: the larger the range, the higher the vehicle’s weight due to the battery cell. Higher weight in turn reduces efficiency.” (Schmidt, 2020, p. 48)*	Battery cell → Battery	Component	Limited range → Low performance	Low energy density
ATZ Volume 122 Issue 05 Article 02	*“For Germany to come even close to the interim goal, the German National Platform Future of Mobility (NPM) has predicted that there will need to be more than ten million electric and one million fuel-cell vehicles on the country’s roads. In addition, the number of public charging points will have to increase from the current figure of around 20,000 to 300,000. Implementing these proposals within the next ten years will be almost impossible and therefore additional measures will be needed.” (Liebl, 2020, p. 7)*	Charging stations → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
ATZ Volume 122 Issue 04 Article 14	*“Covering longer distances is still a challenge for electric mobility. Along highways, charging possibilities are limited and long vehicle charging times are unacceptable.” (Kraft, 2020, p. 66)*	Charging stations → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
				Long charging time → Low performance	-

ATZ Volume 122 Issue 04 Article 14	*“The estimated range of an electric automobile is a much-discussed parameter with regard to a limited number of charging stations with acceptable charging power.” (Kraft, 2020, p. 67)*	Charging station → Electric charging infrastructure	Complement	Long charging time → Low performance	Limited charging station power
				Lack of infrastructure → Low availability	-
ATZ Volume 122 Issue 04 Article 11	*“However, the penetration of BEV and FCEV technologies will require an increase in mining output, particularly for lithium, cobalt and platinum. This will have social, environmental and economic consequences. Occasional shortages and the resulting price increases are a distinct possibility.” (Hendrich and Reuter, 2020, p. 55)*	Battery cathode (Lithium and Cobalt) → Battery cell → Battery	Component	Costs of raw material → High costs	Supply shortage
ATZ Volume 122 Issue 04 Article 11	*“The cooperation of processing industries and recycling companies would make it easier to set up and operate profitable collection systems and recycling plants. In addition, the “Design for Recycling” approach is also to be recommended here in order to keep raw materials in the recycling loop and lower the costs.” (Hendrich and Reuter, 2020, p. 55)*	Disposal and recycling	Complement	Lack of capabilities → Low availability	Missing collaboration between manufacturer and recycling industry
ATZ Volume 122 Issue 04 Article 03	*“Changing the existing feet over to electric vans, trucks, and buses will present a major challenge in terms of feet management, the establishment of the charging infrastructure, operational planning, and many other considerations.” (Schlott, 2020, p. 13)*	Charging stations → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
ATZ Volume 122 Issue 02 Article 10	*“Despite established standards for charging plugs and the communication between the vehicles and charging stations, the wide variety of implementation options lead to unsuccessful charging attempts. The reasons*	Charging station → Electric charging infrastructure	Complement	Missing interoperability → Low performance	Communication network issues

	range from communication problems between charging station and vehicle to “bad electricity,” thus voltage and frequency fluctuations in the grid that cause vehicles to stop the charging process.” (Horn et al., 2020, p. 42)	Electric grid	Complement	Performance fluctuations → Low performance	-
ATZ Volume 122 Issue 02 Article 10	*“While public infrastructure is planned, built and adapted over the course of decades, an electric vehicle can change rapidly as the vehicle development process progresses within multiple years, and a software function in a smartphone’s charging app may be subject to new updates on a monthly basis.” (Horn et al., 2020, p. 43)*	Digital integration → Electric charging infrastructure	Complement	Missing interoperability → Low performance	Different development cycles of EV, charging apps, and infrastructure
ATZ Volume 122 Issue 02 Article 10	*“Most car manufacturers still lack experience in dealing with aspects such as cell chemistry, the mechanical and thermal properties of batteries and optimum battery management with regard to performance and aging.” (Horn et al., 2020, p. 44)*	Battery cell → Battery	Component	Low performance Limited lifetime expectation → Low quality	Lack of experience in cell chemistry, etc.
ATZ Volume 122 Issue 02 Article 10	*“The broad expansion of charging infrastructure is overseen by different manufacturers, each with their own interpretation of how exactly to implement charging communication, regardless of the agreed standards. This leads to problems with interoperability that have been massive in some cases.” (Horn et al., 2020, p. 44)*	Charging station → Electric charging infrastructure	Complement	Missing interoperability → Low performance	A different interpretation of the charging communication of various manufacturer
ATZ Volume 122 Issue 02 Article 09	*“The development of Lithium-ion Batteries (LIBs) remains a major challenge to meet all market requirements for BEVs. High dependency of LIBs performance on temperature and furthermore thermal safety issues are the main concerns which influences large distribution of BEVs in general. Cold temperatures make the battery efficiency drop because of increasing*	Battery	Component	Low efficiency → Low performance Safety risks → Low quality	Temperature sensitivity of Lithium-ion batteries

	resistance leaving discharge capacity minimal.” (Mirsalehian and Beykirch, 2020, p. 37)				
ATZ Volume 122 Issue 02 Article 09	*“The life cycle is also adversely influenced by promotion of Loss of Active Lithium Inventory (LLI), caused, for example, by Solid Electrolyte Interface (SEI) growth. Lithium-plating is the other consequence which occurs by lithium agglomeration on anode particles during charge. On the other side, hot temperatures trigger undesired side reactions which cause LLI and Loss of Active Material (LAM). Furthermore, temperature non-uniformity within the battery, which is intensive during the operation with high currents such as fast charging, leads to different aging rates and pre-mature failure in the battery. Thermal abuse conditions, for example TR event and fire exposure, are the key safety failures for the LIBs which can endanger passengers.” (Mirsalehian and Beykirch, 2020, p. 37)*	Battery cell → Battery	Component	Limited lifetime expectation → Low quality	Temperature sensitivity of Lithium-ion batteries causes e.g., aging
				Safety risks → Low quality	
ATZ Volume 122 Issue 02 Article 09	*“Production and growth of SEI film on anode particles’ surface leads to increasing irreversible loss of lithium and potential drop. Charge transport in electrolyte is also adversely affected by reduced electrolyte volume fraction due to expanding the SEI layer in solid phase.” (Mirsalehian and Beykirch, 2020, p. 38)*	Battery anode → Battery cell → Battery	Component	Limited lifetime expectation → Low quality	Loss of Lithium
ATZ Volume 122 Issue 02 Article 03	*“The Center Automotive Research (CAR) at the University of Duisburg-Essen has identified that the production process represents only 5 % of the cost of a lithium-ion battery [3].The cathode and the materials needed to manufacture it make up the majority of the cost at 70 %, while the anode and other materials contribute 25 %. For battery manufacturers these are*	Battery cathode → Battery cell → Battery	Component	Costs of raw material → High costs	High level of dependency on supplier

	transitory items that involve a high level of dependency on the suppliers of raw materials." (Backhaus, 2020, p. 10)				
ATZ Volume 122 Issue 01 Article 18	*"But on the other hand, there are also technical limitations, including battery capacity and the efficiency of electric vehicles." (Tarabbia, 2020, p. 84)*	Battery	Component	Limited capacity → Low performance	-
ATZ Volume 122 Issue 01 Article 17	*"Thermal management and cabin climatization are crucial factors influencing the driving range of battery and fuel cell electric vehicles. Currently mostly electrically powered components are used for this purpose, for example Positive Temperature Coefficient (PTC) heaters or electrical compressors, which lead to a driving range reduction of up to 50 % during hot or cold weather conditions [1]." (Hegner and Weckerle, 2020, p. 79)*	Thermal Management HVAC → Thermal Management	Component	Low performance	Electrically powered components like PTC heater
ATZ Volume 122 Issue 01 Article 14	*"The market for battery raw materials is subject to its own laws and arbitrary political decisions, just as other industrial sectors are. The most recent example is the cancellation of a joint German-Bolivian joint venture for the extraction of lithium hydroxide. I also have my doubts concerning dependencies and the associated price fluctuations." (Schöttle, 2020, p. 61)*	Battery	Component	Costs of raw material → High costs	High dependency on supplier
ATZ Volume 122 Issue 01 Article 14	*"The high energy requirements for the manufacturing of battery cells and the effort required to acquire raw materials balance out in a circular process. The price of batteries can and must fall."(Schöttle, 2020, p. 60)*	Battery production → Battery	Component	High costs	-
IJoAT Volume 21 Issue 01 Article 05	*"Hybrid cars can be considered a realistic alternative because of the drawbacks such as the high prices of electric cars and hydrogen fuel cell cars and the lack of charging infrastructure." (Lim et al., 2020, p. 41)*	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-

IJoAT Volume 21 Issue 01 Article 15	*“In tropical countries, the power demand from the air conditioning system of an electric vehicle can be up to 40 percent of the total power demand of the traction battery.” (Pathak et al., 2020, p. 147)*	HVAC → Thermal management	Component	Low performance	Electric power from battery is used for the air conditioning
IJoAT Volume 21 Issue 01 Article 15	*“The battery cost of electric vehicles has the highest contribution to the overall cost of the vehicle.” (Pathak et al., 2020, p. 147)*	Battery	Component	High costs	-
IJoAT Volume 21 Issue 01 Article 15	*“In tropical countries, the cooling demand of the vehicle from the traction battery can be as high as 30 ~ 40 % of the total driving demand.” (Pathak et al., 2020, p. 147)*	HVAC → Thermal management	Component	Low performance	Electric power from battery is used for the air conditioning
IJoAT Volume 21 Issue 02 Article 24	*“Recently, electric vehicles (EVs) such as plug-in hybrid electric vehicles (PHEVs), pure electric vehicles (PEVs) which are also named as battery electric vehicles (BEVs) have been actively developed to reduce the effects of air pollution caused by automobiles. One of the main challenges in the EV system is reducing the battery charging time.” (Kim and Choi, 2020, p. 519)*	Battery	Component	Long charging time → Low performance	**-**
IJoAT Volume 21 Issue 02 Article 24	*“To achieve the better interoperability on EV charging communication, ISO 15118 standardization committee is making efforts, such as holding a testing symposium since November 2014.” (Kim and Choi, 2020, p. 520)*	Charging station → Electric charging infrastructure	Complement	Missing interoperability → Low performance	Charging communication problems
IJoAT Volume 21 Issue 06 Article 08	*“However, pure electric vehicles are currently limited by factors such as high cost, short mileage and long charging time which are mainly caused by the storage device; it is difficult to put them into mass production and large-scale use.” (Xiong et al., 2020, p. 1409)*	Battery	Component	High costs Limited range → Low performance Long charging time → Low performance	-

ATZ Volume 121 Issue 12 Article 03	*"The most valuable components of electric cars are undoubtedly their battery systems. Lithium-ion cells with a high storage capacity can only be operated within a narrow temperature range. Increased temperatures can lead to a premature loss of performance, overheating, and even the destruction of the battery cell." (Heintzel et al., 2019, p. 17)*	Battery cell → Battery	Component	Limited lifetime expectation → Low quality	Premature loss of performance or destruction of the battery cell
ATZ Volume 121 Issue 12 Article 02	*"The automotive industry is still in turmoil. The EU is introducing the strictest emission regulations in the world, forcing the industry to move toward electric mobility despite the inadequate state of the charging infrastructure." (Liebl, 2019a, p. 7)*	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
ATZ Volume 121 Issue 11 Article 03	*"Storage facilities with sufficient capacity are currently neither under construction nor even in the planning in Europe. And yet they, as well as a vehicle charging infrastructure, would be "essential to meeting the demand that would follow the market success of electric vehicles," says Klaus Fröhlich, CEO of Development at BMW, before adding, "From my point of view, the issue of infrastructure has been neglected" [5]." (Heintzel, 2019, p. 9)*	Charging stations → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
ATZ Volume 121 Issue 11 Article 03	*"This has contributed to pervasive inertia in the area of Electric Vehicle (EV) charging infrastructure. Around 10 to 15 EV fast-charge stations would have to be installed for each conventional gasoline pump to accommodate a robust EV market penetration." (Heintzel, 2019, p. 9)*	Charging stations → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
ATZ Volume 121 Issue 10 Article 12	*"Thereto, a laboratory test bench with the electric traction machine was connected with two HiL simulators. It was determined that the temperatures of the traction machine are a limiting factor for the vehicle performance in an exemplarily simulated high load*	E-Motor	Component	Low performance	Vehicle performance is hugely influenced by temperature

	driving cycle on the Nürburgring Nordschleife." (Etzold et al., 2019, p. 54)				
ATZ Volume 121 Issue 10 Article 08	*"The high-voltage battery is the largest and most expensive component of an electric car." (Handtmann, 2019, p. 35)*	Battery	Component	High weight → Low performance	-
				High costs	-
ATZ Volume 121 Issue 10 Article 05	*"High-energy cells have a high capacity and can therefore store a large amount of energy, which has a direct influence on the range of a battery electric vehicle. However, they are not dynamic in the way that they store and supply the power." (Mückenhoff et al., 2019, p. 17)*	Battery cell → Battery	Component	Bad dynamic behavior → Low performance	Storage and supply of power
ATZ Volume 121 Issue 10 Article 05	*"In this respect, high-performance cells have a clear advantage, but this is at the expense of a significantly lower capacity, which leads to a decreased range. An electric vehicle with high-performance cells can accelerate faster and recuperate better." (Mückenhoff et al., 2019, p. 17)*	Battery cell → Battery	Component	Limited capacity → Low performance	-
ATZ Volume 121 Issue 10 Article 04	*"The success of electric mobility is heavily dependent on the capacity of batteries. The goal is to develop traction batteries with a modular, flexible, and more cost-effective design in terms of both power and capacity." (Jung, 2019, p. 15)*	Battery	Component	Limited capacity → Low performance	-
ATZ Volume 121 Issue 09 Article 17	*"The small capacity of current energy storage systems (batteries) in combination with the fragmentary infrastructure for charging facilities requires a precise and robust method for range prediction. Such a method could promote the long-lasting confidence of future users in this key technology." (Simonis, 2019, p. 75)*	Battery	Component	Limited capacity → Low performance	-
		Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-

ATZ Volume 121 Issue 09 Article 13	*“Especially for electric vehicles, the air conditioning decreases the range of the electric vehicle dramatically.” (Becker and Büter, 2019, p. 51)*	HVAC → Thermal management	Complement	Low performance	Energy from the battery is used for air conditioning
ATZ Volume 121 Issue 09 Article 12	*“Furthermore, planned charging power of up to 350 kW and beyond lead to very large heat input into the cell. In order to be able to control cell degradation, the demands on heat dissipation and on a homogeneous temperature distribution at cell and system levels are growing.” (Massonet et al., 2019, p. 45)*	Battery	Component	Limited lifetime expectation → Low quality	-
ATZ Volume 121 Issue 06 Article 15	*“The battery pack is a crucial component that must be considered in the body structure of an electric car due to its high mass and the required large installation space.” (Kampker et al., 2019, p. 73)*	Battery	Component	High weight → Low performance	-
ATZ Volume 121 Issue 06 Article 15	*“The battery system has a particularly strong influence on the development and production cost in the electric car. According to rough estimations, the battery system’s share of total vehicle costs can be estimated between 35 and 50 %.” (Kampker et al., 2019, p. 73)*	Battery	Component	High costs	-
ATZ Volume 121 Issue 06 Article 15	*“The battery cell of an electric car is a sensitive component in the overall body structure, which is considered a potential source of danger for users and the environment due to the energy and chemicals it contains.” (Kampker et al., 2019, p. 73)*	Battery cell → Battery	Component	Safety risk → Low quality	Storage of energy and chemicals
ATZ Volume 121 Issue 06 Article 02	*“Sales of electric vehicles are growing, and manufacturers are investing billions of euros in new models. The market will only really take off when the vehicles and the infrastructure are in perfect harmony. The ATZlive conference “Grid Integration of Electric Mobility” made it clear that we urgently need to speed up the expansion of our charging infrastructure.” (Liebl, 2019b, p. 7)*	Charging stations → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-

ATZ Volume 121 Issue 05 Article 16	*“The biggest technical obstacles to the widespread adaption of electric vehicles are the short driving range and the time-consuming and uncomfortable charging process.” (Franke et al., 2019, p. 79)*	Battery	Component	Long charging time → Low performance	-
		Charging stations → Electric charging infrastructure	Complement		
ATZ Volume 121 Issue 05 Article 11	*“Energy required for generating heating or cooling for thermal management represents a bigger burden on the traction battery in case of EVs than it is for the gasoline or diesel cars [1]. Lacking the steadily available waste heat from the engine, most EVs today rely on direct resistive heating by electric heaters to heat the cabin and traction battery in winter. This represents an expansive drain on the traction battery and can reduce full-charge driving range by as much as 45 to 50 % in cold weather, compared with that of moderate weather where thermal management energy demand is minimal.” (Chowdhury et al., 2019, p. 49)*	Thermal management of battery → Thermal management	Component	Low performance	Electric energy from the battery is used for cabin and battery heating
		HVAC → Thermal management	Component		
ATZ Volume 121 Issue 05 Article 11	*“While battery manufacturers are steadily improving the energy density and cost of traction batteries to increase EV nominal range, the significant range reduction for cold and warm weather driving with cabin thermal management will continue to be a loss. Any system that offers a reduction of that loss will be attractive to the industry.” (Chowdhury et al., 2019, p. 49)*	HVAC → Thermal management	Component	Low performance	Electric energy from the battery is used for cabin and battery heating
ATZ Volume 121 Issue 05 Article 05	*“The variety of lithium-ion batteries poses new challenges for battery development in the automotive industry. Until now, no cell format has proven dominant. The challenge is to meet the current requirements for range and performance.” (Kollmeier et al., 2019, p. 18)*	Battery cell → Battery	Component	Limited range → Low performance	-

ATZ Volume 121 Issue 04 Article 03	*“A glance at the data sheets of a selection of electric vehicles shows that the majority of manufacturers, including Nissan (the Leaf), for example, and BMW (the i3), only guarantee a distance of 100,000 km. The figure for the Opel Ampera, which was launched in 2016, is 160,000 km. The range is based on the critical limit under intensive use when only 70 to 80 % of the original battery capacity is available. While a fuel cell can last the entire lifetime of a car, replacing the batteries after five to six years makes the car a financial write-off.” (Burkert, 2019, p. 12)*	Battery	Component	Limited lifetime expectation → Low quality	Reduction of battery capacity
ATZ Volume 121 Issue 03 Article 14	*“The fulfillment of crash requirements also poses a significant challenge, especially where intrusion space is low, as is the case with side and underfloor intrusion. In addition to crash safety, thermal management also presents the particular challenge of ensuring batteries are maintained at the ideal operating temperature of between 15 and 35 °C for maximum range.” (Lindner, 2019, p. 64)*	Battery	Component	Safety risk → Low quality	Battery penetration or short-circuit
		Thermal management of battery → Thermal management	Component	High complexity → Low performance	Temperature sensitivity of batteries
ATZ Volume 121 Issue 03 Article 14	*“At temperatures above 45 °C, battery damage occurs due to chemical reactions inside the cell. At the other extreme, performance and charging capacity decrease at temperatures below -5 °C, thus lowering vehicle range.” (Lindner, 2019, p. 65)*	Battery cell → Battery	Component	Limited lifetime expectation → Low quality	Battery damage on higher temperatures
				Limited range → Low performance	Performance limitation in the low temperature range

ATZ Volume 121 Issue 03 Article 08	*“One of the biggest hurdles for a comprehensive fast-charging infrastructure has been the disproportionately high mains connection costs. The intermittent load peaks also create a high burden for the power networks.” (Kreisel Electric, 2019, p. 35)*	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	High costs for building the infrastructure
		Electric grid	Complement	Performance fluctuations → Low performance	Intermediate load peaks
ATZ Volume 121 Issue 02 Article 15	*“The range of electric vehicles is constantly growing and, in order to make this possible, batteries with an increasingly large capacity are needed. As a result, short circuits in the vehicle electrical system caused by accidents can lead to short circuit currents of up to 20,000 A. As the capacity of the batteries grows in the future, so too will this figure. Fuses and automotive high voltage protection mechanisms have in many cases reached the limits of their potential.” (TU Vienna, 2019, p. 66)*	HV protection systems → Power electronics	Component	Low performance	Technical limitations
ATZ Volume 121 Issue 02 Article 11	*“Air conditioning and heating of the interior are considerable power consumers and significantly limit the EVs range, especially at extremely low or high ambient temperatures.” (Drage et al., 2019, p. 44)*	HVAC → Thermal management	Component	Low performance	-
ATZ Volume 121 Issue 02 Article 09	*“Major challenges associated with stationary charging infrastructure are, for example, congested cities, high real estate, construction and material costs, trips to the charging station or a poor utilization rate of charging stations. All this leads to a low return on investment for key stakeholders and considerable inconveniences for end users.” (Singh and Boissiere, 2019, p. 37)*	Charging stations → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	Lack of attractiveness for stakeholder

ATZ Volume 121 Issue 02 Article 09	*“Public charging stations (AC and DCFC) have a relatively poor rating due to high investments and large space requirements. Additional challenges are penalties for the end customer (if no charging) and a comparatively low usage rate – less than 20 % according to various studies.” (Singh and Boissiere, 2019, p. 37)*	Charging stations → Electric charging infrastructure	Complement	Costs for electricity → High costs	Penalties for end-user due to low usage rate
ATZ Volume 121 Issue 02 Article 09	*“A fully functional MCV (Mobile charging vehicle) would require several subsystems and integration strategies in addition to the battery and charging system. These include the integrated service app, the vehicle communication system, energy management strategies for optimum charge utilization, special considerations for thermal management and a chassis system adaptation. Accordingly, considerations for development partnerships would be necessary.” (Singh and Boissiere, 2019, p. 38)*	Digital Integration → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	Missing digitalization
ATZ Volume 121 Issue 02 Article 03	*“At cell level, the costs are around 100 euros per kWh. Heimes explained that no further reductions can be expected in this area, because Asian manufacturers had recently been selling cells almost at cost price in order to prevent competitors from building their own plants. The battery cell is ultimately the key competitive factor.” (Heerwagen, 2019, p. 11)*	Battery cell → Battery	Component	High costs	-
IJoAT Volume 20 Issue 01 Article 09	*“However, due to the limited traveling distance and battery life cycle of the fully electric vehicles, hybrid electric vehicles have been developed as the most promising short-term solution.” (Xu et al., 2019, p. 99)*	Battery	Component	Limited lifetime expectation → Low quality	-

IJoAT Volume 20 Issue 02 Article 18	*“It is hard to charge additional fuel while driving in electric vehicle, because there is not enough charging station and it takes a long time to charge.” (Lee et al., 2019, p. 390)*	Battery	Component	Long charging time → Low performance	-
		Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	
IJoAT Volume 20 Issue 04 Article 09	*“Moreover, it is inevitable that a significant amount of heat is generated when an EV climbs steep slopes, because the energy efficiency of electric motors is low at low speed rotations.” (Bang, 2019, p. 739)*	E-Motor	Component	Low efficiency → Low performance	Heat generation in climb steep slopes
IJoAT Volume 20 Issue 04 Article 10	*“Due to heavy battery packs, the weight of an electric vehicle is possibly higher than that of combustion engine one.”* (Kim et al., 2019, p. 749)	Battery	Component	High weight → Low performance	-
IJoAT Volume 20 Issue 05 Article 02	*“For electric vehicle (EV), due to its low efficiency and the current low energy-storage capacity of electric batteries, new transmission structures have been contrived, such as multi-speed transmission (MST) proposed in Roozegar and Angeles (2018) and Roozegar et al. (2017), and the inverse automated manual transmission (I-AMT) proposed in Gao et al. (2015).” (Sun et al., 2019, p. 886)*	Battery	Component	Limited capacity → Low performance	-
IJoAT Volume 20 Issue 06 Article 18	*“The decrement of a battery SOH is mainly caused by the battery aging and degradation, namely durability problems.” (Lee and Wu, 2019, p. 1268)*	Battery	Component	Limited lifetime expectation → Low quality	Aging and degradation

IJoAT Volume 20 Issue 06 Article 20	*“As an important onboard energy storage system, battery has been widely applied to various types of EVs, however, the commonly used single energy storage systems (ESS) has limitations which, depending on the specific energy storage technology, are related to the high cost, insufficient lifetime or low power density […].”* (Bai et al., 2019, p. 1287)	Battery	Component	High costs	-
				Limited lifetime expectation → Low quality	-
				Bad dynamic behavior → Low performance	Low power density
ATZ Volume 120 Issue 12 Article 12	*“To make electric mobility competitive, in addition to the expansion of a comprehensive and correspondingly efficient charging infrastructure and progress in battery cell and system technology to increase the performance, the implementation of innovative system architectures represents an important lever in optimizing the costs of HV systems.”* (Adler et al., 2018, p. 56)	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
		Battery cell → Battery	Component	Low performance	-
ATZ Volume 120 Issue 11 Article 15	*“The global demand for electric vehicles is forecast to rise sharply, with an expected 25 million of new vehicle registrations per year by 2025. New technical solutions for the charging infrastructure will be needed for cars to be charged quickly and even without the driver’s involvement.”* (TU Graz, 2018, p. 62)	Charging station → Electric charging infrastructure	Complement	Long charging time → Low performance	Charging station power
ATZ Volume 120 Issue 11 Article 03	*“The sales staff in the dealerships are not fully informed and have to spend a lot of time encouraging customers to take an interest in the technology. In a study published in the journal “Nature Energy,” the University of Aarhus came to the conclusion that “car dealerships*	Dealer and workshop	Complement	Lack of capabilities → Low availability	Lack of experience in EV

	represent a significant barrier to the market launch of electric cars.” (Liebl, 2018a, p. 9)				
ATZ Volume 120 Issue 11 Article 01	*“Electric mobility is still in its infancy; there are not enough charging stations. Klaus Fröhlich, member of the board of management of BMW AG with responsibility for development, said in the anniversary issue of ATZ: “The charging infrastructure is a decisive factor in generating demand and ensuring market success.” (Heintzel, 2018b, p. 3)*	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
ATZ Volume 120 Issue 10 Article 14	*“However, DC charging stations are expensive due to the charging station technology required, meaning that expanding the network poses a challenge. As a result, it is difficult for the driver of an EV to refuel sufficiently to cover the range required for every form of usage. Either their vehicle does not have the necessary technology on board, or the charging station to which they have access is too weak.” (Brüll and Graf, 2018, p. 62)*	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	High expansion costs
				Long charging time → Low performance	Charging station power
ATZ Volume 120 Issue 10 Article 14	*“Rapid DC charging covers a large range requirement, but the network of charging stations is sparse. Often, it is only possible to charge these DC-capable vehicles on a single-phase basis at an AC station, because in many cases the On-board Charger (OBC) permanently installed within the vehicle often no longer supports charging.” (Brüll and Graf, 2018, p. 63)*	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
		On-board charger → Power electronics	Component	Low performance	-
ATZ Volume 120 Issue 10 Article 01	*“An adequate supply of raw materials and battery cells must be available to allow the production lines for electric cars to get up to full speed.” (Reichenbach, 2018, p. 3)*	Battery cell → Battery	Component	Lack of raw material → Low availability	-

ATZ Volume 120 Issue 09 Article 17	*“Lithium-ion batteries are the state-of-the-art power source for smartphones, tablets, and electric cars. Their storage capacity and power density are far superior to other types of rechargeable battery. Despite all the progress that has been made in this area, smartphone batteries still need charging every day and electric cars take hours to recharge.” (Forschungszentrum Jülich, 2018, p. 75)*	Battery	Component	Long charging time → Low performance	-
ATZ Volume 120 Issue 09 Article 04	*“Electric-vehicle batteries constitute the enfant terrible of modern mobility. They are energy-intensive to manufacture, have a limited range and require rare and expensive raw materials to produce.” (Burkert, 2018a, p. 11)*	Battery	Component	Limited range → Low performance	-
				Costs of raw material → High costs	-
ATZ Volume 120 Issue 09 Article 04	*“Unlike conventional vehicles, electric vehicles require – above all – more special metals in their powertrain, for example rare earths for electric motors and lithium, nickel and cobalt in particular for batteries – the latter metallic, blue-gray shimmering material proving the greatest concern for the electric mobility sector. While it is possible to do without cobalt, it is key in improving the performance of cathodes – the negatively charged electrodes in a lithium-ion battery – by several orders of magnitude in terms of rated voltage and energy density. However, both properties come at a hefty price.” (Burkert, 2018a, p. 11)*	Battery cathode → Battery cell → Battery	Component	Costs of raw material → High costs	-
ATZ Volume 120 Issue 09 Article 04	*“Some of these raw materials are unpredictable, for example, expensive cobalt, which is mined primarily in the Congo. The latest developments on the raw materials market show just how volatile the price of this highly sought-after metal really is. In fact, it has tripled*	Battery cathode → Battery cell → Battery	Component	Costs of raw material → High costs	Difficult mining conditions

	within just two years [1], climbing 26 % within the first quarter of 2018 alone. Given mining conditions that are far from easy for such raw materials, the price is unlikely to drop.” (Burkert, 2018a, p. 12)				
ATZ Volume 120 Issue 09 Article 04	*“Moreover, the battery design must allow for automated recycling. Which makes a recycling model for old electric-vehicle batteries a top priority.” (Burkert, 2018a, p. 13)*	Battery	Component	Lack of capabilities → Low availability	-
		Disposal and recycling	Complement		
ATZ Volume 120 Issue 09 Article 04	*“With 10 million batteries from electrical vehicles alone, weighing anywhere between 10 and 100 kg, this will mean recycling systems having to handle several 100,000 t a year in Europe alone in future. If the recycling requirements from other applicable fields are also included, recycling capacities will be needed in 20 to 30 years’ time that we ought to be establishing now.” (Burkert, 2018a, p. 13)*	Disposal and recycling	Complement	Lack of capacities → Low availability	**Assumption:** Missing recycling plants
ATZ Volume 120 Issue 06 Article 03	*“A breakthrough in electric transport is only likely to come about when the infrastructure is extended, fully compatible with the products available and the financing issues have been resolved.” (Liebl, 2018b, p. 9)*	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	Expansion costs for infrastructure
ATZ Volume 120 Issue 05 Article 15	*“Electric mobility is one of the most outstanding present-day industrial issues. To boost prominence even more, both the charging points and grid infrastructure must be further expanded. And here, the focus has to be on developing technologies and concepts to accommodate electric vehicles within intelligent power grids in a user-friendly manner.” (Springer Fachmedien Wiesbaden, 2018, p. 64)*	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
		Electric grid	Complement	Performance fluctuations → Low performance	-

ATZ Volume 120 Issue 05 Article 14	*“Activating the air conditioning brings thermal management into play. This push of a button signifies a reduction in range of 25 to 45% in today’s electric vehicles.” (Teuschl et al., 2018, p. 61)*	HVAC → Thermal management	Component	Low performance	-
ATZ Volume 120 Issue 05 Article 14	*“Even when doubling the charging voltage, having the same battery size in terms of energy and cells results in the same issue on the cell level. The high current in the power cell substantially reduces the charging performance due to the coulomb losses generating heat.” (Teuschl et al., 2018, p. 61)*	Battery	Component	Long charging time → Low performance	Coulomb losses generating heat
ATZ Volume 120 Issue 05 Article 14	*“Preconditioning the battery system whilst driving is essential to achieve maximum charging speed, but leads to range restrictions and, in turn, to a quickly decreasing range on the dashboard.” (Teuschl et al., 2018, p. 61)*	Thermal management of battery → Thermal management	Component	Low performance	-
ATZ Volume 120 Issue 05 Article 04	*“For years, however, the capacity limit has been reached “because we simply cannot produce more batteries.” (Burkert, 2018b, p. 16)*	Battery production → Battery	Component	Lack of capacity → Low availability	Lack of production plants
ATZ Volume 120 Issue 03 Article 06	*“One of the main factors is the air conditioning in the vehicle, that is, cooling the interior in the summer and warming it in the winter. Experience from the field, along with test and simulation data, indicates that the cruising range at ambient winter temperatures can drop by 30 to 50 % relative to nominal values.” (Scharrer et al., 2018, p. 21)*	HVAC → Thermal Management	Component	Low performance	-
ATZ Volume 120 Issue 02 Article 17	*“Many people currently regard range, cost, and the availability of charging infrastructure as the major challenges facing e-vehicles.” (Rinderknecht, 2018, p. 74)*	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-

ATZ Volume 120 Issue 02 Article 14	*“Batteries in phones, laptops, and electric cars are now an essential part of our everyday lives. And to meet the expectations of today’s consumers, these batteries are becoming lighter in weight, more powerful, and longer lasting. Lithium-ion batteries are currently the most widely used commercial solution, but the technology is relatively expensive and can represent a risk if incorrectly used.” (Empa, 2018, p. 63)*	Battery	Component	High costs	-
				Safety risks → Low quality	Misuse behavior
ATZ Volume 120 Issue 02 Article 12	*“Besides the endeavors to keep the battery temperature in the optimal range, also the homogeneity of cooling is crucial. Any thermal gradient across the battery cells will inevitably create a misbalance within the cell – mechanically and chemically – causing a reduced performance over the lifetime of the battery.” (Frieß et al., 2018, p. 51)*	Battery	Component	Limited lifetime expectation → Low quality	Temperature sensitivity of the battery
ATZ Volume 120 Issue 02 Article 12	*“The most challenging scenario for cooling is by far the fast charging. The high current strengths necessary to charge the battery within a short time produces large amounts of heat. This is easily understood when bringing to one’s mind that the dissipated power depends quadratically on the current strength. On the other hand, it is crucial to keep the minimum temperature above the critical limit for lithium plating, meaning that the overall cooling power has to be restricted with regard to the coldest cell in the battery pack.” (Frieß et al., 2018, p. 51)*	Thermal management of battery → Thermal management	Component	High complexity → Low performance	Temperature sensitivity of the battery
ATZ Volume 120 Issue 02 Article 12	*“Here, more radical transformations are necessary to compete with conventional vehicles for market share on a large scale. In the following, a promising route along that line will be discussed. It is motivated by the reduction of battery costs as the key enabler to market access.” (Frieß et al., 2018, p. 52)*	Battery	Component	High costs	-

ATZ Volume 120 Issue 02 Article 04	*“In order to establish e-mobility, fast-charging points with a capacity of 350 kW each need to be set up across the country. If only 10 % of the 1 million electric cars called for by the German government by 2020 “fill up” at fast-charging points simultaneously, the electricity grid will have to provide 35 GW of capacity for this purpose – in addition to the normal electricity requirement. This is around half of German peak load and can only be assured through additional new power plants or storage facilities for volatile energy.” (Heintzel, 2018a, p. 12)*	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
		Electric grid	Complement	Performance fluctuations → Low performance	-
ATZ Volume 120 Issue 02 Article 03	*“The power transmission networks are only designed for moderate loads and cannot accommodate peak demand. The plan is to construct fast charging stations all over the country to allow electric transport to become established. However, the supply of electricity cannot be guaranteed, even if it is bought in from abroad.” (Liebl, 2018c, p. 9)*	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
		Electric grid	Complement	Performance fluctuations → Low performance	Peak loads
ATZ Volume 120 Issue 01 Article 14	*“The performance of state-of-the-art lithium-ion traction batteries is significantly lower at low as well as high temperatures. A battery temperature of 0 °C results in a 20 % decrease of battery efficiency compared to a battery temperature of 20 °C.” (Steiner et al., 2018, p. 63)*	Battery	Component	Low efficiency → Low performance	Temperature sensitivity of the battery
ATZ Volume 120 Issue 01 Article 14	*“Current EVs have the problem of a strongly varying driving range depending on the ambient conditions. At winter conditions and the use of resistance heating the driving range can drop by 50 %.” (Steiner et al., 2018, p. 62)*	Thermal management	Component	Low performance	-

IJoAT Volume 19 Issue 01 Article 12	*“Because of the limited energy storage ability on board, torque distribution optimization aiming at high-efficiency drive of FRMDEV as an effective way to improve energy efficiency and extend driving range is of high importance, but still lack of study.” (Sun et al., 2018, p. 122)*	Battery	Component	Limited capacity → Low performance	Limited energy storage ability
IJoAT Volume 19 Issue 01 Article 12	*“However, this conclusion ignores the negative effect of the non-work permanent magnet synchronous motor (PMSM) on system power loss, which has been overthrown by experiment tests carried out by Gu et al. (2013) as there still exists friction and iron losses in the motored PMSM.” (Sun et al., 2018, p. 122)*	E-Motor	Component	Low efficiency → Low performance	Friction and iron losses even when the PMSM is not working
IJoAT Volume 19 Issue 02 Article 12	*“Electric vehicle can effectively solve the energy crisis and environmental pollution. However, the composition of lithium battery is the largest cost problem to be solved for pure electric vehicles, which depends on the battery capacity, driving mileage and the charging station construction lags behind and so on.” (Boyan et al., 2018, p. 313)*	Battery	Component	High costs	More capacity means higher costs
		Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
IJoAT Volume 19 Issue 03 Article 18	*“Electric vehicles have emerged, at first, as the most promising solution to address the pollution problems which are increasingly critical. But several decades later, still victim of their low autonomy and the excessive cost of their batteries, they struggle to compete with conventional internal combustion engine-based vehicles.”* (Ouddah et al., 2018, p. 572)	Battery	Component	High costs	-
IJoAT Volume 19 Issue 04 Article 16	*“The EV batteries’ long recharging time, poor durability, weight, cost and short lifetime are causing the largest resistance to the EV mobility infrastructure development.” (Aksjonov et al., 2018, p. 728)*	Battery	Component	Long charging time; High weight → Low performance	-
				High costs	

				Limited lifetime expectation → Low quality	
IJoAT Volume 19 Issue 04 Article 16	*“Vehicle deceleration is a very fast process. In regenerative braking, huge amount of energy is released within a very short time. Most of the EV batteries are not able to save this energy.” (Aksjonov et al., 2018, p. 732)*	Battery	Component	Bad dynamic behavior → Low performance	-
IJoAT Volume 19 Issue 05 Article 12	*“As a relatively small battery can cover most journeys, a larger battery would lead to excessive weight, which would then increase the energy consumption.” (Herold et al., 2018, p. 870)*	Battery	Component	High weight → Low performance	Heavy batteries to reach an acceptable driving range
ATZ Volume 119 Issue 12 Article 08	*“A decisive acceptance factor in e-mobility is trouble-free and fast charging. In addition to large-scale charging parks at high-performance grid connections, decentralized fast chargers will also be needed in the distribution grids.” (Ads-Tec, 2017, p. 34)*	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
ATZ Volume 119 Issue 12 Article 01	*“Let’s take a look at what is happening in Norway, Europe’s environmental role model. Here 98 % of the electricity is generated by predictable hydropower. But the problem is that the growth in the charging station infrastructure cannot keep pace with the registrations of electric cars. The Norwegian association for electric cars has recently advised the country’s citizens not to buy an e-model.” (Heintzel, 2017, p. 3)*	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	Infrastructure growth cannot keep pace with the registration of new EVs
ATZ Volume 119 Issue 11 Article 16	*“Electric mobility is nowadays becoming increasingly attractive for the automotive industry. However, the low energy density of on-board batteries presents pure electric vehicles with a challenge of range limitation.” (Shen et al., 2017, p. 69)*	Battery	Component	Limited range → Low performance	Low energy density

ATZ Volume 119 Issue 11 Article 07	*“As a rule of thumb, a battery ages twice as quickly for each 10-K increase in temperature. In principle, this behavior has been replicated in measurements by Akasol on various cells in the relevant region between 35 and 65 °C. Conversely, excessively low temperatures also lead to problems as they generally cause a sharp drop in output and especially as they often necessitate significant restrictions on charging current.” (Eberleh and Raiser, 2017, p. 30)*	Battery	Component	Long charging time → Low performance	Temperature sensitivity of the battery
				Limited lifetime expectation → Low quality	Temperature sensitivity of the battery accelerates aging
ATZ Volume 119 Issue 10 Article 06	*“European legislation on the further implementation of the COP 21 Paris Agreement will also result in growth in electric mobility, which in the early stages will be strongly influenced by legislation, but it still requires a significant establishment and expansion of the charging infrastructure as well as measures to persuade the market to accept changes.” (Gutzmer, 2017, p. 23)*	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
ATZ Volume 119 Issue 10 Article 05	*“In order to pave the way for a successful market launch of EV the well-known inhibitors, in other words limited ranges and time-consuming re-charging, should be addressed directly. Hence, the presented article promotes the technology of rapid charging as a potential measure capable of facing the perceptual bias described before.” (Ladwig et al., 2017, p. 18)*	Charging station → Electric charging infrastructure	Complement	Long charging time → Low performance	-
ATZ Volume 119 Issue 09 Article 12	*“Another requirement for modern electric mobility is significantly shorter charging times for the electric energy store, which is currently still quite long. In contrast to filling a tank with fuel, however, charging a battery is subject to losses due to physical constraints. The faster the charging process, the higher the electrical current needed and thus the higher the losses due to heat.” (Wawzyniak et al., 2017, p. 49)*	Battery	Component	Long charging time → Low performance	High currents lead to high heat losses

ATZ Volume 119 Issue 09 Article 12	*“Thermal management is a key technology for the acceptance of electric mobility, in terms of battery service life and range, drive system performance, and passenger comfort. In order to address the various thermal issues, coolant circuits at different temperature levels are required.” (Wawzyniak et al., 2017, p. 46)*	Thermal Management	Component	High complexity → Low performance	-
ATZ Volume 119 Issue 09 Article 11	*“The thermal management, the efficient control of all energy flows within the vehicle and the conditioning of the passenger compartment, has a significant impact to maximum driving range, fuel consumption and CO2 emissions. The strategies for heating and cooling of high voltage batteries (HV batteries) of electric vehicles need to be implemented in combination with Heating, Ventilation and Air Conditioning (HVAC) for the passenger compartment, taking into account all operational and driving conditions. Heating and cooling of the passenger compartment in order to optimize the passenger comfort is likely to become even more important in future. The upcoming trade-offs between comfort and consumption need to be solved under consideration of smart thermal management control strategies.” (Drage et al., 2017, p. 42)*	Thermal management of battery → Thermal management	Component	High complexity → Low performance	A tradeoff between comfort and energy consumption
		HVAC → Thermal management			
ATZ Volume 119 Issue 05 Article 14	*“Lithium-ion batteries, which are the most efficient systems currently available, dominate the market for mobile energy storage. But due to limited reserves the raw material is becoming increasingly expensive. There is a need for alternative storage technologies and material systems with high energy densities that use readily available raw materials.” (TU Bergakademie Freiberg, 2017, p. 62)*	Battery	Component	Costs of raw material → High costs	Limited reserves

ATZ Volume 119 Issue 05 Article 13	*“Upgrading charging infrastructure to higher charging power is ongoing. Nevertheless, a widespread installation of rapid charging stations will be limited by the costs for grid connection and the available and transferable amount of electric energy. Moreover, rapid charging may shorten the expected lifetime of batteries drastically.” (Müller et al., 2017, p. 56)*	Battery	Component	Limited lifetime expectation → Low quality	Fast charging
		Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	High costs for expansion
ATZ Volume 119 Issue 03 Article 14	*“The batteries in electric cars are made from lithium cells, which are highly flammable.” (Ruhr-University Bochum, 2017, p. 64)*	Battery cell → Battery	Component	Safety risk → Low quality	Flammability of Lithium
ATZ Volume 119 Issue 02 Article 12	*“Generally speaking, the severe deformation of a cell or the penetration of an external object into the cell leads to damage of the separator layers in the cell, which in turn lead to a cell internal short-circuit between the cathode and anode. The consequences can be cell venting, formation of thick smoke and even cell fire.” (Brunnsteiner et al., 2017, p. 57)*	Battery cell → Battery	Component	Safety risks → Low quality	Battery penetration or internal short-circuits
ATZ Volume 119 Issue 02 Article 12	*“In order to maintain the acceptance of battery-driven electric vehicles (BEVs), there are diverse challenges like optimized driving range and lifetime of the batteries or reduced costs. However, over all of these challenges, there is one essential: safety. Beside the prediction of electrical short-circuits or cooling system leakage, for AVL this is understanding of the Li-ion cell from a safety-relevant point of view.” (Brunnsteiner et al., 2017, p. 55)*	Battery	Component	Lifetime expectations; Safety risks → Low quality	-
				High costs	-
				Limited range → Low performance	-

ATZ Volume 119 Issue 02 Article 12	*“One of the goals in high voltage traction batteries (HV batteries) based on Lithium-ion(Li) technology is the prevention of electrical short-circuits in the high voltage system, even after severe distortion for example, after an accident. Another goal is the protection of the Li-ion cells in the HV battery from heat, penetration by sharp objects or severe mechanical loading. If the previously mentioned challenge of customer acceptance is to be met, a safe battery design is required.”* (Brunnsteiner et al., 2017, p. 54)	Battery	Component	Safety risks → Low quality	-
ATZ Volume 119 Issue 01 Article 17	*“The Mission E concept with its 800-V technology represents our vision for future mobility: technological progress in the electrification of the drivetrain combined with digitalization and connectivity, such as the ability to pay at the charging station. In the future, simply overcoming technical limitations will not be enough – the introduction of e-mobility is an economic task, as it will only be possible to provide real added value to the mobility users of tomorrow with a standardized infrastructure with a high level of availability.”* (Steiner, 2017, p. 78)	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
		Digital integration → Electric charging infrastructure	Complement	Missing interoperability → Low performance	Missing digitalization and connectivity
ATZ Volume 119 Issue 01 Article 17	*“The increasing range of E-vehicles does however present a new dilemma – if the destination lies outside the action radius of the vehicle, then the battery must be recharged on the way, since an unchanged charging output means the charging time increases proportionally with the capacity of the battery. This means that drivers must take long breaks, hugely increasing the duration of a journey and quickly putting the advantages of a large range into perspective. In the future, charging speed will therefore be just as important as top speed. To make the charging process*	Charging station → Electric charging infrastructure	Complement	Long charging time → Low performance	Charging station power

	as fast as conventional refueling, significantly higher performance than that supplied by 50-kW DC fast-charging stations is required.” (Steiner, 2017, p. 78)				
ATZ Volume 119 Issue 01 Article 07	*“Furthermore, specific components of electric vehicles, like the traction battery or power electronics have to be conditioned within certain temperature limits in order to ensure functionality and extend their life span.” (Rabl et al., 2017, p. 27)*	Thermal management of battery → Thermal management Thermal management of power electronics → Thermal management	Component	High complexity → Low performance	Temperature sensitivity of components
ATZ Volume 119 Issue 01 Article 07	*“Since driving range currently is the biggest influencing factor when it comes to customer acceptance of electric vehicles, the energetic optimization of vehicle’s air conditioning systems comes to the fore. Therefore, it is imperative to significantly lower the total energy demand under all ambient and operating conditions.” (Rabl et al., 2017, p. 27)*	HVAC → Thermal management	Component	Low performance	-
ATZ Volume 119 Issue 01 Article 04	*“The thermal management of cars, in other words, heating and cooling the interior, needs to be made more efficient and more environmentally friendly. In particular in the case of electric cars, the consumption of the energy on board the vehicle must be kept as low as possible. The electricity stored in the battery should primarily be used to move the car. It is important that the range of battery-electric vehicles is not reduced in order to improve the well-being of the passengers.” (Reichenbach, 2017, p. 15)*	HVAC → Thermal management	Component	Low efficiency → Low performance	-

IJoAT Volume 18 Issue 01 Article 12	*“Safety issue of lithium-ion battery is crucial in automotive application of lithium-ion battery. Lithium-ion batteries have potential to undergo exothermic reaction so called thermal runaway which may lead to catastrophic event such as explosion or fire when the batteries are exposed to high temperature condition.” (Jung et al., 2017, p. 117)*	Battery	Component	Safety risks → Low quality	The danger of explosion or fire
IJoAT Volume 18 Issue 01 Article 12	*“In addition, although it depends on the battery type, conventional lithium-ion batteries suffer from severe degradation such as capacity fade and resistance growth accompanied by various side reactions under high temperature condition.” (Jung et al., 2017, p. 117)*	Battery	Component	Limited lifetime expectation → Low quality	Capacity fade due to temperature sensitivity
IJoAT Volume 18 Issue 04 Article 07	*“Especially, in battery electric vehicles (BEV), light weighting becomes more stringent issue, because their batteries take more than 10 % of the car weight.” (Yoo et al., 2017, p. 625)*	Battery	Component	High weight → Low performance	-
IJoAT Volume 18 Issue 04 Article 13	*“However, shorter driving range due to limited energy density is one of the major limitations faced by electric vehicles as compared to conventional vehicles.” (Zhao et al., 2017, p. 686)*	Battery	Component	Limited range → Low performance	Limited energy density
IJoAT Volume 18 Issue 05 Article 12	*“Battery high discharged currents are causes of warming battery’s cells. The temperature of 40 ºC and above reduces battery life span.” (Ataur et al., 2017, p. 875)*	Battery	Component	Limited lifetime expectation → Low quality	Temperature sensitivity of battery
IJoAT Volume 18 Issue 05 Article 12	*“Heat control and management is one of the most important issues in the lithium-ion batteries at high charge/discharge rate.” (Ataur et al., 2017, p. 876)*	Thermal management of battery → Thermal management	Component	High complexity → Low performance	-

IJoAT Volume 18 Issue 05 Article 12	*“They have reported that the Li-ion battery capacity drops seriously under low temperature and temperature above 60°.” (Ataur et al., 2017, p. 876)*	Battery	Component	Limited capacity → Low performance	Temperature sensitivity of batteries limits operation capacity
ATZ Volume 118 Issue 12 Article 13	*“Germany’s chancellor Angela Merkel wants to see one million electric vehicles on the country’s roads by 2020. However, they are not proving easy to sell. Potential buyers are being discouraged by the short range of the batteries and the high price of the cars.” (University of Mannheim, 2016, p. 54)*	Battery	Component	Limited range → Low performance	-
ATZ Volume 118 Issue 12 Article 03	*“Electric mobility is expanding on a number of different levels. The cost and the range of electric cars are improving as the technology becomes more advanced, but it is difficult to speed up this process. However, faster progress is needed in designing payment systems to charge for the electricity that has been used. In this case all the stakeholders need to apply the same standards.” (Siebel, 2016, p. 13)*	Charging station → Electric charging infrastructure	Complement	Missing interoperability → Low performance	Standardization issue for power ordering system
ATZ Volume 118 Issue 12 Article 03	*“Some locations were not suitable for charging stations because the capacity of the electric power lines was inadequate. If he had insisted that charging stations were installed in the chosen places, the grid operator would have had to pay around 15,000 euros to increase the grid capacity on top of the 5000 euros for the charging station itself. “A lot of small problems can make the installation difficult and quickly bring everything to a standstill.” (Siebel, 2016, p. 11)*	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	Costs of expansion of the charging infrastructure
		Electric Grid	Complement	Performance fluctuations → Low performance	Costs of expansion of the charging infrastructure
ATZ Volume 118 Issue 10 Article 16	*“In electric cars, using electricity to heat the passenger compartment in winter can reduce the range by up to 50 %. Heat pumps can compensate for this problem to a certain extent, but in the case of R1234yf heat pumps*	HVAC → Thermal management	Component	Low performance	Electrically powered components for

	this is only possible at ambient temperatures no lower than -5 °C.” (Großmann, 2016, p. 70)				heating and cooling
ATZ Volume 118 Issue 10 Article 06	*“The concerns in this area are understandable, but in my opinion, there is a bottleneck in the production of battery cells over the next five to ten years, because the electric vehicle market will enjoy lasting success during this period.”* (Kagermann, 2016, p. 23)	Battery production → Battery	Component	Lack of capacity → Low availability	-
ATZ Volume 118 Issue 10 Article 01	*“The success of the new measure can easily be evaluated. In 2015 only 0.7 % of new vehicles registered in Germany were electric cars, while in the Netherlands the figure was 10 % and in Norway 23 %, because the infrastructure in these countries is widely established. Thanks to the subsidy, 936 German buyers had opted for electric vehicles by 14 July and 1523 by 29 July. If the charging infrastructure is extended in Germany, the growth rate should increase even further.”* (Reichenbach, 2016b, p. 3)	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
ATZ Volume 118 Issue 09 Article 16	*“Since the grids cannot support static charging with off-peak electricity, a charging infrastructure is urgently required that has electronically controlled charging. It is important that the next step is to enable bi-directional charging of vehicles.”* (Heintzel, 2016, p. 71)	Charging station → Electric charging infrastructure	Complement	Low performance	Electronically controlled charging not possible
ATZ Volume 118 Issue 09 Article 02	*“In order to allay customers’ fears about the range of electric cars, large sums will be invested in developing the public charging infrastructure between now and 2020. A total of 100 million euros will be spent on conventional charging stations and 200 million on fast ones. I cannot understand why the German government is investing in conventional technology*	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	High costs for the expansion of the fast charging infrastructure

	which many people already have at home. Alongside the development of battery technology, the creation of a dense network of fast charging stations is the key to the breakthrough of electric vehicles.” (Liebl, 2016, p. 7)			Long charging time → Low performance	Power of the available charging stations
ATZ Volume 118 Issue 07/08 Article 10	*“Beyond high purchase price and the inadequate charging infrastructure, potential buyers cite limited range as an important deterrent to the acquisition of an electric vehicle [1]. Climate control systems in electric vehicles must be operated using energy from the traction batteries, which further reduces range.” (Nerling et al., 2016, p. 38)*	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
		HVAC → Thermal management	Component	Low performance	Usage of electric energy for cooling and heating
ATZ Volume 118 Issue 07/08 Article 10	*“The limited range of electric vehicles is additionally reduced through the thermal conditioning of the passenger compartment. Due to the vehicle mass’ high thermal storage capacity the energy necessary for heating up and cooling of the passenger compartment is comparatively high.” (Nerling et al., 2016, p. 38)*	HVAC → Thermal management	Component	Low performance	Usage of electric energy for cooling and heating
ATZ Volume 118 Issue 07/08 Article 03	*“In the long term, the energy density of batteries will remain very low when compared with that of many fuels. The charging infrastructure is difficult to use in precisely the area where it is really needed: our cities. And vehicles suitable for long-distance travel come with heavy batteries and long charging time.” (Goppelt, 2016, p. 9)*	Battery	Component	Long charging time → Low performance	-
				High weight → Low performance	Low energy density
		Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-

ATZ Volume 118 Issue 06 Article 12	*"The range of electric vehicles is reduced in particular in winter by the need for climate control and interior heating. For this reason, the joint project "Integrated thermal management in electric cars" (GaTE) has been established by Mahle, Bosch, Daimler, sitronic and the Research Institute of Automotive Engineering and Vehicle Engines Stuttgart (FKFS) with the aim of improving thermal management in order to significantly reduce the electric energy needed for heating the vehicle and keeping the powertrain components at the correct temperature." (Mahle, 2016, p. 55)*	Thermal Management	Component	Low efficiency → Low performance	High energy requirements for cooling and heating
ATZ Volume 118 Issue 06 Article 12	*"By 2020, there will be one million electric cars on German roads if the German government achieves its target. The most common reasons why many consumers are still not choosing this environmentally friendly alternative to gasoline-or diesel-engined vehicles are the long charging times for the battery and the short range of the cars." (University of Ulm, 2016, p. 55)*	Battery	Component	Long charging time → Low performance	-
ATZ Volume 118 Issue 05 Article 16	*"When outside temperatures are low, the range can be reduced by up to 47 %, while the comfort of the interior of the electric vehicles is also limited. Under certain conditions, a 5 kW PTC heating system, which is a common choice today, is no longer able to reach the comfort temperature within the cycle when the outside temperature is lower than -10 °C." (Minnrich et al., 2016, p. 77)*	HVAC → Thermal management	Component	Low performance	High energy requirements for cooling and heating

ATZ Volume 118 Issue 05 Article 16	*“Battery electric vehicles (BEVs) are limited in their range and are also restricted in terms of the comfort they offer when compared with conventional vehicles, particularly in the winter. The reason for this lack of comfort lies primarily in the considerably greater efficiency of the electric power train. Consequently, thermal losses cannot be used to heat the passenger compartment. This is why, in addition to the operating power, the battery also has to provide the electric heating energy.” (Minnrich et al., 2016, p. 75)*	HVAC → Thermal management	Component	Low performance	The battery must provide electric heating energy
ATZ Volume 118 Issue 05 Article 07	*“Not only a low battery capacity contributes to the restriction of electric vehicle ranges, but also wind and weather have a great influence. In the GreenNavigation project and on the basis of weather data, Bosch, FZI and IPG investigate the meteorological influence on the energy demand and lay down a range usage optimization.” (Viehl et al., 2016, p. 26)*	Battery	Component	Limited range → Low performance	-
ATZ Volume 118 Issue 05 Article 04	*“With its SpeedE project, it wants to make the extensive innovation potential of battery-powered vehicles tangible. Bosch, FZI and IPG are focusing their work on battery range, which is still too low, by examining the meteorological influence on energy requirements in the GreenNavigation project.” (Reichenbach, 2016a, p. 15)*	Battery	Component	Limited range → Low performance	-
ATZ Volume 118 Issue 02 Article 08	*“Ageing is a key issue with lithium-ion batteries, because it significantly reduces their potential storage capacity. However, research into the reasons behind this is still ongoing in academic institutions and in industry.” (Technical University of Munich, 2016, p. 33)*	Battery	Component	Limited lifetime expectation → Low quality	Aging effect
IJoAT Volume 17 Issue 01 Article 15	*“In this regard, the aging effect can also become a critical problem for driving motors. As a result, motor parameters can change significantly under those different working conditions. More importantly, motor*	E-Motor	Component	Limited lifetime expectation → Low quality	Aging effect

	life will be affected too which can increase the possibility of sudden failures that are unacceptable for any fast-moving vehicle." (Liu et al., 2016, p. 153)				
IJoAT Volume 17 Issue 01 Article 15	*"Considering the aging phenomenon during the lifetime of motors, magnet capability can remain only 70 % of their original value at the end of their lives for permanent magnet motors." (Liu et al., 2016, p. 155)*	E-Motor	Component	Limited lifetime expectation → Low quality	Aging effect
IJoAT Volume 17 Issue 02 Article 16	*"The lithium ion moves in the battery by diffusion according to the input current. Therefore, a sudden and large change of current causes great nonuniform distribution of the concentration, which damages the battery." (Jung et al., 2016, p. 342)*	Battery	Component	Limited lifetime expectation → Low quality	Damaging effect due to significant change of current
IJoAT Volume 17 Issue 03 Article 12	*"One of the cell degradation modes for lithium-ion batteries reported in the literature is the loss of lithium inventory (LLI) (Dubarry et al., 2012). This takes place mainly due to the constant formation and growth of the solid electrolyte interface (SEI), which consumes lithium that therefore cannot be used anymore for the main cell reaction." (Marongiu and Sauer, 2016, p. 467)*	Battery cell → Battery	Component	Limited lifetime expectation → Low quality	Loss of Lithium
IJoAT Volume 17 Issue 03 Article 12	*"Another phenomenon which causes LLI is lithium plating. As shown in Figure 3 (b)), the main consequence of the LLI is the shifting of the cathode voltage curve in respect to the anode curve. This results in a cell capacity reduction and a change of the length of plateau IIIA." (Marongiu and Sauer, 2016, p. 467)*	Battery cell → Battery	Component	Limited lifetime expectation → Low quality	Loss of Lithium
IJoAT Volume 17 Issue 03 Article 15	*"When a LIB is in service, either under storage or during an automotive duty cycle, it is subject to a loss of capacity and power. As the battery ages, its physicochemical characteristics, such as the kinetic and transport quantities of Li(-ion), can change ." (Sung et al., 2016, p. 493)*	Battery	Component	Limited lifetime expectation → Low quality	Aging effect

IJoAT Volume 17 Issue 03 Article 16	*“The connection between battery volume and vehicle weight is very noticeable in terms of energy constraints, because a bigger battery to increase the range also increases the weight and thus, consumption.” (Roche et al., 2016, p. 513)*	Battery	Component	High weight → Low performance	To increase the range, the battery gets heavier
IJoAT Volume 17 Issue 05 Article 16	*“The representative issue of the BMS is the ability to monitor the charging status of the battery pack, namely the state-of-charge (SOC). Highly accurate SOC information provides reliability and safety to the battery pack by prohibiting over-discharging and over-charging that can cause permanent internal damage.” (Chun et al., 2016, p. 910)*	Battery management system → Battery	Component	High complexity → Low performance	Difficulties in SoC estimation
IJoAT Volume 17 Issue 06 Article 05	*“Although the EV (Electric Vehicle) and PHEV (Plug-in Hybrid Electric Vehicle) are considered as one of the solution for relieving exhaust gases and traffics, their commercialization has been delayed due to the lack of relevant regulations, policies and charging infrastructures.” (Kim, 2016, p. 977)*	Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
IJoAT Volume 17 Issue 06 Article 17	*“Electric vehicles (EV) are one possible solution because they have no emissions as they are powered by electricity. However, their short travel due to their limited battery capacity is a major drawback.” (Pi et al., 2016, p. 1101)*	Battery	Component	Limited range → Low performance	-
ATZ Volume 117 Issue 09 Article 11	*“To achieve a thermally comfortable indoor climate in electric vehicle models, the air masses are heated electrically or by load shifts overheat pump processes [2]. In these cases, the required energy is not available for the driving powers anymore, which can limit the range of the vehicle – in extreme cases even to 50 %.” (Schmidt and van Treeck, 2015, p. 57)*	HVAC → Thermal management	Component	Low performance	Battery must provide electric heating energy

ATZ Volume 117 Issue 09 Article 10	*“Due to the low energy density of the electrochemical storages that are used in electric vehicles, the BEV’s range is nevertheless not comparable to that of conventional vehicles.” (Eghtessad et al., 2015, p. 49)*	Battery	Component	Limited range → Low performance	Low energy density
ATZ Volume 117 Issue 09 Article 10	*“To attract a broader customer base for pure electric vehicles, conflicting goals need to be solved, for example reducing the costs of the battery and simultaneously increasing the achievable electric range.” (Eghtessad et al., 2015, p. 48)*	Battery	Component	High costs	-
ATZ Volume 117 Issue 07/08 Article 12	*“Even if a heat pump is used, some of the energy to heat the cabin has to be drawn from the battery. The problem is aggravated at low temperatures due to the reduced discharge capacity of the battery. In warm weather not only the vehicle cabin but also the battery has to be cooled. Typically, the required refrigerant compressor power is drawn from the battery. The heat deficit in winter and the required cooling capacity in summer result in a significantly shorter range for these conditions.” (Auer et al., 2015, p. 65)*	HVAC → Thermal management	Component	Low performance	The battery must provide electric heating energy
		Thermal management of battery → Thermal management	Component		The battery must provide electric heating energy
ATZ Volume 117 Issue 07/08 Article 12	*“One of the main topics of the battery electric vehicle is the low range. Serious efforts are being undertaken to increase the range, or respectively to reduce the cost of batteries for an equal range.”(Auer et al., 2015, p. 64)*	Battery	Component	High costs	-
ATZ Volume 117 Issue 07/08 Article 07	*“As they do so, climate control represents a major challenge. For example, a battery’s usable electricity depends on its temperature, which means that low temperatures result in reduced range. Furthermore, there is an increased need for heat energy to provide climate control in the passenger compartment, which in turn limits a vehicle’s range.” (Kritzer et al., 2015, p. 33)*	HVAC → Thermal management	Component	Low performance	The battery must provide electric heating energy

ATZ Volume 117 Issue 07/08 Article 06	*“A comprehensive market penetration of electromobility has been hampered to date by various acceptance issues. Significant amongst them are the limited driving range and higher capital costs both affected by the batteries.” (Barkow et al., 2015, p. 27)*	Battery	Component	Limited range → Low performance	-
				High costs	-
ATZ Volume 117 Issue 07/08 Article 03	*“The storage elements in an electric vehicle (EV) remain a key challenge to wide-scale, successful deployment of EVs that are appealing to customers and are adequately functional (for example in terms of range).” (Funcke et al., 2015, p. 11)*	Battery	Component	Limited range → Low performance	-
ATZ Volume 117 Issue 07/08 Article 03	*“These require high level safety measures to avoid for example mechanical damage of the cells, which increases the pack mass and reduces the propulsion efficiency of the vehicle.” (Funcke et al., 2015, p. 11)*	Battery	Component	Safety risks → Low quality	-
ATZ Volume 117 Issue 04 Article 10	*“These new requirements for future vehicle concepts are diverse. For one thing, lightweight design is an important key technology in electric vehicles in order to compensate for the battery's added weight and thus to achieve sufficient range.” (Höfer et al., 2015, p. 49)*	Battery	Component	High weight → Low performance	Heavy batteries are necessary to achieve a sufficient range
ATZ Volume 117 Issue 03 Article 07	*“One example is the decreasing capacity of a battery over its lifetime depending not only on the operation profile but also on the battery technology in use.” (Kampker et al., 2015, p. 29)*	Battery	Component	Limited lifetime expectation → Low quality	Decreasing battery capacity
ATZ Volume 117 Issue 03 Article 07	*“What are the impacts of adding a number of electric vehicles to an existing fleet, which reliably operates a fixed set of routes in its current configuration? It is the capacity of the battery that often limits the operational range of an electric vehicle.” (Kampker et al., 2015, p. 29)*	Battery	Component	Limited range → Low performance	-

ATZ Volume 117 Issue 03 Article 04	*“However, the chemical safety of the high-energy compositions will decrease significantly. Therefore, the monitoring of the battery cells becomes increasingly crucial.” (Nalbach and Wagner, 2015, p. 17)*	Battery cell → Battery	Component	Safety risks → Low quality	-
ATZ Volume 117 Issue 02 Article 05	*“The air conditioning system is one of the most relevant auxiliary consumers in a passenger car with a significant energy demand. Especially for hybrid and electrical vehicles the waste heat, which is produced by the conventional internal combustion engine, is drastically diminished, or even completely missing. If this is compensated by means of electric heating elements, the driving range is decreased significantly.” (Steiner et al., 2015, p. 20)*	HVAC → Thermal management	Component	Low performance	The battery must provide electric heating and cooling energy
ATZ Volume 117 Issue 01 Article 05	*“A strong constraint of the high-voltage battery with respect to its loading capacity takes place in particular at low temperatures.” (Sawazki et al., 2015, p. 22)*	Battery	Component	Long charging time → Low performance	Temperature sensitivity of the batteries
ATZ Volume 117 Issue 01 Article 05	*“The experiences from the first phase of electromobility have shown that a cool ambient environment significantly limits the range of electric vehicles. In contrast to vehicles with an internal combustion engine, at low temperatures the heating energy is received from the high-voltage battery. Depending on the outside temperature and the interior space requirements, the used heating energy amounts to up to 50 % of the total energy consumption.” (Sawazki et al., 2015, p. 20)*	Thermal Management	Component	Low performance	The battery must provide electric heating and cooling energy
IJoAT Volume 16 Issue 02 Article 15	*“According to recent studies, solvent decomposition by oxidation reactions finally cause loss of active material in LiMn2O4 spinel cathode.” (Baek et al., 2015, p. 311)*	Battery cathode → Battery cell → Battery	Component	Limited lifetime expectation → Low quality	Capacity fade due to loss of active material

IJoAT Volume 16 Issue 02 Article 15	*“One of well-known cause of capacity fade is film formation on the surface of active materials especially in the anode. The film grows due to the side reactions, a phenomenon which is not clearly known yet.” (Baek et al., 2015, p. 312)*	Battery anode → Battery cell → Battery	Component	Limited lifetime expectation → Low quality	Capacity fade due to film formation
IJoAT Volume 16 Issue 03 Article 01	*“One of the main challenges for its market success is the electric driving range achievable with the current battery technology, which allows the vehicle to store only a small fraction of the energy available using conventional fuels, such as gasoline or Diesel oil.” (Mattarelli et al., 2015, p. 351)*	Battery	Component	Limited range → Low performance	Low energy density
IJoAT Volume 16 Issue 03 Article 15	*“There has been an advent of the production BEVs in recent years; however their low range and high cost still remain the two important drawbacks. The battery is the element which strongly affects the cost and range of the BEV.” (Dhand and Pullen, 2015b, p. 487)*	Battery	Component	High costs	-
				Limited range → Low performance	
IJoAT Volume 16 Issue 03 Article 15	*“At present the most important bottleneck in BEVs is the battery itself, which strongly affects the range and cost of the BEV.” (Dhand and Pullen, 2015b, p. 488)*	Battery	Component	High costs	-
				Limited range → Low performance	
IJoAT Volume 16 Issue 04 Article 17	*“However, the road towards total vehicle electrification still poses some big challenges [..]. Currently, the main hurdle resides in the battery technology […]: compared with liquid fuels, they display much lower specific energy, energy density and refueling/ recharging rate. The issues of limited driving range and long charging time are both centered on the battery package of the car.” (Gebrehiwot and van den Bossche, 2015, p. 707)*	Battery	Component	Limited range → Low performance	Limited energy density
				Long charging time → Low performance	Low recharging rate

IJoAT Volume 16 Issue 05 Article 13	*“Furthermore, the high initial manufacturing cost of BEVs, most particularly due to the high battery cost offsets any advantages of the inexpensive electrical energy used to power them.” (Li et al., 2015, p. 827)*	Battery	Component	High costs	-
IJoAT Volume 16 Issue 05 Article 13	*“Unlike gasoline refueling, however, BEV charging takes time, requiring as much as 7 hours to fully charge a Nissan Leaf BEV.” (Li et al., 2015, p. 827)*	Battery	Component	Long charging time → Low performance	-
IJoAT Volume 16 Issue 05 Article 13	*“One of the long-term goals for EV infrastructure is the fast charging capability which allows EV batteries to be fully recharged within a short time. However, the upgrade involves considerable investment and is not practical at the present time.” (Li et al., 2015, p. 834)*	Charging station → Electric charging infrastructure	Complement	Long charging time → Low performance	Charging stations do not have the power for fast charging
				Lack of infrastructure → Low availability	High investment costs
IJoAT Volume 16 Issue 06 Article 04	*“Most current electric vehicles are equipped with high-capacity batteries and fueled with limited electrical energy […]. Electric vehicles are thus inferior, in terms of cruising range, to conventional vehicles that are equipped with internal combustion engines. Turning on the air conditioner or heater makes it even worse. Particularly in winter, when conventional vehicles heat cabin room by using engine coolant from the heat exchanger of air handing system, electric vehicles use an electric heater because they do not have such a source of heat from coolant. Much consideration is therefore given to the application of heat pump systems.” (Lee, 2015, p. 923)*	Battery	Component	Limited range → Low performance	Limited electrical energy
		HVAC → Thermal management	Component	Low performance	-

IJoAT Volume 16 Issue 06 Article 12	*“Electric vehicles (EVs) are becoming more and more popular because of the high fossil fuel prices and strict emission rules […]. However, even the lithium-based batteries possess a low specific energy (90 ~ 180 Wh/kg); therefore, heavy vehicles require large quantity of batteries. Moreover, lithium-based batteries are pricey (350$/kWh).”* (Tanik and Parlaktaş, 2015, p. 997)	Battery	Component	Limited capacity → Low performance	Low specific energy
				High costs	-
IJoAT Volume 16 Issue 06 Article 12	*“Unless a new type of battery that costs under 100$/kWh is invented, producing a low cost compact electric car which is also competitive in price seems not possible.” (Tanik and Parlaktaş, 2015, p. 997)*	Battery	Component	High costs	-
IJoAT Volume 16 Issue 06 Article 13	*“For the cask effect of the battery, namely the battery performance and life are determined by the worst cell, the lifetime of the battery is short, and the electric vehicle using the battery cannot popularize in the present.” (Cui and Zhang, 2015, p. 1007)*	Battery	Component	Limited lifetime expectation → Low quality	-
IJoAT Volume 16 Issue 06 Article 13	*“The battery equalization management technology is the core technology of the BMS. The equalization system in present has low equalization efficiency.” (Cui and Zhang, 2015, p. 1015)*	Battery management system → Battery	Component	Low efficiency → Low performance	-
ATZ Volume 116 Issue 11 Article 01	*“A second important point is the necessary infrastructure. Many potential purchasers of electric cars do not have their own charging facility. For that reason, if local authorities, cities and companies do not make vigorous efforts to address this problem, electric mobility will remain a marginal phenomenon.” (Heintzel, 2014, p. 3)*	Charging Station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
ATZ Volume 116 Issue 10 Article 10	*“Figure 6 shows a qualitative comparison of various mobile energy storage units. It shows that chemical and electrical systems offer relatively high energy densities, but due to their lower power densities, large units are*	Battery	Component	Bad dynamic behavior → Low performance	Low power density

	required to supply the required power." (Bader et al., 2014, p. 42)				
ATZ Volume 116 Issue 07/08 Article 02	*"The challenge to be addressed within the framework of electromobility involves the low waste heat volumes at low temperature levels for the electrical drivetrain, the significantly stronger influence of the heating and interior cooling on the range, and the greater temperature dependency of the electronic components like the high voltage battery." (Suck and Spengler, 2014, p. 9)*	HVAC → Thermal management	Component	Low performance	-
		Thermal management of battery → Thermal management	Component	High complexity → Low performance	Temperature sensitivity
ATZ Volume 116 Issue 07/08 Article 02	*"The component most sensitive to temperature is the HV accumulator. At excessively low temperatures below the range between 5 and 0 °C, neither sufficient electric power can be taken from the battery nor can the battery be recuperated." (Suck and Spengler, 2014, p. 7)*	Battery	Component	Low efficiency → Low performance	Temperature sensitivity of the battery
ATZ Volume 116 Issue 07/08 Article 02	*"To an increasing extent, large auxiliary consumers such as the heating (up to 5 kW) or air conditioning (up to 5.5 kW) are becoming the focus of examination. Depending on the use case, the consumption for heating and air conditioning can be in the range of that for forward momentum. The consequence of this is that the range can be significantly reduced depending on the outside temperature. Also, the challenges already mentioned, it is important to note that the electrical components are significantly more sensitive to the effects of temperature." (Suck and Spengler, 2014, p. 5)*	Thermal management	Component	Low performance	The battery must provide electric heating and cooling energy

ATZ Volume 116 Issue 07/08 Article 02	*“The major challenge in the area of electromobility is the significantly lower energy content of the high voltage (HV) battery in comparison to the fuel tank. The HV battery of the electric car BMW i3, for example, has a capacity of 18.8 kWh. A liter of gasoline, on the other hand, has a calorific value of 9.3 kWh/l.” (Suck and Spengler, 2014, p. 5)*	Battery	Component	Limited capacity → Low performance	Low energy content
ATZ Volume 116 Issue 05 Article 03	*“The two focuses of body development for such pure electric driven vehicles are lightweight design and cost efficiency, in order to compensate at least partially the weight and cost caused by the power batteries and to maximize the achievable driving range of the vehicle.” (Fang et al., 2014, p. 10)*	Battery	Component	High weight → Low performance	-
				High costs	-
ATZ Volume 116 Issue 04 Article 13	*“Lithium ion batteries are currently not able to meet the challenge to provide electric cars with energy. The batteries provide, based on their weight, lack of energy. An average car needs for a distance of 500 km, approximately 37 l (33 kg) diesel, an electric-powered vehicle would require a battery with a capacity of 360 l (540 kg).” (Spange and Böttger-Hiller, 2014, p. 61)*	Battery	Component	High weight → Low performance	Low energy density
ATZ Volume 116 Issue 04 Article 13	*“With the progress of electric mobility powerful batteries with high energy density are needed. Current state of the art in electric cars are lithium-ion batteries. Because of the lower energy density compared to fossil fuel powered vehicles such accumulators reach only a part of the range of a comparable diesel model.” (Spange and Böttger-Hiller, 2014, p. 61)*	Battery	Component	Limited range → Low performance	Low energy density
ATZ Volume 116 Issue 04 Article 08	*“Battery climatization is of major importance in the thermal management of electric vehicles. In order to ensure a long life expectancy and high-power supply from the energy storage, it should be operated within*	Thermal management of battery →	Component	High complexity → Low performance	Temperature sensitivity of battery

	the optimum temperature range." (Pischinger et al., 2014, p. 39)	Thermal management			
ATZ Volume 116 Issue 04 Article 08	*"The automotive industry meets the growing demand for sustainability with the increasing use of electrification of vehicles. A challenge in these concepts is the thermal management concerning the special thermal characteristics of the electric components. These offers compared to a combustion engine high efficiency, hence lower heat emission. Also, the temperature limits of the electric components are considerably lower than the limits of combustion engines." (Pischinger et al., 2014, p. 37)*	Thermal Management	Component	High complexity → Low performance	Temperature sensitivity of the components
ATZ Volume 116 Issue 04 Article 03	*"Acceptance of battery electric vehicles suffers from their severely limited driving range compared to conventionally powered vehicles. In addition to better battery technologies, the main challenge is the optimization of energy efficiency, for example by energy recovery during deceleration." (Flehmig et al., 2014, p. 11)*	Battery	Component	Limited range → Low performance	-
IJoAT Volume 15 Issue 01 Article 03	*"However, due to the limitations in energy storage of current batteries, driving electric vehicles for long distances requires greater efficiency from each part of the vehicle." (Shen and Lu, 2014, p. 20)*	Battery	Component	Limited range → Low performance	Limitations in energy storage
IJoAT Volume 15 Issue 01 Article 10	*"An accurate battery State-of-Charge (SoC) estimation method is one of the most significant and difficult techniques to promote the commercialization of electric vehicles." (Xiong et al., 2014, p. 89)*	Battery management system → Battery	Component	High complexity → Low performance	-
IJoAT Volume 15 Issue 01 Article 10	*"But how to avoid the adverse effect of cell inconsistency on battery pack performance and prolong the service life of both the pack and the cells are posing tremendous technological challenges to battery State-*	Battery management system → Battery	Component	High complexity → Low performance	-

	of-Charge (SoC) estimation techniques." (Xiong et al., 2014, p. 89)	Battery cell → Battery	Component	Limited lifetime expectation → Low quality	
IJoAT Volume 15 Issue 01 Article 15	*"The key factor to hybrid and electric vehicle success is a good overall mileage achieved from the battery back." (Chindamo et al., 2014, p. 135)*	Battery	Component	Limited range → Low performance	-
IJoAT Volume 15 Issue 05 Article 12	*"During the charging – discharging cycles, electrochemical reactions cause the generation of reaction heat at the positive and negative electrodes of the battery. The elevated temperature of the batteries due to this process affects the performance of EVs and the life cycle of batteries significantly." (Cho et al., 2014, p. 795)*	Battery	Component	Low performance Limited lifetime expectation → Low quality	Temperature sensitivity of batteries
IJoAT Volume 15 Issue 05 Article 12	*"Among the various technological challenges related to the development of EV's, battery heat management during charging – discharging cycles is one of the biggest." (Cho et al., 2014, p. 795)*	Thermal management of battery → Thermal management	Component	High complexity → Low performance	-
IJoAT Volume 15 Issue 06 Article 14	*"However, the battery constrains the performance, such as vehicle range, output torque, and safety." (Yin and Hu, 2014, p. 979)*	Battery	Component	Limited range → Low performance Safety risks → Low quality	-
IJoAT Volume 15 Issue 07 Article 07	*"The thermal management of the battery is one of the most significant factors impacting both the battery performance and life." (Lee, 2014, p. 1102)*	Thermal management of battery →	Component	High complexity → Low performance	Influences the performance and service life

		Thermal management			
IJoAT Volume 15 Issue 07 Article 14	*“While the technological limitations on pure electric vehicles, such as lesser than customer expected driving range due to the limited power and energy capacity of the on-board energy storage device, and the developing phase of charging infrastructure, are still exist, the automotive industry and its stakeholders are paying significant attention to the electric vehicle technology.” (Suh et al., 2014, p. 1165)*	Battery	Component	Limited range → Low performance	Limited power and energy capacity
		Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
IJoAT Volume 15 Issue 07 Article 14	*“Although many people believe that electric vehicle will be the future of transportation, pure electric vehicle (EV) itself has many problems that are slowing down its commercialization. Most of these problems are coming from the heavy, inconvenient and costly battery system which is commonly used as the power source in electric vehicle.” (Suh et al., 2014, p. 1165)*	Battery	Component	High weight → Low performance	-
				High costs	
ATZ Volume 115 Issue 12 Article 03	*“Unlike the PSM, the technology used does not require any rare earth elements such as neodymium and dysprosium. The availability and price of these raw materials on global markets fluctuate wildly – which entails a cost risk that is virtually impossible to assess for OEMs and suppliers of electromobility.” (Domian et al., 2013, p. 11)*	E-Motor	Component	Costs of raw material → High costs	-
ATZ Volume 115 Issue 12 Article 03	*“Despite continual progress in battery technology, energy storage remains a limiting factor on the range of all-electric vehicles.” (Domian et al., 2013, p. 11)*	Battery	Component	Limited range → Low performance	-
ATZ Volume 115 Issue 11 Article 09	*“Unlike combustion engines, electrified powertrains have much lower levels of waste heat that can be used to heat the passenger cabin. Additionally, the refrigerant compressor that is traditionally linked directly*	HVAC → Thermal management	Component	Low performance	The battery must provide electric heating

	to the internal combustion engine needs to be powered electrically. Consequently, in fully electrically powered vehicles, independent heating and air-conditioning systems need to be implemented, and these have to be powered by the vehicle’s battery itself. The operation of these systems has immediate effects on the driving range.” (Wirth et al., 2013, p. 46)				and cooling energy
ATZ Volume 115 Issue 11 Article 02	*“BEVs provide the advantage of locally emission-free driving and make significant progress towards reducing traffic-related noise emissions. However, the range of BEVs is limited to 100 to 150 km as a result of the low energy density of modern battery cell technology.” (Ogrzewalla et al., 2013, p. 5)*	Battery cell → Battery	Component	Limited range → Low performance	Low energy density
ATZ Volume 115 Issue 07/08 Article 04	*“Especially the electric driven cars need energy efficient concepts. The current operating radius of electric cars is significantly lower compared to combustion engine driven cars, as the current energy capacity of electric car batteries is significantly lower compared to a petrol tank.” (Venneborger et al., 2013, p. 17)*	Battery	Component	Limited capacity → Low performance	-
ATZ Volume 115 Issue 06 Article 03	*“Heating the passenger compartment in winter reduces the driving range of an electric vehicle far more than cooling does. At an outside temperature of -20 °C, approximately twice the amount of energy is needed to give vehicle occupants a level of warmth they feel comfortable in.” (Ackermann et al., 2013, p. 11)*	HVAC → Thermal management	Component	Low performance	The battery must provide electric heating and cooling energy
ATZ Volume 115 Issue 03 Article 08	*“Using state-of-the-art internal combustion engines with and without hybridization will be an absolutely vital option in the future. One of the reasons for this is that it will take some time for fully electric vehicles to make their breakthrough, since a supporting infrastructure is not yet in place.” (Timmann et al., 2013, p. 44)*	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-

ATZ Volume 115 Issue 03 Article 07	*“Permanently excited motors require rare earths, but these raw materials are becoming increasingly scarce and more expensive due to market economic reasons.”* (Röhrl et al., 2013, p. 40)	E-Motor	Component	Costs of raw material → High costs	Scarcity of raw materials
ATZ Volume 115 Issue 02 Article 06	*“For a successful introduction in the private sector, the government would have to make large investments and set up charging stations in the public housing estates where over 80% of the population live.”* (Schickram et al., 2013, p. 25)	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
ATZ Volume 115 Issue 01 Article 05	*“At the center of these discussions is the question of whether these new drive systems will be accepted by potential customers. Apart from rather technical factors, such as a relatively short range and long charging times for battery-powered vehicles or the lack of infrastructure for battery-powered and fuel-cell vehicles, and therefore high purchasing price in particular – compared to vehicles with conventional drive systems – that represents a major obstacle to achieving wide customer acceptance.”* (Kreyenberg et al., 2013, p. 23)	Battery	Component	Long charging time → Low performance	-
		Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
				Long charging time → Low performance	-
ATZ Volume 115 Issue 01 Article 03	*“The actual weight and volume of Chinese battery packs is higher than acceptable for a vehicle, for example approximately 60% higher for A0-class (sub-compact) BEVs, and about 80% higher for C-class (upper middle-class) BEVs.”* (Li, 2013, p. 14)	Battery	Component	High weight → Low performance	-
IJoAT Volume 14 Issue 03 Article 14	*“As the battery capacity increases, more electric energy can be stored onboard and more energy is provided for vehicle propulsion; however, the additional weight has a negative effect on the vehicle range.”* (Lee et al., 2013, p. 462)	Battery	Component	Limited range → Low performance	Additional weight decreases range

IJoAT Volume 14 Issue 05 Article 12	*“Electric vehicle is considered to be the solution for energy and environment crisis, but it’s still not competitive enough with conventional vehicles because of the limited energy density and high cost of the power battery.” (Gu et al., 2013, p. 763)*	Battery	Component	Limited capacity → Low performance	Low energy density
				High costs	-
IJoAT Volume 14 Issue 05 Article 12	*“As we know, the efficiency of PMSM is low at the low-torque and low-speed range.” (Gu et al., 2013, p. 764)*	E-Motor	Component	Low efficiency → Low performance	Inefficient in low torque and speed range
ATZ Volume 114 Issue 11 Article 12	*“However, electric vehicles still have a limited driving range because batteries are expensive and heavy.” (Schürmann et al., 2012, p. 59)*	Battery	Component	Limited Range, High weight → Low performance	-
				High costs	-
ATZ Volume 114 Issue 10 Article 10	*“Up to now, batteries still represent the major cost item.” (Picron et al., 2012, p. 47)*	Battery	Component	High costs	-
ATZ Volume 114 Issue 10 Article 02	*“It is a way to compensate the disadvantages of the relatively small energy density which is provided by electrochemical energy storage devices.” (Heim et al., 2012, p. 6)*	Battery	Component	Limited capacity → Low performance	Low energy density
ATZ Volume 114 Issue 09 Article 02	*“Compared to other alternatives, electric drive systems have no local emissions and a low noise level. However, batteries have a relatively low energy density, which means that these vehicles will have a significantly shorter range than a vehicle powered by an internal combustion engine or a fuel cell.” (Töpler et al., 2012, p. 5)*	Battery	Component	Limited range → Low performance	Low energy density

ATZ Volume 114 Issue 07/08 Article 09	*“An electric driving performance above 100 kW implies an electric current of more than 350 A in the high-voltage power network (DC) if 600-V IGBT technology is used in the inverter of the traction motor. Notwithstanding extensive progress in the development of high-power battery cells, these currents still remain the limiting factor considering the desired operating life of the high-voltage battery.” (Engstle et al., 2012, p. 41)*	Battery cell → Battery	Component	Limited lifetime expectation → Low quality	High electric currents damage the battery cell
ATZ Volume 114 Issue 07/08 Article 03	*“The provision of power presents a considerably greater challenge because there must be practically 100 % balancing of generation and load everywhere in the grid at all times due to the lack of comparable buffers otherwise available in the liquid fuel system. Preventing overloads and grid instability are the most demanding requirements for grid managers.” (Prestl and Wagner, 2012, p. 13)*	Electric grid	Complement	Performance fluctuations → Low performance	Storage buffers are not available
ATZ Volume 114 Issue 06 Article 05	*“Currently, the urban driving range of EVs is about 140 to 160 km on a single charge. While using HVAC cooling, however, it is reduced by 20 to 30 %. Unlike cars powered by internal-combustion engines, which utilize waste heat from the engine to heat the cabin, EVs also lack heat resources.” (Lee et al., 2012a, p. 23)*	HVAC → Thermal management	Component	Low performance	Lack of heat resources
ATZ Volume 114 Issue 06 Article 05	“In an electric vehicle (EV), the maximum cruising range is adversely affected by electric power consumption of auxiliary electric components such as heating and cooling. Hyundai works on a special heating, ventilation, and air-conditioning (HVAC) control system that significantly increases the cruising range of electric vehicles by air-conditioning only the occupied seats within the vehicle.” (Lee et al., 2012a, p. 22)	HVAC → Thermal management	Component	Low performance	-
ATZ Volume 114	*“Furthermore, the heavy battery weight in hybrid and electric vehicles makes the lightweight design concept*	Battery	Component	High weight →	-

Issue 05 Article 11	*essential [1]. Maximizing weight saving helps to achieve an acceptable driving range in traffic.” (Schweizer et al., 2012, p. 55)*			Low performance	
ATZ Volume 114 Issue 03 Article 09	*“One of the greatest challenges in designing the electric drive train for a BEV (battery electric vehicle) lies in the balance between conflicting requirements, with a suitable, practical range on the one hand, and acceptable battery costs and weight on the other.” (Ebner et al., 2012, p. 41)*	Battery	Component	High weight → Low performance	-
				High costs	
ATZ Volume 114 Issue 02 Article 07	*“Nearly all mentioned characteristics directly or indirectly depend on the thermal physical comfort of the energy storage media. Batteries are very sensitive and cannot tolerate too hot or too cold environment – something they have in common with their weaker siblings in DVD players, flashlights, mobile phones etc. Infringements are immediately punished by reduced performance, early wrongdoing or overheating.” (Hu, 2012, p. 34)*	Battery	Component	Low performance	Temperature sensitivity of batteries
ATZ Volume 114 Issue 01 Article 11	*“The maximum charging power is controlled by battery design, power supply and charging set. Even though most of the private trips can be covered by such a BEV [7], they do not necessarily match the customer’s requirements: Longer trips can only be realized with time-consuming intermediate charging.” (Schulz et al., 2012, p. 61)*	Battery	Component	Long charging time → Low performance	-
		Charging station → Electric charging infrastructure	Complement		-

ATZ Volume 114 Issue 01 Article 11	*“The large initial costs of BEV can only be amortized after many years – presuming an optimistic development of consumption and battery life, electricity tariff and taxation. Paradoxically, this means that BEV can only be cost-efficient if being operated at lowermost battery size routinely exhausting the maximum range.” (Schulz et al., 2012, p. 61)*	Battery	Component	High costs	-
ATZ Volume 114 Issue 01 Article 11	*“Compared to conventional gasoline or diesel vehicles, pure electric cars have some inherent disadvantages: due to its specific storage capacity of about 10 kg/kWh the battery is heavy and voluminous but significantly defines the BEV package.” (Schulz et al., 2012, p. 61)*	Battery	Component	High weight → Low performance	Specific storage capacity
ATZ Volume 114 Issue 01 Article 07	*“At these times of the year, electric energy is also required to operate vehicle fans, rear window heaters and, above all, to heat the passenger compartment. When electric heating systems are used, these are operated by the same source of energy as the engine. As a result, according to the vehicle manufacturers, the driving range will be reduced by up to 50%, depending on the heat requirement and operating mode.” (Kohle et al., 2012, p. 37)*	HVAC → Thermal management	Component	Low performance	Battery must provide electric heating and cooling energy
IJoAT Volume 13 Issue 02 Article 17	*“The restriction on long distance driving, as a result of limited breakthroughs in fundamental battery technology, has become the main obstacle limiting EV development.” (Wu et al., 2012, p. 325)*	Battery	Component	Limited range → Low performance	Limited breakthrough in battery technology
IJoAT Volume 13 Issue 02 Article 17	*“The combined battery and ultra-capacitor system in the active parallel scheme benefit from minimizing the voltage variation of the battery and inverter. It helps to address the issue of low specific power in batteries, especially during regenerative braking and electric motor assist.” (Wu et al., 2012, p. 336)*	Battery	Component	Bad dynamic behavior → Low performance	Low specific power

IJoAT Volume 13 Issue 03 Article 17	*“Compared to common gasoline- powered vehicles, the fuel economy and emissions of HEVs, PHEVs, and EVs are greatly improved because relatively inexpensive and clean electricity is used in these vehicles. The wide use of EVs is limited by their battery cost and infrastructure.” (Ma et al., 2012, p. 505)*	Battery	Component	High costs	-
		Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
IJoAT Volume 13 Issue 06 Article 14	*“The maximum energy of the electric vehicle MiEV, manufactured by Mitsubishi, is 16 kWh, and the driving distance after a full charging is 160 km, with a maximum speed of 130 km. However, if the heating system is turned on, the driving distance becomes 100 km because of PTC heater use.” (Kim et al., 2012, p. 972)*	HVAC → Thermal management	Component	Low performance	Electrically powered components (PTC heater)
ATZ Volume 113 Issue 11 Article 03	*“In electrical vehicles, auxiliary energy use is especially critical because of limited battery capacity. In cars with conventional drive trains, the required heat can be provided by a combustion engine, whereas in electric cars, it has to be specifically generated due to significantly smaller heat losses. Every kilowatt hour used for climatizing the interior thus reduces the car’s range or necessitates the early use of a range extender.” (Müller et al., 2011, p. 11)*	HVAC → Thermal management	Component	Low performance	The battery must provide electric heating and cooling energy
		Battery	Component	Limited capacity → Low performance	-
ATZ Volume 113 Issue 11 Article 02	*“A further challenge is the thermal conditioning of the battery in alternative drive concepts. The battery has to operate within a narrow temperature range in order to achieve its highest efficiency.” (Prokop and Lewerenz, 2011, p. 7)*	Thermal management of batteries → Thermal management	Component	High complexity → Low performance	Temperature sensitivity of the battery
ATZ Volume 113 Issue 11 Article 02	*“The thermal energy that is released from electric motors of electric vehicles after a longer ride is insufficient to keep the temperature in the vehicle interior at a comfortable level. Therefore, other sources*	HVAC → Thermal management	Component	Low performance	-

	have to supply additional heat. If not, all basic conditions are taken into consideration and an innovative heating concept is implemented, the demand for electric power is so high that the residual energy for the drive is significantly lower [2]. This results in a further conflict of interests, namely a conflict between range and comfort." (Prokop and Lewerenz, 2011, p. 6)				
ATZ Volume 113 Issue 10 Article 02	*"Unfortunately, standardization of the charging procedure has not so far made much progress internationally, so that many charging technologies and connector concepts are having to be developed in parallel."* (Gräter, 2011, p. 8)	Charging station → Electric charging infrastructure	Complement	Missing interoperability → Low performance	Standardization issues
ATZ Volume 113 Issue 09 Article 02	*"No matter what leaps in efficiency we manage to get out of internal combustion engines – the future belongs to electric drives. The only question is: when is the future? High battery costs, limited ranges – everything points to the fact that the transition to electric mobility will take considerably more than one decade."* (Schlott, 2011, p. 5)	Battery	Component	High costs	-
ATZ Volume 113 Issue 07/08 Article 10	*"In electric vehicles, the quantity of primary energy carried on board is far lower than in a conventional vehicle powered by an internal combustion engine. Petrol has an energy density of 12,800 Wh/kg, which is significantly above that of today's available lithium-ion batteries, which have approximately 125 Wh/kg. Current forecasts are proceeding from an increase in energy density to approximately 200 Wh/kg by 2015 [1]. Even then, the thermal energy required for heating the passenger compartment will no longer be available as a by-product of combustion. Yet consumer demands for thermal comfort remain at the same high level."* (Wehner and Ackermann, 2011, p. 51)	Battery	Component	Limited capacity → Low performance	-
		HVAC → Thermal management	Component	Low performance	-

ATZ Volume 113 Issue 07/08 Article 04	*“If an all-electric vehicle has to be designed from scratch, it is first of all necessary to address the deficits of current models. These are usually the low driving ranges and high costs caused by the battery.” (Kuchenbuch et al., 2011, p. 17)*	Battery	Component	Limited range → Low performance	-
				High costs	-
ATZ Volume 113 Issue 07/08 Article 01	*“According to Behr, around 4.5 kW of thermal energy is required to heat a vehicle interior to a comfortable 22 °C when the temperature outside is below zero. An electric drive system, on the other hand, generates only 0.45 kW of waste heat, which already includes the heat from the electric motor, the power electronics and the battery. Can one not simply use a low-voltage PTC auxiliary heater, as is common in diesel engines? No, as that would be at the expense of driving range. That would fall from 150 to 80 km for an average electric car.” (Reichenbach, 2011, p. 3)*	HVAC → Thermal management	Component	Low performance	The battery must provide electric heating and cooling energy
ATZ Volume 113 Issue 06 Article 06	*“In large-scale battery systems for electric vehicles, it makes sense also to integrate heating elements. In temperatures below 0 °C, the electrical properties of batteries are not only considerably impaired, the cells can also be irreversibly damaged through the formation of lithium dendrites, especially during charging.” (Kritzer and Nahrwold, 2011, p. 28)*	Battery cell → Battery	Component	Limited lifetime expectation → Low quality	Temperature sensitivity of batteries can cause a damaging effect
				Low performance	-
ATZ Volume 113 Issue 06 Article 06	*“Finally, in the event of a fault resulting in pressure overload inside the cell, it is possible that the cell’s sealing seams open up irregularly. In a worst-case scenario, flammable gases such as electrolyte or degradation products can come into contact with current-carrying components, which can lead to fire and/or explosions.” (Kritzer and Nahrwold, 2011, p. 27)*	Battery cell → Battery	Component	Safety risks → Low quality	Explosion risk in case of an overload

ATZ Volume 113 Issue 06 Article 06	*"High-capacity batteries for electric vehicles raise safety issues in many respects." (Kritzer and Nahrwold, 2011, p. 26)*	Battery	Component	Safety risks → Low quality	-
ATZ Volume 113 Issue 05 Article 08	*"In order to maintain the cabin temperature at 22 °C, almost twice as much energy is required for heating than for powering the car. The resultant reduction in driving range can hardly be justified to the end customer." (Jung et al., 2011, p. 3)*	HVAC → Thermal Management	Component	Low performance	The battery must provide electric heating energy
ATZ Volume 113 Issue 05 Article 08	*"With the increasing trend towards powertrain electrification, vehicle air conditioning is becoming vitally important as a means to adequately cool the electrical energy storage unit at a low temperature level. At the same time, the energy consumption of the air conditioning system directly impacts the electric drive range of the vehicle in the wintertime." (Jung et al., 2011, p. 36)*	Thermal Management of battery → Thermal Management	Component	Low performance	Battery must provide electric cooling energy
ATZ Volume 113 Issue 04 Article 05	*"The problem of fast and simple recharging of electric vehicles has still not been sufficiently solved. Cabled systems compete with inductive systems while upright charging pillars are used as an alternative to systems integrated into the road surface." (Nietschke et al., 2011, p. 22)*	Charging station → Electric charging infrastructure	Complement	Missing interoperability → Low performance	-
ATZ Volume 113 Issue 02 Article 13	*"Assuming a CO2-neutral electricity generation the electric vehicle (EV) offers the potential for reducing the emissions. Yet the large-scale launch of the EV is short to medium term handicapped by high costs and limited range due to the low energy density of batteries." (Köll et al., 2011, p. 61)*	Battery	Component	Limited range → Low performance	Low energy density
				High costs	
ATZ Volume 113 Issue 02	*"Li-Ion batteries react very sensitive to fast charging and discharging cycles. An equal charging level has to be closely monitored, otherwise the remaining cells are*	Battery	Component	Limited lifetime expectation →	Fast charging and discharging

Article 09	*overloaded, and they could be easily destroyed." (Schöggl et al., 2011, p. 43)*			Low quality	cycles cause a damaging effect
ATZ Volume 113 Issue 02 Article 07	*"Unlike in conventional cars, the auxiliary electric components in electric vehicles have to compete with the actual drive system. This is above all due to the fact that the auxiliary components and the drive system use the same energy storage, that means the battery. For example, if an auxiliary electric component requires 10 kW of energy, 10 kW less power is available for the drive system. Therefore, the maximum driving range is strongly dependent on the power required by the auxiliary electric components." (Klassen et al., 2011, p. 29)*	HVAC → Thermal Management	Component	Low performance	The battery must provide electric cooling and heating energy
ATZ Volume 113 Issue 02 Article 03	*"But nobody would buy a car like that because it's still too costly. We've still got a lot to do here, especially in terms of the battery costs, but the energy density of the batteries is a problem too. It is easy to realize a range of 100 miles, but a vehicle with a petrol engine gives you a range of 400 miles. We have to give our customers what they want. That's why I don't believe that electric vehicles will replace cars with petrol or diesel engines." (Robertson, 2011, p. 9)*	Battery	Component	Limited range → Low performance	Low energy density
				High costs	-
IJoAT Volume 12 Issue 16 Article 01	*"However, batteries that are used as energy storage devices for automotive applications require chemical reactions during energy input and output processes, which restricts their ability to charge or discharge high current in a short time period." (Shin et al., 2011, p. 126)*	Battery	Component	Bad dynamic behavior → Low performance	Chemical reactions restrict the ability for fast charging and discharging
				Long charging time → Low performance	

IJoAT Volume 12 Issue 17 Article 01	*"NiMH batteries are advantageous, because they have a better energy density and are recyclable, quickly rechargeable, and reliable (compared with PB-acid). On the other hand, some disadvantages of NiMH batteries are their high cost and low cell efficiency." (Suh et al., 2011, p. 137)*	Battery	Component	High costs	-
				Low efficiency → Low performance	-
IJoAT Volume 12 Issue 17 Article 01	*"Li-ion batteries are expensive. However, their high specific energy and low self-discharge make them widely used in most small electronic products, such as cellular telephones, laptop computers, and portable A/V players." (Suh et al., 2011, p. 137)*	Battery	Component	High costs	-
ATZ Volume 112 Issue 10 Article 06	*"A purely battery-driven vehicle has the two problems of limited range (which, depending on the driving style and battery capacity, is around 50 to 60 km) and relatively long battery charging times." (Gabele et al., 2010, p. 33)*	Battery	Component	Limited range → Low performance	Low battery capacity
				Long charging time → Low performance	-
ATZ Volume 112 Issue 07/08 Article 04	*"With current accumulators, the amount of energy that can be stored in electric vehicles is not comparable to combustion vehicles. This results in a reduction in range and leads to a need for significantly lower rolling resistance of tires for electric vehicles." (Schulze et al., 2010, p. 31)*	Battery	Component	Limited range → Low performance	-
ATZ Volume 112 Issue 05 Article 03	*"With significant higher prices for energy storages (batteries) the energy demand of the electric vehicle should be as low as possible." (Sahr et al., 2010, p. 26)*	Battery	Component	High costs	-
ATZ Volume 112 Issue 04 Article 04	*"Customers are not willing to pay more for electric mobility. Therefore, the selling price is crucial for market success. Due to the high additional costs*	Battery	Component	High costs	-

	caused by the battery, there is enormous cost pressure in production." (Kampker et al., 2010, p. 22)				
ATZ Volume 112 Issue 04 Article 04	*"Based on the production costs of a conventional vehicle with an internal combustion engine, shows the derivation of the target costs for a compact electric vehicle with a range of 200 km in the year 2015. Even taking into account the fact that customers are willing to accept a slightly higher selling price of 250 euros and that governments have announced a fiscal subsidy of 2,500 euros to compensate for the high battery costs, the production costs (assembly) of an electric vehicle are still 25 % above those of a conventional vehicle. Therefore, the production process itself must make a major contribution towards reducing the overall costs." (Kampker et al., 2010, p. 19)*	Battery	Component	High costs	-
ATZ Volume 112 Issue 04 Article 03	*"While the optimum temperature range depends on the cell chemistry employed by the different manufacturers, as a general rule temperature of over 60 °C during storage and 40 °C during operation need to be avoided. Operation outside this temperature range shortens the battery life due to irreversible damage occurring within the Li-ion cells and should therefore be avoided." (Neumeister et al., 2010, p. 13)*	Battery cell → Battery	Component	Limited lifetime expectation → Low quality	High temperatures can cause a damaging effect
ATZ Volume 112 Issue 04 Article 02	*"HV PTC coolant heaters represent an ideal solution for a BEV's complicated thermal management. They use the given heater climate module including the climate control of a conventional vehicle and permit the energy-efficient utilization of waste heat from traction motor, power electronics, voltage transformer and battery – including their temperature control at low temperatures through a water circuit. However, this obvious technology for heating by means of an electrical*	Thermal Management	Component	Low performance	The battery must provide electric cooling and heating energy

	heating system reduces the operating range of the car by more than 40 %." (Beetz et al., 2010, p. 11)				
ATZ Volume 112 Issue 04 Article 02	*"Apart from the solution to the problem of the operating range and battery costs the success of these vehicles shall be determined by the climate comfort as customers will only accept minor reductions to the customary level of comfort compared." (Beetz et al., 2010, p. 10)*	HVAC → Thermal Management	Component	High complexity → Low performance	The tradeoff between comfort and driving range
		Battery	Component	High costs	-
ATZ Volume 112 Issue 04 Article 01	*"The cold demand for future car concepts, such as hybrid electric (HEV) or battery electric vehicles (BEV), will be even larger than for actual cars, as the electric storage unit must be climatized. Lithium-ion batteries, for example, should not exceed a critical temperature of about 40 °C, for lifetime and consequently for cost reasons. Even if not under load, the battery has to be climatized as the decomposition reaction is mainly temperature dependent." (Bouvy, 2010, p. 5)*	Battery	Component	Limited lifetime expectation → Low quality	High temperatures can cause a damaging effect
ATZ Volume 112 Issue 01 Article 06	*"In current powertrain development, hybrid technology represents the transition from internal combustion engine drive systems to electric drive systems. As a key technology in this development, the energy density of the batteries is the bottleneck in the complete electrification of the powertrain, as fully electric drive systems still have a limited driving range and their weight is too high." (Maiwald et al., 2010, p. 42)*	Battery	Component	Limited range → Low performance	Low energy density
				High weight → Low performance	Low energy density
IJoAT Volume 11 Issue 02 Article 08	*"A primary area of concern in electric vehicle design, because of limited battery storage, is the amount of energy used by the various vehicle subsystems." (Zhang et al., 2010, p. 205)*	Battery	Component	Limited capacity → Low performance	Limited battery storage
IJoAT Volume 11 Issue 06	*"EVs and HEVs have potential safety problems under the circumstances of a crash or a rollover event. The occupants could be exposed to a hazard due to*	Battery electrolyte → Battery cell	Component	Safety risk → Low quality	Electrolyte spillage or electric shock

Article 08	*electrolyte spillage and/or electric shock during and after these crash events." (Lim and Kim, 2010, p. 825)*	→ Battery			caused by an accident
ATZ Volume 111 Issue 09 Article 01	*"How quickly electric vehicles become established on the market depends above all on the high-cost battery technology." (Backhaus et al., 2009, p. 8)*	Battery	Component	High costs	-
ATZ Volume 111 Issue 09 Article 01	*"Up to 50 % of the battery capacity might be needed for cooling and heating in an electric car if drivers are not prepared to give up what they are used to. Thermal management in the vehicle will compete with the powertrain for the valuable electric energy available." (Backhaus et al., 2009, p. 6)*	Thermal management	Component	Low performance	The battery must provide electric cooling and heating energy
ATZ Volume 111 Issue 07/08 Article 02	*"However, the electrochemistry of the Li-ion battery is much more sensitive to higher temperatures. Cell temperatures even above 45 °C accelerate the aging processes to such an extent that the required lifetime of more than ten years is difficult to achieve." (Wiebelt et al., 2009, p. 13)*	Battery	Component	Limited lifetime expectation → Low quality	High temperatures can cause a damaging effect
ATZ Volume 111 Issue 06 Article 07	*"The results show that the internal combustion engine will keep its dominant role besides all on-going efforts towards hybrid and electric vehicles. Main factors are the energy infrastructure as well as lasting high costs for electric energy storages." (Gies et al., 2009, p. 46)*	Battery	Component	High costs	-
		Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
ATZ Volume 111 Issue 06 Article 03	*"Are all problems solved? For sure not. There are still a lot of issues and questions open and many of them are not even known up to now. Furthermore, the necessary charging infrastructure for a widespread energy supply needs to be introduced." (Teuschl, 2009, p. 23)*	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
ATZ Volume 111 Issue 06	*"For making the EV in future compatible to conventional vehicles, on the one hand the cost for the energy storage systems needs to be dramatically reduced and*	Battery	Component	High costs	-

Article 03	*on the other hand the market for these vehicles needs to be more attractive." (Teuschl, 2009, p. 21)*				
ATZ Volume 111 Issue 06 Article 03	*"From the integration point of view the tempering concepts for this storage systems is a quite high effort. Especially the power output and input capability of this systems at low temperatures (<0 °C) and at high temperatures (>45 °C) needs to be considered. At Lithium Ion chemistry further safety measures need to be addressed due to issues like fire risk, gas evolution (e.g. carbon monoxide) and deposit of hydrofluoric acid. For these risks the used chemistry for anode/cathode/separator/electrolyte has a high impact." (Teuschl, 2009, p. 20)*	Thermal management of batteries → Thermal management	Component	High complexity → Low performance	-
		Battery	Component	Safety risks → Low quality	Fire risk, gas evolution, and deposit of hydrofluoric acid
ATZ Volume 111 Issue 02 Article 02	*"EV batteries have a limited service life depending on the number of charge/discharge cycles they undergo during their lifetime. In fact, the battery life can be the single most factor behind the commercial success of a vehicle, since a short battery life usually means escalated life cycle costs for the customers." (Vaidya and Bhere, 2009, p. 15)*	Battery	Component	Limited lifetime expectation → Low quality	-
ATZ Volume 111 Issue 02 Article 01	*"The two major hurdles for a successful market entry of electric vehicles are the limited range and the costs. The main cost driver is the electrochemical storage of the vehicle." (Eckstein et al., 2009, p. 4)*	Battery	Component	High costs	-
IJoAT Volume 10 Issue 02 Article 12	*"Overcharging the battery during regenerative braking reduces battery durability." (Ahn et al., 2009, p. 233)*	Battery	Component	Limited lifetime expectation → Low quality	Sensitivity against overcharging
IJoAT Volume 10 Issue 04 Article 15	*"Electronic vehicles have limitations because the life and performance problems of fuel batteries have not been solved." (Song et al., 2009, p. 523)*	Battery	Component	Limited lifetime expectation → Low quality	-

				Low performance	
ATZ Volume 110 Issue 12 Article 02	*“Furthermore, the energy storage solution influences strongly the global cost of the system. For electrical vehicles, the cost of the battery exceeds 70 % of the hybridization costs.” (Matt and De-Bono, 2008, p. 12)*	Battery	Component	High costs	-
ATZ Volume 110 Issue 05 Article 03	*“Due to the relatively low energy density of electrical energy storage devices, the control strategy of electric vehicles has to fulfil a variety of requirements in order to provide both, the availability of electric functions, and their efficient execution.” (Wilde et al., 2008, p. 19)*	Battery	Component	Limited capacity → Low performance	-
ATZ Volume 110 Issue 03 Article 05	*“The replacement or final utilization of these stores leads to an enormous amount of a wide range of different chemicals and heavy metals, whose disposal or recycling routes cannot be assured.” (Sontheim, 2008, p. 31)*	Disposal and Recycling	Complement	Lack of capabilities → Low availability	-
ATZ Volume 110 Issue 03 Article 05	*“The evaluation simply shows the energy that is dissipated by the mechanical brake. If this is stored in the form of electrical energy, it can provide charging power of up to 30 kW for the battery. Standard batteries are unable to absorb these powers. Even in new types of batteries such as nickel-metal hydride batteries (NiMH), lithium-ion batteries (Li-Ion) or double-layer condensers, this load in association with high charging cycles leads to significant fluctuations in voltage and considerable thermal ageing.” (Sontheim, 2008, p. 31)*	Battery	Component	Limited lifetime expectation → Low quality	Thermal aging due to fluctuations
IJoAT Volume 09 Issue 01 Article 14	*“The battery has a high energy density, and thus has the advantage in driving distance. However, its low power density is a disadvantage for the dynamic characteristic.” (An et al., 2008, p. 111)*	Battery	Component	Bad dynamic behavior → Low performance	Low power density

ATZ Volume 109 Issue 12 Article 04	*“But the greater thermal sensitivity of Li-ion batteries presents a particular challenge. Their upper temperature limit of 40°C should not be exceeded too often, and then only for brief periods at peak performance. Furthermore, the temperature gradient within and between each individual battery cell should be tightly constrained. Thermal management is thus a key factor in utilizing the full potential of the Li-ion battery in driving mode.” (Brotz et al., 2007, p. 13)*	Thermal management of batteries → Thermal management	Component	High complexity → Low performance	Temperature sensitivity of battery
ATZ Volume 109 Issue 12 Article 04	*“[…] lithium-ion batteries have the advantages of greater storage density, dynamic range, and service life. One drawback is their greater thermal sensitivity, which requires a special focus on cooling.” (Brotz et al., 2007, p. 13)*	Battery	Component	Low performance	Temperature sensitivity of battery
ATZ Volume 108 Issue 07/08 Article 05	*“After-sales service personnel must receive further training and workshops need to be prepared for handling high voltages, Figure 5. For legal considerations (labor law), it is still unclear as to which automotive mechanics will be allowed to repair HV components.” (Voß et al., 2006, p. 18)*	Dealer and workshop	Complement	Lack of capabilities → Low availability	Missing legal regulations and training for service personnel
ATZ Volume 108 Issue 07/08 Article 05	*“Irrespective of whether batteries, high-performance capacitors or even both options are employed, these components demand particular attention, Figure 2. Operation of the traction battery is a tightrope walk between making maximum use of battery capacity and easing strain on the system from the aspect of its service life.” (Voß et al., 2006)*	Battery	Component	Limited lifetime expectation → Low quality	The tradeoff between maximum use of capacity and service life
				Low performance	The tradeoff between maximum use of capacity and service life

IJoAT Volume 07 Issue 04 Article 09	*“As a result, alternative clean vehicle technologies such as electric vehicles, hybrid electric vehicles (HEVs), and fuel cell vehicles have been suggested. However, considering the technical and infrastructural limitations of electric vehicles, the HEV is currently seen as an alternative and ready-to-use solution.” (Cho and Vaughan, 2006a, p. 459)*	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
IJoAT Volume 07 Issue 06 Article 12	*“These characteristics allow the best utilization of the limited battery capacity (extension of the running distance per battery charge) and the minimization of the size and the weight of the motor and the drive.” (Zidani et al., 2006, p. 730)*	Battery	Component	Limited capacity → Low performance	Low energy density
IJoAT Volume 07 Issue 07 Article 04	*“Deep charging or discharging affects the battery life. Therefore, the SOC of the battery should be maintained in the proper level.” (Cho and Vaughan, 2006b, p. 789)*	Battery	Component	Limited lifetime expectation → Low quality	Damaging effect of deep charging and discharging
ATZ Volume 107 Issue 05 Article 06	*“The chances of an increased use of electric powertrain vehicles are closely connected to the development of high-performance energy storage, which has a large influence on the weight and costs of the vehicle. Even though large progress has already been achieved in the development of battery technologies, the low storage capacities, limited power spectrum, short lifetime and the high costs represent major obstacles against an enhanced use of electric vehicles.” (Blesl et al., 2005, p. 18f)*	Battery	Component	Limited capacity → Low performance	-
				Limited lifetime expectation → Low quality	-
				High costs	-
IJoAT Volume 04 Issue 02 Article 03	*“The electric vehicles in Europe all have an “on-board” charger that can be coupled on a domestic socket-outlet. Besides private socket-outlets, which are broadly present in houses, there is a shortage of public charging stations.” (van Mierlo et al., 2003, p. 78)*	Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-

ATZ Volume 103 Issue 01 Article 07	*“Vehicles equipped with electric drives thus achieve only low ranges and require long charging times. The power connection required is only available when there is a garage for the vehicle. Electric vehicles will remain, in future, too, an alternative to vehicles powered by internal combustion engines only in very few exceptional cases.” (Marker et al., 2001, p. 23)*	Battery	Component	Long charging time → Low performance	-
		Charging station → Electric charging infrastructure	Complement	Lack of infrastructure → Low availability	-
				Long charging time → Low performance	-
ATZ Volume 103 Issue 01 Article 07	*“Due to their characteristics, electric drives are ideal for motor vehicles. The disadvantage in their use is the insufficient energy density of the batteries necessary for the storage of the electric power. In addition, batteries are expensive, have only a limited service life and require a long time for charging.” (Marker et al., 2001, p. 23)*	Battery	Component	Limited capacity → Low performance	-
				Long charging time → Low performance	-
				High costs	-
				Limited lifetime expectation → Low quality	-
ATZ Volume 102 Issue 07/08 Article 10	*„Außerdem können absolut emissionsfreie Fahrzeuge nur mit Elektroantrieben realisiert werden. Da selbst sehr gute Traktionsbatterien zu geringe Energiedichten besitzen, bietet sich die Brennstoffzelle als elektrochemischer Energiewandler an.“ (Herbst, 2000, p. 622)*	Battery	Component	Limited capacity → Low performance	Low energy density

ATZ Volume 102 Issue 02 Article 04	*„Für solche Zwecke erscheint ein kompaktes und preiswertes Fahrzeug mit einem Beschleunigungsverhalten, das einem üblichen Stadtzyklus entspricht und darüber hinaus eine extrem niedrige Schadstoff- und Schallemission im Stadtbereich vorweisen kann, als besonders zukunftsträchtig. Elektromotoren mit Batterien als Energiequellen erfüllen zum großen Teil diese Anforderungen, haben allerdings den Nachteil einer sehr begrenzten Reichweite, der durch die Batteriemasse selbst und durch die Ladedauer noch verstärkt wird."* (Stan and Personnaz, 2000, p. 119)	Battery	Component	Limited range → Low performance	-
				Long charging time → Low performance	-
				High weight → Low performance	-
IJoAT Volume 01 Issue 01 Article 02	*"For zero emission vehicles, battery electric vehicles have been one of the most viable alternatives and have been introduced to the market by several major automotive manufacturers. However, the shortcomings associated with the battery performance, such as weight, charging time, cycle life and driving range, have been the major inhibitors against the widespread acceptance by consumers."* (Yang, 2000, p. 9)	Battery	Component	Limited range → Low performance	-
				High weight → Low performance	-
				Long charging time → Low performance	-

Appendix M: Text passages that declare a bottleneck for FCEVs

Journal	Text passage	(Sub) - component / complement	Component or Complement	Type of bottleneck	Trigger / Comment
ATZ Volume 122 Issue 10 Article 16	*“The requirements for fuel cell air intake filtration are even higher than for a modern combustion engine.” (Berger, 2020, p. 76)*	Air filter → Oxygen supply	Component	High complexity → Low performance	-
ATZ Volume 122 Issue 10 Article 14	*“The H2 Mobility initiative in Germany is already planning a nationwide network of hydrogen refueling stations, which is gradually being developed. [...] We must continue to focus on the regulatory framework and ensure that the legal obstacles to the introduction of re-fuels are removed.” (Heintzel and Eisenkrämer, 2020, p. 66)*	Hydrogen refueling infrastructure	Component	Lack of infrastructure → Low availability	Legal obstacles
ATZ Volume 122 Issue 06 Article 08	*“A recycling process that is tailor-made for fuel cells is not yet available on an industrial scale.“ (Fraunhofer IWKS, 2020, p. 32)*	Disposal and recycling	Complement	Lack of infrastructure → Low availability	-
ATZ Volume 122 Issue 04 Article 11	*“However, the penetration of BEV and FCEV technologies will require an increase in mining output, particularly for lithium, cobalt and platinum. This will have social, environmental and economic consequences. Occasional shortages and the resulting price increases are a distinct possibility.” (Hendrich and Reuter, 2020, p. 55)*	Fuel Cell catalyst (Platinum is part of the catalyst) → Membrane electrode assembly → Fuel Cell	Component	Costs of raw material → High costs	Supply shortage
ATZ Volume 122 Issue 04	*“The cooperation of processing industries and recycling companies would make it easier to set up and operate profitable collection systems and*	Disposal and recycling	Complement	Lack of capabilities →	Missing collaboration between

Article 11	*recycling plants. In addition, the "Design for Recycling" approach is also to be recommended here in order to keep raw materials in the recycling loop and lower the costs." (Hendrich and Reuter, 2020, p. 55)*			Low availability	manufacturer and recycling industry
ATZ Volume 122 Issue 01 Article 17	*"Thermal management and cabin climatization are crucial factors influencing the driving range of battery and fuel cell electric vehicles. Currently mostly electrically powered components are used for this purpose, for example Positive Temperature Coefficient (PTC) heaters or electrical compressors, which lead to a driving range reduction of up to 50 % during hot or cold weather conditions." (Hegner and Weckerle, 2020, p. 79)*	Thermal management	Component	Low performance	Electrically powered components like PTC heater
		HVAC → Thermal management	Component		
ATZ Volume 122 Issue 01 Article 15	*"To use the fuel cell across other automotive segments and in large volumes in the future, the main task is now to further develop a basic fuel cell module in such a way that it can be even more efficiently integrated into the group-wide electric modular system. This would generate a maximum of flexibility with respect to different applications in various vehicle segments including commercial vehicles." (Mohrdieck and Dehn, 2020, p. 68)*	Fuel Cell	Component	Low efficiency → Low performance	Modularity issues
ATZ Volume 121 Issue 12 Article 08	*"The Fraunhofer Institute for Production Technology (IPT) aims to enable bi-polar plates for fuel cells to be produced more cost-effectively and on a large scale. Researchers at the institute are concentrating on developing a hot forming process for the plates, which account for a large proportion of the weight of the fuel cells and for almost half the production costs." (Fraunhofer IPT, 2019, p. 40)*	Bipolar plates → Fuel Cell	Component	Costs of production → High costs	-
				High weight → Low performance	

ATZ Volume 121 Issue 10 Article 12	"Thereto, a laboratory test bench with the electric traction machine was connected with two HiL simulators. It was determined that the temperatures of the traction machine are a limiting factor for the vehicle performance in an exemplarily simulated high load driving cycle on the Nürburgring Nordschleife." (Etzold et al., 2019, p. 54)	E-Motor (Synergy BEV and FCEV)	Component	Low performance	Vehicle performance is hugely influenced by temperature
ATZ Volume 121 Issue 04 Article 03	*"Until then fuel cells had been seen as the long-term solution for electric transport, but the lack of an adequate infrastructure and, more importantly, the progress made with lithium-ion batteries forced the developers of hydrogen-powered vehicles onto the back foot." (Burkert, 2019, p. 9)*	Hydrogen refueling infrastructure	Complement	Lack of infrastructure → Low availability	-
ATZ Volume 121 Issue 04 Article 03	*"The membrane electrode assembly with a proton exchange membrane that is just 0.01 mm thick, the most complex component in a fuel cell, offers the greatest potential for improvement. Together with the mass production process, this is the most important means of reducing the costs per kWh." (Burkert, 2019, p. 11)*	Membrane electrode assembly → Fuel Cell	Component	High costs	-
		Fuel Cell production → Fuel Cell	Component	Costs of production → High costs	Economy of scale
ATZ Volume 121 Issue 04 Article 03	*"Honda, Hyundai, and Toyota have demonstrated that they have systems ready for mass production, and Daimler is also in the running. This will lead to the necessary fall in costs. The challenge from the perspective of the vehicle is the hydrogen tank and, of course, we also need a user-friendly hydrogen infrastructure." (Burkert, 2019, p. 11)*	Hydrogen tank → Hydrogen system	Component	High complexity → Low performance	-
		Hydrogen refueling infrastructure	Complement	Lack of infrastructure → Low availability	-
ATZ Volume 121 Issue 02 Article 15	*"The range of electric vehicles is constantly growing and, in order to make this possible, batteries with an increasingly large capacity are needed. As a result, short circuits in the vehicle electrical system caused*	HV protection systems → Power electronics	Component	Low performance	Technical limitations

	by accidents can lead to short circuit currents of up to 20,000 A. As the capacity of the batteries grows in the future, so too will this figure. Fuses and automotive high voltage protection mechanisms have in many cases reached the limits of their potential.” (TU Vienna, 2019, p. 66)	(Synergy BEV and FCEV)			
ATZ Volume 121 Issue 01 Article 08	*“The truck manufacturer is also tackling the problem of the lack of a hydrogen infrastructure. Together with the Norwegian company Nel Hydrogen, Nikola aims to set up a network of hydrogen fuel stations by 2022.” (Nikola, 2019, p. 32)*	Hydrogen refueling infrastructure	Complement	Lack of infrastructure → Low availability	-
IJoAT Volume 20 Issue 04 Article 09	*“Moreover, it is inevitable that a significant amount of heat is generated when an EV climbs steep slopes, because the energy efficiency of electric motors is low at low speed rotations.” (Bang, 2019, p. 739)*	E-Motor (Synergy BEV and FCEV)	Component	Low efficiency → Low performance	Heat generation in climb steep slopes
IJoAT Volume 20 Issue 06 Article 04	*“Due to these advantages, PEFCs are expected to be the main energy source for Fuel Cell Electric Vehicles (FCEVs), the next generation eco-friendly vehicles. However, before the commercialization of FCEVs, durability is one of the most important issues to be solved. Several degradation phenomena such as decomposition of the electrolyte membrane and deterioration of the electrode activity for fuel cell reactions have been reported.” (Yang et al., 2019, p. 1113)*	Fuel Cell	Component	Limited lifetime expectation → Low quality	Several degradation phenomena
IJoAT Volume 20 Issue 06 Article 04	*“Recent investigations reveal that the Pt/C catalyst is severely deteriorated during repeated potential cycling rather than constant potential holding at cathode side. Especially, among many deterioration factors, the formation of Pt surface oxide layer (Pt-OH, Pt-O) and subsequent dissolution of Pt is*	Fuel Cell catalyst → Membrane electrode assembly → Fuel Cell	Component	Limited lifetime expectation → Low quality	Repeated potential cycling (load changes)

	considered to be one of the main reasons for the Pt/C catalyst deterioration." (Yang et al., 2019, p. 1114)				
ATZ Volume 120 Issue 12 Article 14	*"The hydrogen storage tanks in the vehicle can be filled just as quickly as fuel tanks in conventional gasoline or diesel cars. However, the hydrogen tanks are currently very heavy and expensive to manufacture." (BAM, 2018, p. 65)*	Hydrogen tank → Hydrogen system	Component	High weight → Low performance	-
				High costs	
ATZ Volume 120 Issue 11 Article 03	*"The sales staff in the dealerships are not fully informed and have to spend a lot of time encouraging customers to take an interest in the technology. In a study published in the journal "Nature Energy," the University of Aarhus came to the conclusion that "car dealerships represent a significant barrier to the market launch of electric cars." (Liebl, 2018a, p. 9)*	Dealer and workshop (Synergy BEV and FCEV)	Complement	Lack of capabilities → Low performance	Lack of experience in EV
ATZ Volume 120 Issue 05 Article 04	*"If we now switch to the fuel cell, we will have a far lower level of energy efficiency," says Hey, rejecting the suggestion that the fuel cell drive is the ideal solution. He argues in detail that "roughly twice as much energy has to be consumed propelling a vehicle with a fuel cell as far as one directly powered by electricity." (Burkert, 2018b, p. 16)*	Fuel Cell	Component	Low efficiency → Low performance	Energy demanding
ATZ Volume 120 Issue 02 Article 10	*"One major challenge in the intake system lies in rating the air filter. This needs to protect the fuel cell system from contamination. Solid and gaseous components must be kept away from compressor, heat exchanger and, above all, the MEA." (Pundt et al., 2018, p. 40)*	Air filter → Oxygen supply	Component	High complexity → Low performance	High effort in air filtration effort due to a sensitive MEA
IJoAT Volume 19 Issue 01 Article 12	*"However, this conclusion ignores the negative effect of the non-work permanent magnet synchronous motor (PMSM) on system power loss, which has been overthrown by experiment tests carried out by Gu et al. (2013) as there still exists*	E-Motor (Synergy FCEV and BEV)	Component	Low efficiency → Low performance	Friction and iron losses even when the PMSM is not working

	friction and iron losses in the motored PMSM.” (Pundt et al., 2018, p. 122)				
ATZ Volume 119 Issue 09 Article 16	*“Fuel cells can make an important contribution to the goal of zero-emissions mobility, provided that they use regenerative hydrogen (H2). However, the cost of automotive fuel cells is currently still very high.” (FVV, 2017, p. 66)*	Fuel Cell	Component	High costs	-
ATZ Volume 119 Issue 09 Article 12	*“Thermal management plays an important role in vehicles powered by fuel cells as well. While the requirements for the battery, electric motor, and electronics remain the same, heating the hydrogen is yet another task. Compared with a combustion engine, about 30 % more specific cooling capacity must be provided for the powertrain.” (Wawzyniak et al., 2017, p. 50)*	Thermal Management of powertrain → Thermal Management	Component	High complexity → Low performance	Energy demanding due to additional heating of the hydrogen
ATZ Volume 119 Issue 06 Article 14	*“The move to fuel cell cars will help significantly in reducing CO2 emissions. The hydrogen infrastructure required for this transition could be the key to replacing fossil fuels with renewable energies in future. Scientists at the Forschungszentrum Jülich, Germany, estimate that investments totaling 61 billion euros will be needed to set up the complete infrastructure for passenger car transport in Germany.” (Forschungszentrum Jülich, 2017, p. 63)*	Hydrogen refueling infrastructure	Complement	Lack of infrastructure → Low availability	High costs for expansion
ATZ Volume 119 Issue 06 Article 14	*“New materials are needed for fuel cells which can act as highly efficient catalysts for the required chemical reaction, but which also last as long as possible without their properties changing.” (TU Wien, 2017, p. 62)*	Fuel Cell catalyst → Membrane electrode assembly → Fuel Cell	Component	Low efficiency → Low performance	-

ATZ Volume 119 Issue 05 Article 13	*“A BEV, extended by a fuel cell (FC), is able to compensate the current insufficient hydrogen infrastructure as it benefits of an existing infrastructure for electric charging and meets customer’s needs for short refueling durations, excellent drivability, long driving range and high-power demand.” (Müller et al., 2017, p. 57)*	Hydrogen refueling infrastructure	Complement	Lack of infrastructure → Low availability	-
ATZ Volume 119 Issue 05 Article 13	*“On account of the significant higher energy density of hydrogen compared to batteries [1], the sensitivity of the FCEV powertrain costs and weight to the amount of energy stored is lower. Therefore, hydrogen represents an outstanding energy carrier when high power and huge energy amount are required (heavy loads, long range). Nevertheless, today’s insufficient hydrogen refueling stations represents a barrier for a wider use.” (Müller et al., 2017, p. 57)*	Hydrogen refueling infrastructure	Complement	Lack of infrastructure → Low availability	-
ATZ Volume 119 Issue 03 Article 14	*“Fuel cells convert chemical energy in fuels such as hydrogen and methane into electricity. The key component of fuel cells is the proton exchange membrane, which allows only the tiny hydrogen ions (protons) to diffuse towards the cathode while blocking the oxygen and hydrogen atoms. Until now, NAFION membranes have been the most commonly used type, but these only work efficient at certain humidity levels and at temperatures below 90 °C.” (Helmholtz Centre Berlin, 2017, p. 65)*	Membrane electrode assembly → Fuel Cell	Component	Low efficiency → Low performance	Temperature sensitivity and need for humidity
ATZ Volume 118 Issue 05 Article 14	*“Can core-shell nanostructured catalysts be used in industrial and automotive fuel cells to generate electricity from the electrochemical conversion of hydrogen and oxygen? This is the question that the Low Pt Catalysts research project intends to answer. Core-shell nanostructured catalysts consist of a core*	Fuel Cell catalyst → Membrane electrode assembly → Fuel Cell	Component	Costs of raw material → High costs	-

	containing low levels of platinum surrounded by a wafer-thin, platinum-rich shell, which reduces the amount of costly platinum that is needed." (TU Berlin, 2016, p. 64)				
ATZ Volume 118 Issue 04 Article 15	*"Conventional fuel cells with platinum catalysts are too expensive for large-scale use, but cheaper systems are considerably less efficient." (Jacobs University Bremen, 2016, p. 69)*	Fuel Cell catalyst → Membrane electrode assembly → Fuel Cell	Component	Costs of raw material → High costs	Platinum is required to reach a high efficiency
ATZ Volume 118 Issue 03 Article 14	*"Hydrogen is the lightest chemical element and, under normal conditions, has a very large volume. When it is used as a fuel, it has until now only been possible to store it under high pressure in heavy bottles or at -253 °C in liquid form in tanks. Both methods have limited uses in mobile applications, because they are extremely costly." (University of Hamburg, 2016, p. 64)*	Hydrogen tank → Hydrogen system	Component	High costs	Storage of hydrogen (explosion risk and small molecular size)
IJoAT Volume 17 Issue 01 Article 15	*"In this regard, the aging effect can also become a critical problem for driving motors. As a result, motor parameters can change significantly under those different working conditions. More importantly, motor life will be affected too which can increase the possibility of sudden failures that are unacceptable for any fast-moving vehicle." (Liu et al., 2016, p. 153)*	E-Motor (Synergy FCEV and BEV)	Component	Limited lifetime expectation → Low quality	Aging effect
IJoAT Volume 17 Issue 01 Article 15	*"Considering the aging phenomenon during the lifetime of motors, magnet capability can remain only 70 % of their original value at the end of their lives for permanent magnet motors." (Liu et al., 2016, p. 155)*	E-Motor (Synergy FCEV and BEV)	Component	Limited lifetime expectation → Low quality	Aging effect
ATZ Volume 116 Issue 11	*"In the course of introducing fuel cell cars in series production, outstanding issues still need to be addressed: infrastructure, to support easily accessible*	Fuel Cell	Component	High costs	-
				Limited lifetime expectation	Durability issues

Article 03	*refueling H2 stations, and fuel cell technology, to guarantee comparable costs and durability." (Giczi et al., 2014, p. 14)*			→ Low quality	
		Hydrogen refueling infrastructure	Complement	Lack of infrastructure → Low availability	-
IJoAT Volume 15 Issue 01 Article 11	*"However, hydrogen supply infrastructures are not yet available and need to be developed in the near future." (Falahat et al., 2014, p. 97)*	Availability and transport of hydrogen	Complement	Lack of infrastructure → Low availability	-
		Hydrogen refueling infrastructure	Complement	Lack of infrastructure → Low availability	
IJoAT Volume 15 Issue 04 Article 14	*"However, at the current stage, the PEMFC still suffers from several technical barriers especially in terms of its short lifetime. To prolong the lifetime of the PEMFC, the PEMFC cannot be used to track fast dynamic power transients." (Geng et al., 2014, p. 645)*	Fuel Cell	Component	Limited lifetime expectation → Low quality	-
				Bad dynamic behavior → Low quality	
IJoAT Volume 15 Issue 07 Article 14	*"However, fuel cells have some problems, such as a slow response, difficulty starting cold, braking energy that cannot be recycled (Yun et al., 2010) and most importantly, the fuel cells and the infrastructure for hydrogen stations are extremely costly." (Suh et al., 2014, p. 1165)*	Fuel Cell	Component	Bad dynamic behavior → Low performance	Recycling of braking energy and cold start ability
				High costs	-
		Hydrogen refueling infrastructure	Complement	Lack of infrastructure → Low availability	Expansion costs of infrastructure

ATZ Volume 115 Issue 12 Article 03	*“Unlike the PSM, the technology used does not require any rare earth elements such as neodymium and dysprosium. The availability and price of these raw materials on global markets fluctuate wildly – which entails a cost risk that is virtually impossible to assess for OEMs and suppliers of electromobility.” (Domian et al., 2013, p. 11)*	E-Motor (Synergy FCEV and BEV)	Component	Costs of raw material → High costs	-
ATZ Volume 115 Issue 07/08 Article 08	*“The costs of the stack are dominant and are mainly determined by the size of the active area — higher power requirements and lower power densities both increase its costs.” (Hellmann et al., 2013, p. 40)*	Fuel Cell	Component	High costs	Low power densities and high-power requirements
ATZ Volume 115 Issue 03 Article 07	*“Permanently excited motors require rare earths, but these raw materials are becoming increasingly scarce and more expensive due to market economic reasons.” (Röhrl et al., 2013, p. 40)*	E-Motor (Synergy FCEV and BEV)	Component	Costs of raw material → High costs	Scarcity of raw materials
ATZ Volume 115 Issue 01 Article 05	*“At the center of these discussions is the question of whether these new drive systems will be accepted by potential customers. Apart from rather technical factors, such as a relatively short range and long charging times for battery-powered vehicles or the lack of infrastructure for battery-powered and fuel-cell vehicles, it is the still high purchasing price in particular – compared to vehicles with conventional drive systems – that represents a major obstacle to achieving wide customer acceptance.” (Kreyenberg et al., 2013, p. 23)*	Hydrogen refueling infrastructure	Complement	Lack of infrastructure → Low availability	-
IJoAT Volume 14 Issue 03 Article 13	*“No currently available advanced technology has completely resolved the issues associated with the water balance in the cell. Thus, water management remains a key technical challenge for guaranteeing the performance of PEM fuel cells.” (Park et al., 2013, p. 450)*	Fuel Cell management → Fuel Cell	Component	Low performance	Caused by insufficient water balance

IJoAT Volume 14 Issue 05 Article 12	“As we know, the efficiency of PMSM is low at the low-torque and low-speed range.” (Gu et al., 2013, p. 764)	E-Motor (Synergy FCEV and BEV)	Component	Low efficiency → Low performance	Inefficient in low torque and speed range
ATZ Volume 114 Issue 12 Article 03	*“However, because of its nature such as its low specific gravity and an extremely high diffusivity, hydrogen could be easily diffused and diluted in the air even in the remote chance of a leakage.” (Ikeya et al., 2012, p. 12)*	Hydrogen tank → Hydrogen System	Component	High complexity → Low performance	Storage of Hydrogen (small molecular size, etc.)
ATZ Volume 114 Issue 12 Article 01	*“[…] the fuel cells. At the start of this millennium, the term was on everyone’s lips. In meantime, the concept was already declared dead – too complicated, too expensive was the verdict. Now it is experiencing something of a renaissance as people start to realize that this concept is far superior to electric cars in terms of driving range. Of course, there is still the problem of cost, which has to be solved if fuel-cell vehicles are to be sold in more than merely homeopathic quantities and only for test purposes.” (Heintzel, 2012, p. 3)*	Fuel cell	Component	High costs	-
ATZ Volume 114 Issue 10 Article 03	*“Fuel cell costs, lifetime and environment adaptability still fail to meet vehicle application requirements, so it is difficult to commercialize a fuel cell vehicle within a short term.” (Li, 2012, p. 12)*	Fuel cell	Component	High costs	-
				Limited lifetime expectation → Low quality	-
IJoAT Volume 13 Issue 01 Article 03	*“Therefore, the development of an efficient and realistic hydrogen production device may accelerate fuel cell technology by resolving a primary roadblock, which is the need for an on-board hydrogen supply system.” (Lee et al., 2012b, p. 23)*	On-board Hydrogen supply → Hydrogen system	Component	Low efficiency → Low performance	Actual on-board Hydrogen production systems are inefficient

IJoAT Volume 13 Issue 05 Article 11	*“In a typical fuel cell, hydrogen gas is pumped in and passes through a catalytic bed, where dissolved species contact a catalyst. Some performance degradation is induced in a PEMFC by an unsuitably designed channel route in a bipolar plate.” (Kim and Sun, 2012, p. 783)*	Bipolar plates → Fuel Cell	Component	Low performance	Unsuitable channel routes
ATZ Volume 113 Issue 04 Article 10	*“At the same time, the electric drive system can support acceleration and also has a fuel consumption-reducing effect through regenerative breaking. As the existence of a comprehensive network of hydrogen filling stations is unlikely in the short term, the internal combustion engine will initially run on conventional fuel.” (Fickel et al., 2011, p. 47)*	Hydrogen refueling infrastructure	Complement	Lack of infrastructure → Low availability	-
IJoAT Volume 12 Issue 03 Article 15	*“Furthermore, also Fuel Cells exhibit low transient performances and their development is closely related to the Hydrogen production and supply infrastructure […].” (Liu et al., 2011, p. 433)*	Fuel cell	Component	Bad dynamic behavior → Low performance	-
ATZ Volume 112 Issue 03 Article 03	*“An improvement of competitiveness compared to conventional vehicles powered by gasoline or diesel and other alternative fuel storage technologies requires a significant expansion of cruising range greater than 500 km at lower costs. However, in the segment of passenger cars the effect of manufacturer specific weight restrictions will be applied increasingly, for example the maximum load per axle or restriction for compliance with inertia weight class. This reason requires a reduction of the mass-to-volume ratio below 0.5 kg/l for high pressure cylinders with a working pressure of 20 MPa.” (Novak and Krainz, 2010, p. 20)*	Hydrogen tank → Hydrogen system	Component	High weight → Low performance	-

IJoAT Volume 11 Issue 02 Article 10	*“Similar to the automotive engine, fuel cells have some problems, such as a slow response, difficulty starting cold, and braking energy that cannot be recycled.” (Yun et al., 2010, p. 223)*	Fuel Cell	Component	Bad dynamic behavior → Low performance	Unable to use recuperation energy and slow response
				Low performance	Cold start ability
IJoAT Volume 11 Issue 03 Article 16	*“Many studies have been conducted to prepare for the day when Fuel cell costs become competitive with other energy conversion technologies.” (Choi et al., 2010, p. 429)*	Fuel Cell	Component	High costs	-
IJoAT Volume 11 Issue 06 Article 16	*“Therefore, in the development process of new fuel-cell vehicles, ensuring adequate stack-cooling capacity is an important issue. The stack-coolant temperature is about 65ºC at the radiator inlet, which is far lower than the typical coolant temperature of 90ºC in internal-combustion-engine automobiles. Therefore, it is quite difficult to release all of the heat generated in the stack using a radiator of limited size because of the reduced temperature difference between the coolant and the ambient air.” (Kim et al., 2010, p. 894)*	Thermal management of powertrain → Thermal management	Component	High complexity → Low performance	Difficulties in stack cooling due to low-temperature differences between coolant and ambient air
IJoAT Volume 11 Issue 06 Article 16	*“Insufficient stack cooling allows the temperature of the fuel-cell membrane to increase, and it then starts to dry so that ion conductivity decreases; thus, stack voltage is decreased. If this drying continues for too long or repeatedly, the durability of the fuel-cell stack is reduced, and there is the risk of severe damage to the membrane.” (Kim et al., 2010, p. 897)*	Fuel Cell	Component	Limited lifetime expectation → Low quality	Damaging effect if stack cooling is inefficient
IJoAT Volume 09 Issue 01 Article 14	*“Also, a rapid change in required power may reduce the durability of the fuel cell or result in damages to the fuel cell.” (An et al., 2008, p. 113)*	Fuel Cell	Component	Limited lifetime expectation → Low quality	Rapid load variations

ATZ Volume 109 Issue 09 Article 03	*“First, the entire fuel cell system will have to be made simpler and more robust by reducing the number of components. Fewer components also mean fewer opportunities for faults, which in turn results in lower costs. Another goal is to make existing components smaller in order to save space and reduce weight. Finally, the engineers will also be working to further increase the lifetime and power density of the fuel cell stacks by the time the system is ready for series production.” (Mohrdieck and Docter, 2007, p. 10)*	Fuel Cell	Component	High complexity → Low performance	-
				High costs	
				Limited lifetime expectations → Low quality	
		Oxygen supply	Component	High complexity → Low performance	-
		Hydrogen system	Component	High complexity → Low performance	-
IJoAT Volume 08 Issue 01 Article 15	*“Therefore, water management is an important operation issue in a PEM fuel cell because the liquid water in the fuel cell causes electrode flooding that can lower the cell performance under high current density conditions.” (Ha et al., 2007, p. 119)*	Fuel Cell management → Fuel Cell	Component	Low efficiency → Low performance	-
IJoAT Volume 08 Issue 01 Article 15	*“However, for the PEM fuel cell to be commercially viable, the efficiency and performance should be much improved by proper engineering optimization and design work.” (Ha et al., 2007, p. 119)*	Fuel Cell	Component	Low efficiency → Low performance	-
IJoAT Volume 08 Issue 01 Article 15	“In the case of PEM fuel cell, due to low temperature (< 90°C), water produced by electrochemical reaction in the catalyst layer was not exhausted properly and remained in the gas channel. When this phenomenon occurs, accumulated liquid water causes mass transfer limitation, which leads to the decline of PEM	Fuel Cell management → Fuel Cell	Component	Low efficiency → Low performance	-

	fuel cell performance; this phenomenon is called flooding […].” (Ha et al., 2007, p. 122)				
IJoAT Volume 08 Issue 05 Article 14	*“FCEVs use a fuel cell system, which functions by converting hydrogen into electricity, as the main power source to operate the motor. It has many advantages compared with ICVs and HEVs in that it uses alternate energy sources, is classified as a ZEV, and manages high well-to-wheel fuel efficiency. However, it also has some disadvantages such as a slow response time and low fuel efficiency in the low power region.” (Ahn et al., 2007, p. 651)*	Fuel Cell	Component	Low efficiency → Low performance	Low power regions
				Bad dynamic behavior → Low performance	Slow response time
IJoAT Volume 08 Issue 05 Article 14	*“The efficiency of a fuel cell system is very low during low load operation owing to accessory loads such as the air compressor, hydrogen pump, and water/heat management. Even under high load conditions, the fuel cell is forced to operate with a low power efficiency, since the fuel cell stack voltage drops sharply with increasing load.” (Ahn et al., 2007, p. 653)*	Fuel Cell	Component	Low efficiency → Low performance	Accessory loads (e.g., compressor)
IJoAT Volume 08 Issue 06 Article 11	*“This type of fuel cell has many advantages such as high efficiency, low temperature operation, and it is clean, quiet, and capable of quick startup. However, performance and durability under harsh environments and high cost should be optimized in order to be competitive with conventional combustion power sources.” (Lee et al., 2007, p. 761)*	Fuel Cell	Component	High costs	-
				Low performance	Harsh environments
				Limited lifetime expectations → Low quality	Harsh environments
ATZ Volume 108 Issue 07/08 Article 05	*“After-sales service personnel must receive further training and workshops need to be prepared for handling high voltages, Figure 5. For legal considerations (labor law), it is still unclear as to*	Dealer and workshop (Synergy to BEV)	Complement	Lack of capabilities → Low availability	Missing legal regulations and training for service personnel

	which automotive mechanics will be allowed to repair HV components.” (Voß et al., 2006, p. 18)				
ATZ Volume 108 Issue 05 Article 08	*“A series of problems must be solved before fuel cell vehicles can be successfully introduced into the market. A significant cost reduction of the fuel cells is necessary, as well as a longer lifetime.” (Friedrich and Treffinger, 2006, p. 25)*	Fuel Cell	Component	High costs	-
				Limited lifetime expectations → Low quality	-
ATZ Volume 108 Issue 05 Article 08	*“Based on the CO2 emissions, it can be concluded that the fuel cell vehicle will then be successful when the hydrogen infrastructure, and storage questions are both sufficiently and eco-nomically resolved.” (Friedrich and Treffinger, 2006, p. 25)*	Hydrogen refueling infrastructure	Complement	Lack of infrastructure → Low availability	-
		Hydrogen tank → Hydrogen System	Component	High complexity → Low performance	-
IJoAT Volume 07 Issue 07 Article 15	*“Unfortunately, there are still many problems to be solved in order to make them into the commercial use, such as the thermal and water management in working process of PEMFCs.” (Kim et al., 2006, p. 867)*	Fuel Cell management → Fuel Cell	Component	Low performance	-
		Thermal management of powertrain → Thermal management	Component		
IJoAT Volume 07 Issue 07 Article 15	*“Unfortunately, fuel cell is not mature enough to compete with established battery technologies (Yang, 2000), the cost of fuel cells still remains high and unaffordable for most of the consumers, and very few products are available with full commercial warranties and a track record for reliable operation. Other barriers to commercial use are as following: fuel cell*	Fuel cell	Component	High costs	-
				Limited lifetime expectations → Low quality	Durability
				Low reliability →	-

	cost, fuel cell durability, fuel infrastructure, and hydrogen storage.” (Kim et al., 2006, p. 867)			Low performance	
		Hydrogen refueling infrastructure	Complement	Lack of infrastructure → Low availability	-
		Hydrogen tank → Hydrogen system	Component	High complexity → Low performance	-
ATZ Volume 107 Issue 06 Article 07	*“The Brennstoffzellen-Bündnis Deutschland (fuel cell association in Germany) is preparing a strategic paper for the market launch in Germany, and all leading German manufacturers are participating. The obstacles to the market launch are known, but can they be overcome? The main ones that are usually mentioned are the lack of infrastructure, costs and financing as well as fuel cell reliability.” (Hertel, 2005, p. 25)*	Hydrogen refueling infrastructure	Complement	Lack of infrastructure → Low availability	-
		Fuel Cell	Component	Low reliability → Low performance	-
ATZ Volume 107 Issue 06 Article 07	*“High system costs are a key argument why fuel cells are not yet used in larger quantities. These costs are only partially due to high material costs – the development costs are also enormous. One of the main cost factors is the noble metal catalyst (in most cases platinum).” (Hertel, 2005, p. 25)*	Fuel Cell catalyst → Membrane electrode assembly → Fuel Cell	Component	Costs of raw material → High costs	-
ATZ Volume 107 Issue 06 Article 07	*“In particular, where the membrane is used in vehicles the specific operating conditions always have to be taken into account. Constant load changes and changes in the environmental conditions provide the biggest challenges to the stability of the fuel cells compared to other applications.” (Hertel, 2005, p. 23)*	Membrane electrode assembly → Fuel Cell	Component	Low performance	Environmental conditions hugely influence performance

ATZ Volume 107 Issue 05 Article 06	*“The use of hydrogen in vehicle engines demands a nationwide network of filling stations. This would require an entirely new infrastructure and large investment costs.” (Blesl et al., 2005, p. 19)*	Hydrogen refueling infrastructure	Complement	Lack of infrastructure → Low availability	High costs for expansion
ATZ Volume 106 Issue 07/08 Article 11	*“Since hydrogen fuel cells are still extremely expensive, they could for example find some uses in some individual areas of car traffic and play a kind of alibi role in spite of the CO2 emissions, while the problems to be solved due to the increase of lorry traffic could possibly even force the specific further development of the H2-fuelled internal combustion engine in place of the discontinuation of projects of this kind, which has happened in the past.” (Peschka, 2004b, p. 43)*	Fuel Cell	Component	High costs	-
ATZ Volume 106 Issue 06 Article 06	*“One conclusion often drawn from the higher energy efficiency (often vaguely termed “efficiency”) is that the fuel cell is superior to the combustion engine. However, closer examination reveals that, in the most favorable case, only about 50% of the energy used is available for vehicle propulsion because a part of the electrical energy produced by the cell is necessary for keeping the cell operable, for example, cooling, air pre-compression, gas recirculation etc.” (Peschka, 2004a, p. 25)*	Fuel Cell	Component	Low efficiency → Low performance	Only 50% of the energy used for vehicle propulsion
IJoAT Volume 05 Issue 04 Article 07	*“Although there is a major issue with the hydrogen supply infrastructure, these prototype FCEVs have been demonstrating various favorable features of FCEVs as well as providing the guidelines for the future development directions.” (Park et al., 2004, p. 287)*	Hydrogen refueling infrastructure	Complement	Lack of infrastructure → Low availability	-
		Availability and transport of Hydrogen	Complement	Lack of infrastructure → Low availability	-

ATZ Volume 104 Issue 07/08 Article 01	*“According to data recently released, fuel cells seem to be able to compete with IC engines today in terms of specific power and power density [19]. However, the major challenges facing this technology still remain: efficient on-board storage, a countrywide fuel infrastructure and, last but not least, the fuel cell cost issue.” (Boulouchos et al., 2002, p. 4)*	Hydrogen tank → Hydrogen System	Component	High complexity → Low performance	Storage of Hydrogen (small molecular size, etc.)
		Hydrogen refueling infrastructure	Complement	Lack of infrastructure → Low availability	-
		Fuel Cell	Component	High costs	-
ATZ Volume 104 Issue 02 Article 02	*“In Germany alone there are currently approx. 17,000 service stations for conventional fuels that are supplied by approx. 10,000 tankers. Already today, it is necessary to lay the foundation stone to ensure that such a closely meshed supply network will also be available for hydrogen in several decades.” (Pehr et al., 2002, p. 9)*	Hydrogen refueling infrastructure	Complement	Lack of infrastructure → Low availability	-
ATZ Volume 104 Issue 02 Article 02	*“Nevertheless, challenges such as frost resistance as well as increasing the power density and service life while at the same time drastically reducing production costs still need to be effectively managed before fuel cells can be used effectively in future series production vehicles.” (Pehr et al., 2002, p. 8)*	Fuel Cell	Component	Bad dynamic behavior → Low performance	Low power density
				High costs	-
				Limited lifetime expectations → Low quality	-

ATZ Volume 103 Issue 05 Article 05	*"A third reason for a slow rise in sales is the limited network of methanol filling stations or, later on, hydrogen filling stations." (Dudenhöffer, 2001, p. 19)*	Hydrogen refueling infrastructure	Complement	Lack of infrastructure → Low availability	-
ATZ Volume 103 Issue 05 Article 05	*"From today's perspective, the Californian regulations demand such solutions until direct hydrogen fuel cell vehicles (without a reformer) are ready for series production. The BMW experiment with its H2 internal combustion engines could also be such an intermediate solution. However, as the hydrogen storage problem has to be solved in a marketable way as a precondition for H2 combustion engines, the BMW approach will show its qualities at the same time as fuel cell cars." (Dudenhöffer, 2001, p. 19)*	Hydrogen tank → Hydrogen System	Component	High complexity → Low performance	Storage of Hydrogen (small molecular size, etc.)
ATZ Volume 103 Issue 05 Article 05	*"It is also possible that the conversion of internal combustion engines to natural gas will increase. Analyzing sales of natural gas-powered vehicles show that a dense filling station network will also be necessary for the market success of fuel cell cars." (Dudenhöffer, 2001, p. 19)*	Hydrogen refueling infrastructure	Complement	Lack of infrastructure → Low availability	-
ATZ Volume 103 Issue 04 Article 01	*"Besides the challenge of having the right fuel on board a vehicle, there is also the problem of the fuel infrastructure. H2 is considered to be viable as the only possible long-term option, in particular for reasons of a sustainable energy development. However, this option suffers from the non- availability of an existing fuel infrastructure. Investment cost for the world-wide gasoline infrastructure that exists today are in the range of billions of DM." (Scherer and Röder, 2001, p. 3)*	Hydrogen refueling infrastructure	Complement	Lack of infrastructure → Low availability	High costs for expansion

ATZ Volume 103 Issue 04 Article 01	*"Due to the constraints set up by the operating temperature of the PEFC, only pure hydrogen is considered to be the ideal fuel for this fuel cell type. As a consequence, pure hydrogen must be stored on board the vehicle, either as compressed H2 or liquefied (cryogenic) H2, or H2 must be liberated on-board (reforming process) from a fuel containing H2, e.g. methanol or hydrocarbons (gasoline). Hydrogen storage on board suffers either from the low energy density value of compressed H2 (300 bar: 1.1 kWh/kg, 0.4 kWh/l; values without weight and volume of tank) or the low temperatures (– 253 °C) necessary to store liquefied H2." (Scherer and Röder, 2001, p. 3)*	Hydrogen tank → Hydrogen system	Component	High complexity → Low performance	Storage of Hydrogen (small molecular size, etc.)
ATZ Volume 102 Issue 07/08 Article 10	*„Es ist kein Energieträger bekannt, der diese Forderungen erfüllt und gleichzeitig emissionsfrei umgesetzt werden kann. Zwar ist Wasserstoff in flüssiger oder komprimierter Form ein denkbarer Kompromiss, jedoch hat er gravierende Nachteile in Bezug auf gefahrlosen Umgang und langfristige Speicherfähigkeit." (Herbst, 2000, p. 622)*	Hydrogen tank → Hydrogen system	Component	High complexity → Low performance	Storage of hydrogen (explosion risk and small molecular size)
ATZ Volume 102 Issue 07/08 Article 10	*„Fest-Brennstoffzellen, wie die mechanisch aufladbare Zink-Luft- [3] oder die Aluminium-Luft-Zelle [4] sind schon im Fahrzeugeinsatz getestet worden, konnten sich jedoch wegen der geringen Leistungsdichte und dem zu geringen Wirkungsgrad nicht durchsetzen." (Herbst, 2000, p. 625)*	Fuel Cell	Component	Low efficiency → Low performance	Low power density
IJoAT Volume 01 Issue 01 Article 01	*"The fuel cell is the most likely direct competitor to the internal combustion engine, but the need for a liquid fueling infrastructure and the high cost and inefficiencies associated with the use of an on board fuel reformer are likely to restrict the rate at which*	Hydrogen refueling infrastructure	Complement	Lack of infrastructure → Low availability	-
		On-board Hydrogen supply	Component	High costs	e.g., Methanol has to be

	they supplant the conventional engines.” (Monaghan, 2000, p. 7)	(fuel reformer) → Hydrogen system			transformed in Hydrogen
				Low efficiency → Low performance	e.g., Methanol has to be transformed in Hydrogen
IJoAT Volume 01 Issue 01 Article 02	*“Although DMFC technology has made significant advances in recent years, it still needs to overcome two major issues of low cell performance and methanol crossover.” (Yang, 2000, p. 12)*	Fuel Cell	Component	Low performance	-
IJoAT Volume 01 Issue 01 Article 02	*“Two of the most significant challenges are the hydrogen supply infrastructure and the cost reduction of the fuel cell stacks. The amount of capital investment for establishing various alternative fuel infrastructure are well compared in Storbart and Bentley (1998) showing that the hydrogen requires the biggest investment of $95 billion to displace 1 million barrels per day.” (Yang, 2000, p. 14)*	Fuel Cell	Component	High costs	-
		Hydrogen refueling infrastructure	Complement	Lack of infrastructure → Low availability	High costs for expansion
		Availability and transport of Hydrogen	Complement	Lack of infrastructure → Low availability	High costs for expansion
IJoAT Volume 01 Issue 01 Article 02	*“The performance of present fuel cell stacks is now adequate to meet automotive demands, but the present cost of stacks is approximately ten times too great. The projected cost breakdown for fuel cell stack components manufactured in high volume is shown in Figure 6 and shows that the majority of the stack cost resides in the catalyst and bipolar plates.” (Yang, 2000, p. 14)*	Fuel Cell catalyst → Membrane electrode assembly → Fuel Cell	Component	High costs	-
		Bipolar plates → Fuel Cell	Component	High costs	-
IJoAT Volume 01 Issue 01	*“This requires an air supercharging mechanism at a cost of parasitic loads, Current superchargers used in fuel cell power systems have excessive parasitic*	Compressor → Oxygen supply	Component	High weight → Low performance	-

Article 02	*loads, approaching 10 - 15 kW at a peak power of 50 kW net, and are heavy and big.” (Yang, 2000, p. 14)*				
IJoAT Volume 01 Issue 01 Article 02	*“Due to the low stack temperature of 80 — 90°C for 3 atm operation, the radiator size for a 60 kW net power system is projected to be 1.5 times larger than a compatible internal combustion engine vehicle.” (Yang, 2000, p. 15)*	Thermal management of powertrain → Thermal management	Component	High weight → Low performance	Low stack temperature

Appendix N: Matrix of (co-) occurrence BEV

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery production → Battery	-	-	Lack of capacity	-
Charging stations → Electric charging infrastructure	-	-	Lack of infrastructure	-

Journal: ATZ - Volume 122 - Issue 10 - Article 14

Component / Complement	High costs	Low quality	Low availability	Low performance
Thermal Management	-	-	-	Low reliability
Battery	High costs	-	-	-

Journal: ATZ - Volume 122 - Issue 09 - Article 03

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery Cathode → Battery cell → Battery	Costs of raw material	-	-	-
Disposal and recycling	-	-	Lack of capabilities	-

Journal: ATZ - Volume 122 - Issue 04 - Article 11

Component / Complement	High costs	Low quality	Low availability	Low performance
Digital integration → Electric charging infrastructure	-	-	-	Missing interoperability
Charging station → Electric charging infrastructure	-	-	-	Missing interoperability
Electric grid	-	-	-	Performance fluctuations
Battery cell → Battery	-	Limited lifetime expectation	-	Low performance

Journal: ATZ - Volume 122 - Issue 02 - Article 10

Component / Complement	High costs	Low quality	Low availability	Low performance
Charging station → Electric charging infrastructure	-	-	Lack of infrastructure	-
HVAC → Thermal management	-	-	-	Low performance
Battery	High costs	-	-	-

Journal: IJoAT - Volume 21 - Issue 01 - Article 15

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	-	-	-	Long charging time
Charging station → Electric charging infrastructure	-	-	-	Missing interoperability

Journal: IJoAT - Volume 21 - Issue 02 - Article 24

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	-	-	-	Limited capacity
Charging station → Electric charging infrastructure	-	-	Lack of infrastructure	-

Journal: ATZ - Volume 121 - Issue 09 - Article 17

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	-	-	-	Long charging time
Charging station → Electric charging infrastructure	-	-	-	Long charging time

Journal:: ATZ - Volume 121 - Issue 05 - Article 16

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	-	Safety risk	-	Limited lifetime expectation Limited range
Thermal management of battery	-	-	-	High complexity

→ Thermal management				

Journal: ATZ - Volume 121 - Issue 03 - Article 14

Component / Complement	**High costs**	**Low quality**	**Low availability**	**Low performance**
Electric grid	-	-	-	Performance fluctuations
Charging station → Electric charging infrastructure	-	-	Lack of infrastructure	-

Journal: ATZ - Volume 121 - Issue 03 - Article 08

Component / Complement	**High costs**	**Low quality**	**Low availability**	**Low performance**
Battery	-	-	-	Long charging time
Charging station → Electric charging infrastructure	-	-	Lack of infrastructure	-

Journal: IJoAT - Volume 20 - Issue 02 - Article 18

Component / Complement	**High costs**	**Low quality**	**Low availability**	**Low performance**
Battery cell → Battery	-	-	-	Low performance
Charging station → Electric charging infrastructure	-	-	Lack of infrastructure	-

Journal: ATZ - Volume 120 - Issue 12 - Article 12

Component / Complement	**High costs**	**Low quality**	**Low availability**	**Low performance**
On-board charger → Power electronics	-	-	-	Low performance
Charging station → Electric charging infrastructure	-	-	Lack of infrastructure	Long charging time

Journal: ATZ - Volume 120 - Issue 10 - Article 14

Component / Complement	**High costs**	**Low quality**	**Low availability**	**Low performance**
Battery	Costs of raw material	-	Lack of capabilities	Limited range

Disposal and recycling	-	-	Lack of capabilities Lack of capacities	-

Journal: ATZ - Volume 120 - Issue 09 - Article 04

Component / Complement	High costs	Low quality	Low availability	Low performance
HVAC → Thermal management	-	-	-	Low performance
Thermal management of battery → Thermal management	-	-	-	Low performance
Battery	-	-	-	Long charging time

Journal: ATZ - Volume 120 - Issue 05 - Article 14

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	High costs	Limited lifetime expectation	-	-
Thermal management of battery → Thermal management	-	-	-	High complexity

Journal: ATZ - Volume 120 - Issue 02 - Article 12

Component / Complement	High costs	Low quality	Low availability	Low performance
Electric grid	-	-	-	Performance fluctuations
Charging station → Electric charging infrastructure	-	-	Lack of infrastructure	-

Journal: ATZ - Volume 120 - Issue 02 - Article 04

Component / Complement	High costs	Low quality	Low availability	Low performance
Electric grid	-	-	-	Performance fluctuations
Charging station → Electric charging infrastructure	-	-	Lack of infrastructure	-

Journal: ATZ - Volume 120 - Issue 02 - Article 03

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	-	-	-	Low efficiency
Thermal management	-	-	-	Low performance

Journal: ATZ - Volume 120 - Issue 01 - Article 14

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	-	-	-	Limited capacity
E-Motor	-	-	-	Low efficiency

Journal: IJoAT - Volume 19 - Issue 01 - Article 12

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	High costs	-	-	-
Charging station → Electric charging infrastructure	-	-	Lack of infrastructure	-

Journal: IJoAT - Volume 19 - Issue 02 - Article 12

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	-	-	-	Long charging time
Thermal management	-	-	-	High complexity

Journal: ATZ - Volume 119 - Issue 09 - Article 12

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	-	Limited lifetime expectation	-	-
Charging station → Electric charging infrastructure	-	-	Lack of infrastructure	-

Journal: ATZ - Volume 119 - Issue 05 - Article 13

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	-	Limited lifetime expectation	-	Limited capacity

Thermal management of battery → Thermal management	-	-	-	High complexity

Journal: IJoAT - Volume 18 - Issue 05 - Article 12

Component / Complement	**High costs**	**Low quality**	**Low availability**	**Low performance**
Electric grid	-	-	Performance fluctuations	-
Charging station → Electric charging infrastructure	-	-	Lack of infrastructure	Missing interoperability

Journal: ATZ - Volume 118 - Issue 12 - Article 03

Component / Complement	**High costs**	**Low quality**	**Low availability**	**Low performance**
HVAC → Thermal management	-	-	-	Low performance
Charging station → Electric charging infrastructure	-	-	Lack of infrastructure	-

Journal: ATZ - Volume 118 - Issue 07 - Article 10

Component / Complement	**High costs**	**Low quality**	**Low availability**	**Low performance**
Battery	-	-	-	Long charging time High weight
Charging station → Electric charging infrastructure	-	-	Lack of infrastructure	-

Journal: ATZ - Volume 118 - Issue 07 - Article 03

Component / Complement	**High costs**	**Low quality**	**Low availability**	**Low performance**
Battery	-	-	-	Long charging time
Thermal management	-	-	-	Low efficiency

Journal: ATZ - Volume 118 - Issue 06 - Article 12

Component / Complement	**High costs**	**Low quality**	**Low availability**	**Low performance**
HVAC → Thermal management	-	-	-	Low performance
Thermal management of battery → Thermal management	-	-	-	Low performance
Battery	High costs	-	-	-

Journal: ATZ - Volume 117 - Issue 07 - Article 12

Component / Complement	**High costs**	**Low quality**	**Low availability**	**Low performance**
Battery	-	-	-	Long charging time
Thermal management	-	-	-	Low performance

Journal: ATZ - Volume 117 - Issue 01 - Article 05

Component / Complement	**High costs**	**Low quality**	**Low availability**	**Low performance**
Battery	High costs	-	-	Long charging time
Charging station → Electric charging infrastructure	-	-	Lack of infrastructure	Long charging time

Journal: IJoAT - Volume 16 - Issue 05 - Article 13

Component / Complement	**High costs**	**Low quality**	**Low availability**	**Low performance**
Battery	-	-	-	Limited range
HVAC → Thermal management	-	-	-	Low performance

Journal: IJoAT - Volume 16 - Issue 06 - Article 04

Component / Complement	**High costs**	**Low quality**	**Low availability**	**Low performance**
Battery	-	-	-	Low efficiency Limited capacity

HVAC → Thermal management	-	-	-	Low performance
Thermal management of battery → Thermal management	-	-	-	High complexity

Journal: ATZ - Volume 116 - Issue 07 - Article 02

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	-	Limited lifetime expectation	-	Low performance
Thermal management of battery → Thermal management	-	-	-	High complexity

Journal: IJoAT - Volume 15 - Issue 05 - Article 12

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	High costs	-	-	Limited range High weight
Charging station → Electric charging infrastructure	-	-	Lack of infrastructure	-

Journal: IJoAT - Volume 15 - Issue 07 - Article 14

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	-	-	-	Limited range
E-Motor	Costs of raw material	-	-	-

Journal: ATZ - Volume 115 - Issue 12 - Article 03

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	-	-	-	Long charging time
Charging station → Electric charging infrastructure	-	-	Lack of infrastructure	Long charging time

Journal: ATZ - Volume 115 - Issue 01 - Article 05

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	High costs	-	-	Limited capacity
E-Motor	-	-	-	Low efficiency

Journal: IJoAT - Volume 14 - Issue 05 - Article 12

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	High costs	-	-	Long charging time High weight
Charging station → Electric charging infrastructure	-	-	-	Long charging time

Journal: ATZ - Volume 114 - Issue 01 - Article 11

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	High costs	-	-	-
Charging station → Electric charging infrastructure	-	-	Lack of infrastructure	-

Journal: IJoAT - Volume 13 - Issue 03 - Article 17

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	High costs	-	-	Limited capacity
HVAC → Thermal management	-	-	-	Low performance

Journal: ATZ - Volume 113 - Issue 11 - Article 03

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	-	-	-	Limited capacity
HVAC → Thermal management	-	-	-	Low performance

Journal: ATZ - Volume 113 - Issue 07 - Article 10

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	High costs	-	-	-
HVAC → Thermal management	-	-	-	High complexity
Thermal management	-	-	-	Low performance

Journal: ATZ - Volume 112 - Issue 04 - Article 02

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	High costs	-	-	-
Thermal management	-	-	-	Low performance

Journal: ATZ - Volume 111 - Issue 09 - Article 01

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	High costs	-	-	-
Charging station → Electric charging infrastructure	-	-	Lack of infrastructure	-

Journal: ATZ - Volume 111 - Issue 06 - Article 07

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	High costs	Safety risk	-	-
Charging station → Electric charging infrastructure	-	-	Lack of infrastructure	-
Thermal management of battery → Thermal management	-	-	-	High complexity

Journal: ATZ - Volume 111 - Issue 06 - Article 03

Component / Complement	High costs	Low quality	Low availability	Low performance
Battery	-	Limited lifetime expectation	-	-

Disposal and recycling	-	-	Lack of capabilities	-

Journal: ATZ - Volume 110 - Issue 03 - Article 05

Component / Complement	**High costs**	**Low quality**	**Low availability**	**Low performance**
Battery	-	-	-	Low performance
Thermal management of battery → Thermal management	-	-	-	High complexity

Journal: ATZ - Volume 109 - Issue 12 - Article 04

Component / Complement	**High costs**	**Low quality**	**Low availability**	**Low performance**
Battery	-	Limited lifetime expectation	-	Low performance
Dealer and workshop	-	-	Lack of capabilities	-

Journal: ATZ - Volume 109 - Issue 12 - Article 04

Component / Complement	**High costs**	**Low quality**	**Low availability**	**Low performance**
Battery	High costs	Limited lifetime expectation	-	Long charging time Limited capacity
Charging station → Electric charging infrastructure	-	-	Lack of infrastructure	Long charging time

Journal: ATZ - Volume 103 - Issue 01 - Article 07

Appendix O: Matrix of (co-) occurrence FCEV

Component / Complement	High costs	Low quality	Low availability	Low performance
Fuel Cell catalyst → Membrane electrode assembly → Fuel Cell	Costs of raw material	-	-	-
Disposal and recycling	-	-	Lack of capabilities	-

Journal: ATZ - Volume 122 - Issue 04 - Article 11

Component / Complement	High costs	Low quality	Low availability	Low performance
Hydrogen refueling infrastructure	-	-	Lack of infrastructure	-
Membrane electrode assembly → Fuel Cell	High costs	-	-	-
Fuel cell production → Fuel cell	Costs of production	-	-	-
Hydrogen tank → Hydrogen system	-	-	-	High complexity

Journal: ATZ - Volume 121 - Issue 04 - Article 03

Component / Complement	High costs	Low quality	Low availability	Low performance
Fuel Cell catalyst → Membrane electrode assembly → Fuel Cell	-	-	-	Low efficiency
Hydrogen refueling infrastructure	-	-	Lack of infrastructure	-

Journal: ATZ - Volume 119 - Issue 06 - Article 14

Component / Complement	High costs	Low quality	Low availability	Low performance
Fuel Cell	High costs	Limited lifetime expectation	-	-
Hydrogen refueling infrastructure	-	-	Lack of infrastructure	-

Journal: ATZ - Volume 116 - Issue 11 - Article 03

Component / Complement	High costs	Low quality	Low availability	Low performance
Availability and transport of hydrogen	-	-	Lack of infrastructure	-
Hydrogen refueling infrastructure	-	-	Lack of infrastructure	-

Journal: IJoAT - Volume 15 - Issue 01 - Article 11

Component / Complement	High costs	Low quality	Low availability	Low performance
Fuel Cell	High costs	-	-	Bad dynamic behavior
Hydrogen refueling infrastructure	-	-	Lack of infrastructure	-

Journal: IJoAT - Volume 15 - Issue 07 - Article 14

Component / Complement	High costs	Low quality	Low availability	Low performance
Fuel Cell	-	Limited lifetime expectation	-	-
Thermal management of powertrain → Thermal management	-	-	-	High complexity

Journal: IJoAT - Volume 11 - Issue 06 - Article 16

Component / Complement	High costs	Low quality	Low availability	Low performance
Fuel Cell	High costs	Limited lifetime expectation	-	High complexity
Oxygen supply	-	-	-	High complexity
Hydrogen system	-	-	-	High complexity

Journal: ATZ - Volume 109 - Issue 09 - Article 03

Component / Complement	High costs	Low quality	Low availability	Low performance
Fuel Cell	High costs	Limited lifetime expectation	-	-
Hydrogen refueling infrastructure	-	-	Lack of infrastructure	-
Hydrogen tank → Hydrogen system	-	-	-	High complexity

Journal: ATZ - Volume 108 - Issue 05 - Article 08

Component / Complement	High costs	Low quality	Low availability	Low performance
Fuel Cell management → Fuel Cell	-	-	-	Low performance
Thermal management of powertrain → Thermal management	-	-	-	Low performance
Fuel Cell	High costs	Limited lifetime expectation	-	Low reliability
Hydrogen refueling infrastructure	-	-	Lack of infrastructure	-
Hydrogen tank → Hydrogen system	-	-	-	High complexity

Journal: IJoAT - Volume 07 - Issue 07 - Article 15

Component / Complement	High costs	Low quality	Low availability	Low performance
Fuel Cell	-	-	-	Low reliability
Fuel Cell catalyst → Membrane electrode assembly → Fuel Cell	Costs of raw material	-	-	-
Membrane electrode assembly → Fuel Cell	-	-	-	Low performance
Hydrogen refueling infrastructure	-	-	Lack of infrastructure	-

Journal: ATZ - Volume 107 - Issue 06 - Article 07

Component / Complement	High costs	Low quality	Low availability	Low performance
Availability and transport of hydrogen	-	-	Lack of infrastructure	-
Hydrogen refueling infrastructure	-	-	Lack of infrastructure	-

Journal: IJoAT - Volume 05 - Issue 04 - Article 07

Component / Complement	High costs	Low quality	Low availability	Low performance
Fuel Cell	High costs	-	-	-
Hydrogen tank → Hydrogen system	-	-	-	High complexity
Hydrogen refueling infrastructure	-	-	Lack of infrastructure	-

Journal: ATZ - Volume 104 - Issue 07 - Article 01

Component / Complement	High costs	Low quality	Low availability	Low performance
Fuel Cell	High costs	Limited lifetime expectation	-	Bad dynamic behavior
Hydrogen refueling infrastructure	-	-	Lack of infrastructure	-

Journal: ATZ - Volume 104 - Issue 02 - Article 02

Component / Complement	High costs	Low quality	Low availability	Low performance
Hydrogen tank → Hydrogen System	-	-	-	High complexity
Hydrogen refueling infrastructure	-	-	Lack of infrastructure	-

Journal: ATZ - Volume 103 - Issue 05 - Article 05

Component / Complement	High costs	Low quality	Low availability	Low performance
Hydrogen tank → Hydrogen System	-	-	-	High complexity
Hydrogen refueling infrastructure	-	-	Lack of infrastructure	-

Journal: ATZ - Volume 103 - Issue 04 - Article 01

Component / Complement	High costs	Low quality	Low availability	Low performance
Hydrogen tank → Hydrogen System	-	-	-	High complexity
Fuel Cell	-	-	-	Low efficiency

Journal: ATZ - Volume 102 - Issue 07 - Article 10

Component / Complement	High costs	Low quality	Low availability	Low performance
Hydrogen refueling infrastructure	-	-	Lack of infrastructure	-

On-board Hydrogen supply	High costs	-	-	-

Journal: IJoAT - Volume 01 - Issue 01 - Article 01

Component / Complement	**High costs**	**Low quality**	**Low availability**	**Low performance**
Fuel Cell	High costs	-		Low performance
Fuel Cell catalyst → Membrane electrode assembly → Fuel Cell	High costs	-	-	-
Bipolar plates → Fuel Cell	High costs	-	-	-
Compressor → Oxygen supply	-	-	-	High weight
Thermal management of powertrain → Thermal management	-	-	-	High weight
Hydrogen refueling infrastructure	-	-	Lack of infrastructure	-
Availability and transport of Hydrogen	-	-	Lack of infrastructure	-

Journal: IJoAT - Volume 01 - Issue 01 - Article 02

Appendix P: Interview guide

Introductory question:

What is your research area and for how long have you been working in this field?

Key questions:

Introduction time period I:
In the early 2000s, legislation in California (mandatory ZEV quota from 1998 postponed to 2001 and 2003) brought locally emission-free passenger mobility more and more into the focus of the automotive industry. At that time, the two favored technologies in the field of passenger cars were already battery electric and fuel cell electric vehicles. However, the planned legislation in California was postponed several times due to "challenges with the technology" and was finally introduced in the year 2003 in a weakened form. Until 2006, car manufacturers primarily produced only prototypes, which were presented at trade fairs and operated in test mode, but were still far away from serial production.

1. **BEVs from 2000 to 2006:**

    a. **Which components/complements were the limiting factor in this period and therefore the decisive reason for the missing series production?**
    b. **How critical were limitations in terms of technical performance at that time?**
        i. Which performance dimensions were affected?
        ii. Could you further trace these limitations back to one or more components/complements?
    c. **What influence did the costs of the individual components/complements have on this development?**
        i. Which components/complements represented the main cost drivers?
        ii. What was the reason for the high cost of these components/complements?
    d. **What was the impact of the availability or the access to certain required components/complements at that time?**
        i. Which components/complements were affected?
        ii. How did this limited access to specific components/complements affect the value proposition of the overall vehicle to the end customer?
    e. **Does the poor quality (service life, damage, ...) of individual components/complements also result in limitations at this time?**
        i. If yes: Which components/complements were affected?
        ii. How did these limitations affect the operation of the overall vehicle?

2. **FCEVs from 2000 to 2006:**

    a. **Which components/complements were the limiting factor in this period and therefore the decisive reason for the missing series production?**
    b. **How critical were limitations in terms of technical performance at that time?**
        i. Which performance dimensions were affected?
        ii. Could you further trace these limitations back to one or more components/complements?
    c. **What influence did the costs of the individual components/complements have on this development?**
        i. Which components/complements represented the main cost drivers?

    ii. What was the reason for the high cost of these components/complements?

d. **What was the impact of the availability or the access to certain required components/complements at that time?**
    i. Which components/complements were affected?
    ii. How did this limited access to specific components/complements affect the value proposition of the overall vehicle to the end customer?
e. **Does the poor quality (service life, damage, ...) of individual components/complements also result in limitations at this time?**
    i. If yes: Which components/complements were affected?
    ii. How did these limitations affect the operation of the overall vehicle?

Introduction time period II:

At the end of the 2000s, there was also an agreement on CO_2 limits in Europe for the first time, although they were initially non-binding (from 2008). When it became foreseeable that only a few manufacturers would reach these limits and as a consequence, binding CO_2 limits would be introduced (announced in 2007 for 2012, introduced in 2009 for 2015), in particular, European manufacturers began to produce their concepts in small series and thus tested them in everyday operation (e.g., BEV: from 2007 Daimler Smart EV, from 2008 BMW Mini E, from 2010 VW Golf VI Blue-e-motion, FCEV: from 2009 B-Class F-Cell, from 2009 Honda FCX Clarity). Some vehicles were also distributed to selected customers (mostly leased). However, with a few exceptions, BEVs and FCEVs were still not in series production and sold freely on the market at this time.

3. **<u>BEVs from 2007 to 2013:</u>**

a. **Which components/complements were the limiting factor in this period and therefore the decisive reason for the missing series production?**
b. **How critical were limitations in terms of technical performance at that time?**
    i. Which performance dimensions were affected?
    ii. Could you further trace these limitations back to one or more components/complements?
c. **What influence did the costs of the individual components/complements have on this development?**
    i. Which components/complements represented the main cost drivers?
    ii. What was the reason for the high cost of these components/complements?
d. **What was the impact of the availability or the access to certain required components/complements at that time?**
    i. Which components/complements were affected?
    ii. How did this limited access to specific components/complements affect the value proposition of the overall vehicle to the end customer?
e. **Does the poor quality (service life, damage, ...) of individual components/complements also result in limitations at this time?**
    i. If yes: Which components/complements were affected?
    ii. How did these limitations affect the operation of the overall vehicle?

4. **<u>FCEVs from 2007 to 2013:</u>**

a. **Which components/complements were the limiting factor in this period and therefore the decisive reason for the missing series production?**
b. **How critical were limitations in terms of technical performance at that time?**
    i. Which performance dimensions were affected?
    ii. Could you further trace these limitations back to one or more components/complements?

c. **What influence did the costs of the individual components/complements have on this development?**
    i. Which components/complements represented the main cost drivers?
    ii. What was the reason for the high cost of these components/complements?

d. **What was the impact of the availability or the access to certain required components/complements at that time?**
    i. Which components/complements were affected?
    ii. How did this limited access to specific components/complements affect the value proposition of the overall vehicle to the end customer?

e. **Does the poor quality (service life, damage, ...) of individual components/complements also result in limitations at this time?**
    i. If yes: Which components/complements were affected?
    ii. How did these limitations affect the operation of the overall vehicle?

Introduction time period III:

In 2015, right before the first mandatory CO_2 limits became effective in the EU, the next phase began: many automotive manufacturers successively started series production of BEVs (e.g., BMW i3 from 2013, Daimler Smart EV 3rd Gen from 2012, VW e-UP! from 2013) and FCEVs (e.g., Toyota Mirai from 2014, Honda Clarity Fuel Cell from 2016, Hyundai iX35 FCEV from 2013). Nevertheless, the previously predicted high registration rates are still not present.

5. **BEVs from 2014 to today:**

a. **Which components/complements were the limiting factor in this period and therefore the decisive reason for the missing series production?**

b. **How critical were limitations in terms of technical performance at that time?**
    i. Which performance dimensions were affected?
    ii. Could you further trace these limitations back to one or more components/complements?

c. **What influence did the costs of the individual components/complements have on this development?**
    i. Which components/complements represented the main cost drivers?
    ii. What was the reason for the high cost of these components/complements?

d. **What was the impact of the availability or the access to certain required components/complements at that time?**
    i. Which components/complements were affected?
    ii. How did this limited access to specific components/complements affect the value proposition of the overall vehicle to the end customer?

e. **Does the poor quality (service life, damage, ...) of individual components/complements also result in limitations at this time?**
    i. If yes: Which components/complements were affected?
    ii. How did these limitations affect the operation of the overall vehicle?

6. **FCEVs from 2014 to today:**

a. **Which components/complements were the limiting factor in this period and therefore the decisive reason for the missing series production?**

b. **How critical were limitations in terms of technical performance at that time?**
    i. Which performance dimensions were affected?

        ii. Could you further trace these limitations back to one or more components/complements?

c. **What influence did the costs of the individual components/complements have on this development?**
    i. Which components/complements represented the main cost drivers?
    ii. What was the reason for the high cost of these components/complements?
d. **What was the impact of the availability or the access to certain required components/complements at that time?**
    i. Which components/complements were affected?
    ii. How did this limited access to specific components/complements affect the value proposition of the overall vehicle to the end customer?
e. **Does the poor quality (service life, damage, ...) of individual components/complements also result in limitations at this time?**
    i. If yes: Which components/complements were affected?
    ii. How did these limitations affect the operation of the overall vehicle?

Summary and outlook:

We are now coming to the end of the interview. We have prepared a few final questions:

a. **Do you think we have forgotten any significant aspect regarding the limiting components/complements of battery electric and fuel cell electric vehicles in the period from 2000 to today?**
b. **Which (scientific) journals would you rate as appropriate in terms of focus and quality to identify limiting components/complements in the two ecosystems?**
    i. If not mentioned: Would you rate the ATZ and the International Journal of Automotive Technology as suitable?
c. **If there is time left: Identify personal bias**
    i. Which of the two technologies is, in your opinion, more likely to replace the ICE in the medium term?
    ii. Do you have personal preferences for one of the two technologies? If yes, why?

Appendix Q: Comparison of BEV analysis results with validation interviews

Period	Results of analysis		Interview A		Interview B		Interview C	
	Component	Type of bottleneck	Component	Type of bottleneck	Component	Type of bottleneck	Component	Type of bottleneck
2000-2006	Battery	Low performance	Battery	Low performance	Battery	Low performance	Battery	Low performance
		High costs		High costs		High costs		Low quality
	Electric charging infrastructure	Low availability	Electric charging infrastructure	Low availability	Electric charging infrastructure	Low availability	E-Motor	Low availability
				Low performance		Low performance	Vehicle architecture	Low performance
	-	-	-	-	Power Electronics	Low performance	-	-
	-	-	-	-	E-Motor	Low performance	-	-
2007-2013	Battery	Low performance	Battery	No statements to bottleneck → only improvement of the performance, costs and quality	Battery	Low performance	Battery	Low performance
		High costs				Low quality		
		Low quality				High costs		
	Thermal Management	Low performance						
		Low availability		Low availability		Low availability		Low availability

	Electric charging infrastructure	Low performance	Electric charging infrastructure	Low performance	Electric charging infrastructure		Electric charging infrastructure	Low performance
2013-2020	Battery	Low performance	Battery	Low performance	Battery	High costs	Battery	Low performance
		High costs		High costs		Low performance		High costs
		Low quality		Low quality		Low quality		Low quality
	Thermal Management	Low performance	Electric charging infrastructure	Low availability	Electric charging infrastructure	Low performance	Electric charging infrastructure	Low availability
	Electric charging infrastructure	Low availability	-	-	Electric Grid	Low performance		Low performance
		Low performance	-	-	-	-	-	-
	Electric Grid	Low performance	-	-	-	-	-	-

Appendix R: Comparison of FCEV analysis results with validation interviews

Period	Results of analysis		Interview A		Interview B		Interview C	
	Component	Type of bottleneck	Component	Type of bottleneck	Component	Type of bottleneck	Component	Type of bottleneck
2000-2006	Fuel cell	Low performance	Fuel cell	Low performance	Fuel cell	Low performance	Fuel cell	Low performance
		High costs		High costs		High costs		High costs
						Low quality		
	Hydrogen system	Low performance	Hydrogen system	Low performance	Hydrogen system	Low performance	Hydrogen system	Low performance
				High costs		High costs		High costs
								Low quality
	Hydrogen refueling infrastructure	Low availability	Hydrogen refueling infrastructure	Low availability	Hydrogen refueling infrastructure	Low availability	Vehicle architecture	Low performance
	-	-	Oxygen supply	Low performance	Power Electronics	Low performance	-	-
	-	-	-	-	E-Motor	Low performance	-	-
2007-2013	Fuel cell	Low performance	Fuel cell	High costs	Fuel cell	Low quality	Fuel cell	Low performance
		High costs				High costs		

		Low quality						High costs
	Hydrogen refueling infrastructure	Low availability	Hydrogen refueling infrastructure	Low availability	Hydrogen refueling infrastructure	Low availability	Hydrogen refueling infrastructure	Low availability
	Hydrogen system	Low performance	Hydrogen system	High costs	Hydrogen system	High costs	Hydrogen system	High costs Low quality
	-	-	-	-	Power Electronics	Low performance	Oxygen supply	Low performance
	-	-	-	-	E-Motor	Low performance		
2013-2020	Fuel cell	High costs Low performance	Fuel cell	High costs	Fuel cell	High costs	Fuel cell	High costs
	Hydrogen system	High costs Low performance	Hydrogen system	High costs	Hydrogen system	High costs	Hydrogen system	High costs
	Hydrogen refueling infrastructure	Low availability	Hydrogen refueling infrastructure	Low availability	Hydrogen refueling infrastructure	Low availability	Hydrogen refueling infrastructure	Low availability
	E-Motor	Low performance	-	-	-	-	Oxygen supply	High costs