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**Research Report**

## Batteries for electric cars: Fact check and need for action. Are batteries for electric cars the key to sustainable mobility in the future?

Perspectives - Policy Brief, No. 01 / 2020

**Provided in Cooperation with:**

Fraunhofer Institute for Systems and Innovation Research ISI

*Suggested Citation:* Thielmann, Axel et al. (2020) : Batteries for electric cars: Fact check and need for action. Are batteries for electric cars the key to sustainable mobility in the future?, Perspectives - Policy Brief, No. 01 / 2020, Fraunhofer-Institut für System- und Innovationsforschung ISI, Karlsruhe, <https://doi.org/10.24406/publica-fhg-300931>

This Version is available at:

<https://hdl.handle.net/10419/233460>

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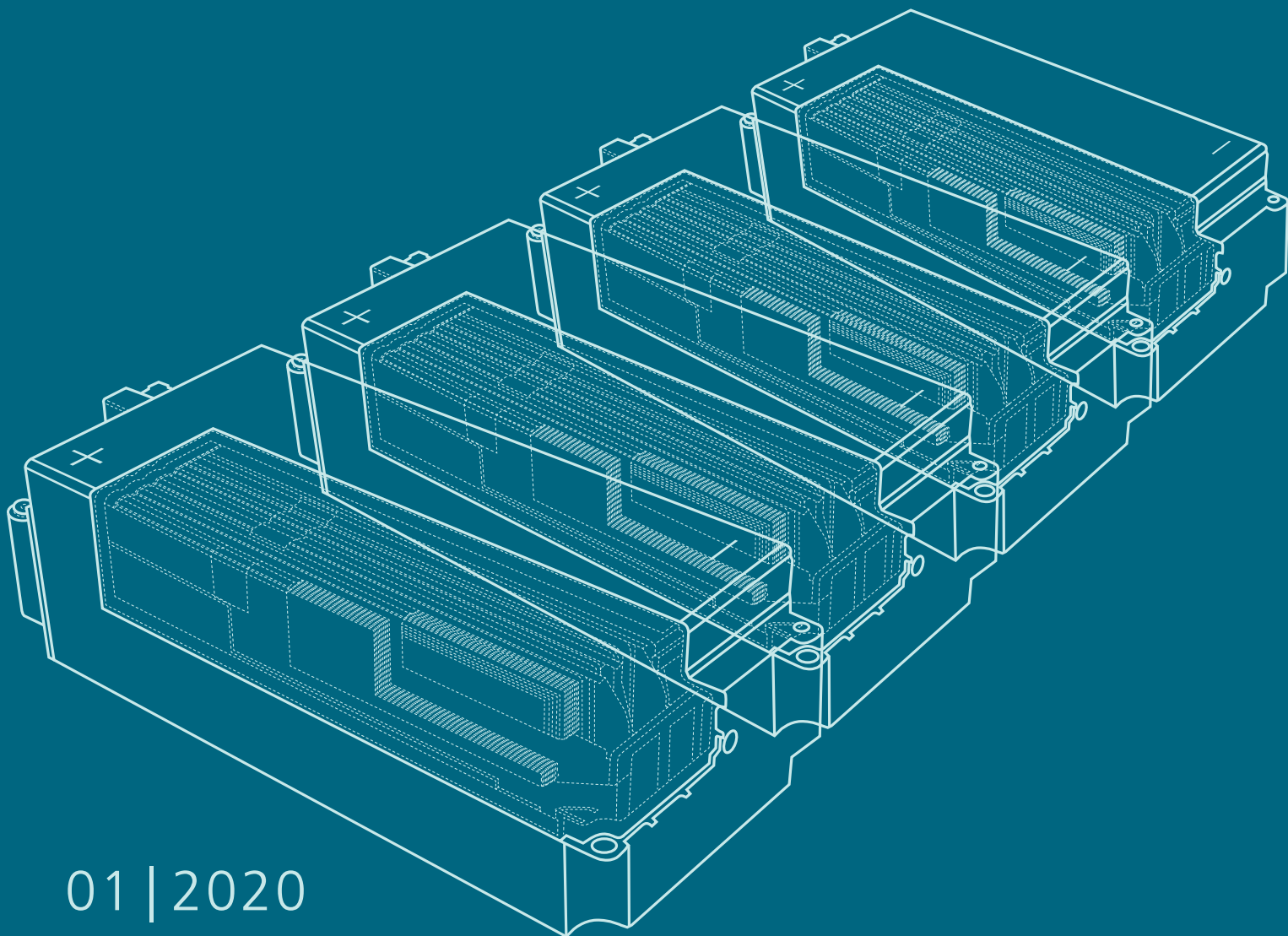
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# Batteries for electric cars: Fact check and need for action



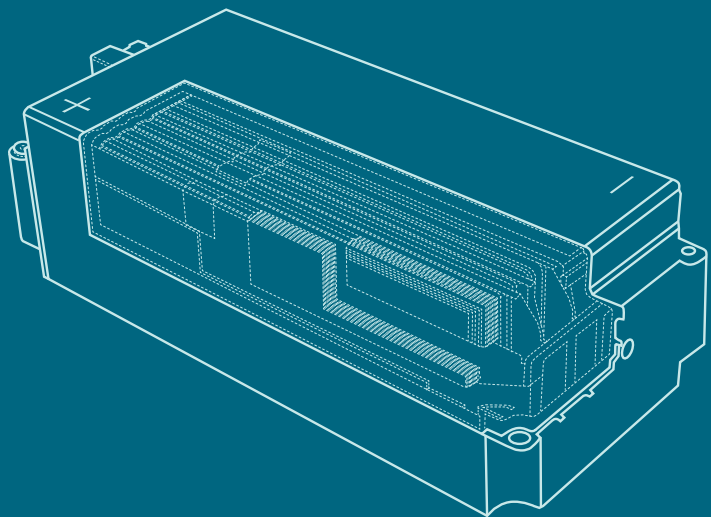
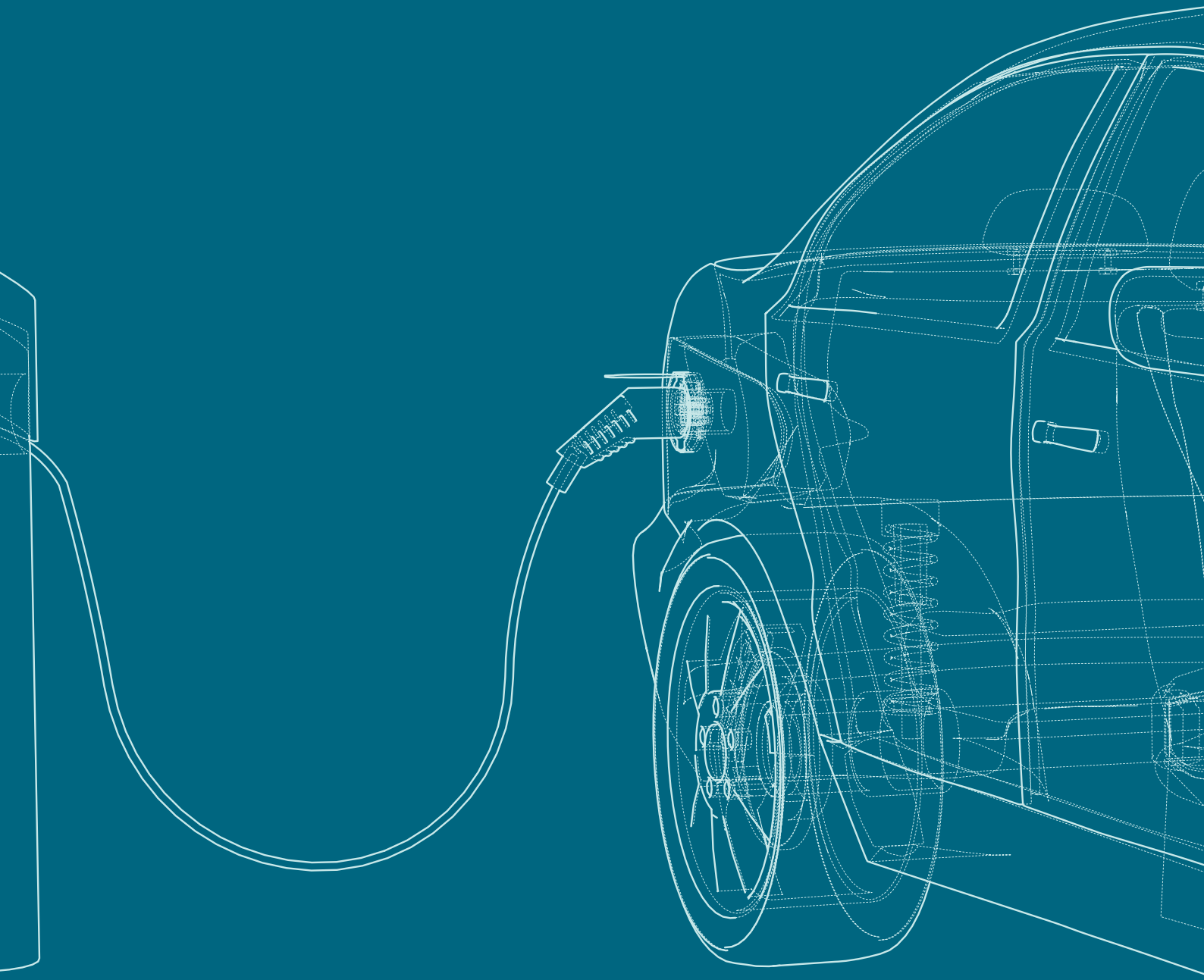


# Batteries for electric cars: Fact check and need for action

**Are batteries for electric cars the key to sustainable mobility in the future?**

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# Overview and core statements

When looking at the main questions along the entire battery value chain, it becomes clear that there are no insurmountable obstacles that could prevent the widespread market diffusion of battery-electric passenger cars, particularly during the decisive ramp-up phase between 2020 and 2030+. However, numerous technological, economic, ecological, regulatory and societal challenges still need to be tackled in the coming decade. The most important findings are summarized below, followed by a more detailed description in the individual chapters.

## 01

### **Do electric cars have a better environmental footprint than conventional passenger cars?**

The electric cars sold in Germany today have a much better greenhouse gas emissions balance than conventional passenger cars over their entire service life, if the energy transition progresses as planned. Their climate footprint and environmental performance can be further improved through energy-efficient battery production that is focused on renewable energy sources, more renewable power used for charging and driving, and a closed-loop resource cycle. Like all passenger cars, however, electric cars also have negative environmental impacts, so that transforming the transport sector must also involve changed mobility behavior (fewer and smaller vehicles, fewer trips).

→ [More information on page 11](#)

## 02

### **What measures can improve the social and environmental impacts?**

Extracting the raw materials and producing technical components are associated with ecological and social risks regardless of the drive technology used. These risks vary in their severity depending on how weak the legislation and state institutions are in the respective countries. The impacts of battery production and resource extraction represent ecological hotspots in the value creation chain of electric cars. International initiatives with regard to corporate due diligence obligations including their legal framework are sensible starting points. Improved conditions can be achieved by management and support and not by relocating production.

→ [More information on page 12](#)

## 03

### **Do we have enough global resources?**

From a global point of view, the raw materials required for batteries like lithium, cobalt, nickel, manganese and graphite are available in sufficient quantities. The development towards low-cobalt and nickel-rich high-energy batteries will further relieve the pressure on the resource situation for cobalt. The situation concerning lithium is uncritical, but there are still uncertainties about nickel. Temporary shortages or supply bottlenecks or price increases cannot be ruled out in the short to medium term for individual raw materials. For lithium, more advanced recycling processes on an industrial scale will become increasingly important in the future.

→ [More information on page 13](#)

## 04

### **What factors are important for competitive battery cell production?**

Access to affordable raw materials and components for batteries will continue to be decisive for competition in the future as well. It is also important that costs decrease for plants, equipment and labor; this can be achieved through economies of scale as well as energy-efficient and automated production (with smart control for example). The experience of Asian producers here gives them an obvious advantage, and European and German manufacturers will have to compensate for this through learning effects and interim additional costs. Unique selling points that are decisive for competition could be created in the future by higher energy densities, rapid charging capacities, lower costs and sustainable production (for example, by using renewable energy sources for production).

→ [More information on page 14](#)

## 05

### Will the diffusion of electric mobility mean job losses?

Although there are different assessments of the employment effects in the automobile industry and its suppliers, the majority reckon with a significant drop in employment in Germany. Battery cell production itself is highly automated, which is why its positive employment effects are limited. However, there are relevant employment effects resulting from upstream and downstream value chains. There are likely to be positive employment effects in other areas such as electricity generation or the construction of charging infrastructure. Regions and companies that rely on internal combustion engine powertrains and that are particularly affected by structural change must develop a sustainable business and employment model. If required, they must be supported by proactive industrial and employment policy measures so that, combined with the natural age fluctuation – structural change can be shaped in a socially compatible way.

→ [More information on page 15](#)

## 06

### Will there be supply bottlenecks along the value creation chain?

Today, there are already various reasons for isolated temporary supply bottlenecks along the value chain. Examples include the raw materials needed for batteries and cell production and the production and distribution of electric cars. The companies are aware of these and counteract the risks by diversifying their suppliers, for example, through strategic industrial cooperation along the value chain, research cooperation, joint ventures and in-house production. These efforts are supported by the government, and this coordinated approach should not be changed in the future in order to reduce the industry's supply dependency.

→ [More information on page 16](#)

## 07

### How will batteries develop and what ranges can we expect?

In the last ten years, the energy density of the large lithium-ion batteries (LIB) used in electric cars has almost doubled to an average of 200 Wh/kg or 400 Wh/l today. The energy density (especially the volumetric density) could double again by 2030, provided that the major R&D challenges involved are successfully managed. Other battery parameters must continue to meet the application-specific minimum requirements. This means that driving range will increase for electric cars as will user acceptance of them. However, to realize this doubling of energy density at the battery system level and reach real driving ranges in most electric car models of more than 600 kilometers, additional space and weight-reducing innovations are needed in battery module/pack production and must be integrated into the vehicles as well. Other strategies are needed to reduce the energy consumption of electric cars (for example, improved insulation, and reducing heating and energy consumption through electronics, lightweight construction etc.).

→ [More information on page 17](#)

## 08

### How will charging infrastructure develop?

Charging infrastructure at home or at the workplace is already important for electric cars today and will continue to be so in the future. The public fast-charging network is already well developed for today's needs, but will have to be expanded in the future. Financial support of private charging infrastructure should be combined with mandatory participation in managed charging to avoid costs for expanding the electricity distribution networks and support the integration of renewable energies. Action is required for those electric car users who do not have the option of private charging, and for legal measures to expand the charging infrastructure in rental and jointly owned properties. The currently very dynamic development of fast-charging infrastructure is expected to meet the demand for rapid charging in the coming decade. The current trend towards charging capacities of up to 100 kW for medium-sized cars and considerably higher up to 350 kW for top-range models will significantly reduce the charging time needed for electric cars in the future.

→ [More information on page 18](#)

# 09

## Are electric vehicles economical?

Today and without additional funding support, it is more expensive to purchase an electric vehicle than a conventional one. There has been a reduction in purchasing costs in recent years, however, due to falling battery prices. This trend is likely to continue and prices could be at a similar level by about 2025. Due to their lower utilization costs, some electric vehicles already perform better today in terms of total costs of ownership (TCO). Purchasing subsidies help to reduce the cost difference when buying an electric vehicle. There are still uncertainties with regard to their resale value. The TCO benefits should be clearly communicated to final users, since the purchase price is often the main factor influencing decisions to buy today.

→ [More information on page 19](#)

# 10

## Will we have enough electricity and are the electricity networks equipped for e-mobility?

There are sufficient amounts of electricity available in Germany for electric vehicles in the next few years so this is not an obstacle to the expansion of e-mobility. Only some electricity networks need to be expanded for electric vehicles, because EV charging is often staggered over time. Managed charging will continue to reduce the need for grid expansion and should be promoted. Expanding the electricity networks can be financed via the existing grid use fees.

→ [More information on page 20](#)

# 11

## What role is played by the secondary use of vehicle batteries?

Concepts for the secondary use of traction batteries are currently being tested and could become relevant from about 2030 - when significant numbers of returned used vehicle batteries are expected. It is not yet clear today what proportion of these used batteries can still find use as stationary storage systems or in other applications. For viable business models, second-life batteries must be available with sufficient residual performance that can be integrated at correspondingly low costs. Standardization and warranty issues must be considered in a cost-effective business model (for example, through appropriate owner and operator models). Whether this can be implemented is a controversial topic at present and requires further techno-economic research.

→ [More information on page 21](#)

# 12

## What happens to the used batteries?

Recycling vehicle batteries is now considered technically feasible and is being implemented industrially in pilot plants. The research on economical, energy- and material-efficient recycling processes is not yet complete given the background of changing cell chemicals. Current legislation on battery recycling is not suitable for the expected sharp rise in the number of used batteries in Europe and is currently being revised.

→ [More information on page 22](#)



# Introduction

## Background

The current climate movements and protests taking place around the globe have increased the demands for politicians to introduce and implement stricter climate measures. Examples include putting a price on CO<sub>2</sub>, making flying more expensive or limiting or banning cars powered by internal combustion engines. The decarbonization goals affect every sector including energy, industry, buildings/households and transport. However, the transport sector is responsible for about 25 percent of the greenhouse gas emissions in Europe and is the only sector to display rising greenhouse gas emissions over the last few years due to the increasing demand for mobility services. Therefore, the need for sustainable mobility concepts and the corresponding technical solutions is and will continue to be particularly urgent here.

There is now widespread consensus in science and industry: batteries, especially optimized lithium-ion batteries, are a key technology for electric cars and the most important powertrain technology of the future. The market will really take off during the period 2020–2030+. Other fuels and drive technologies, such as hydrogen combined with fuel cells or synthetic fuels, will also play a role in the future in the context of ambitious climate protection strategies - although less in passenger cars, and more in long-distance and heavy-duty goods transport as well as rail, aviation, and shipping. These segments will only become more widespread in the later phases of the energy transition beyond 2030, and are closely connected with the expansion of renewable energies.

For batteries, electric cars are the most important and the biggest growth market by far. From 2030, they could account for between 25 and 75 percent of newly registered passenger cars worldwide, depending on the underlying study [1]. This leads to a battery demand of 1 to 6 TWh/year. Batteries are also used in smaller (e.g. e-bikes) and larger mobility applications (e.g. electric buses, electric trucks), stationary (e.g. power storage systems at home), and industrial applications (e.g. forklift trucks). In addition, they are the basis for many other consumer applications such as smartphones and tablets.

The sustainability, economic efficiency and technological maturity of battery technology is frequently doubted by the public, the media, politicians, decision-makers in enterprises and even some experts. In this context, the following chapters perform a fact check on batteries in electric cars from a scientific perspective and use this to highlight the fields requiring action. This Policy Brief addresses politicians, experts and the public in equal measure, and summarizes the state of knowledge and current insights with its focus on “Batteries for electric cars”.

## Approach and methodology

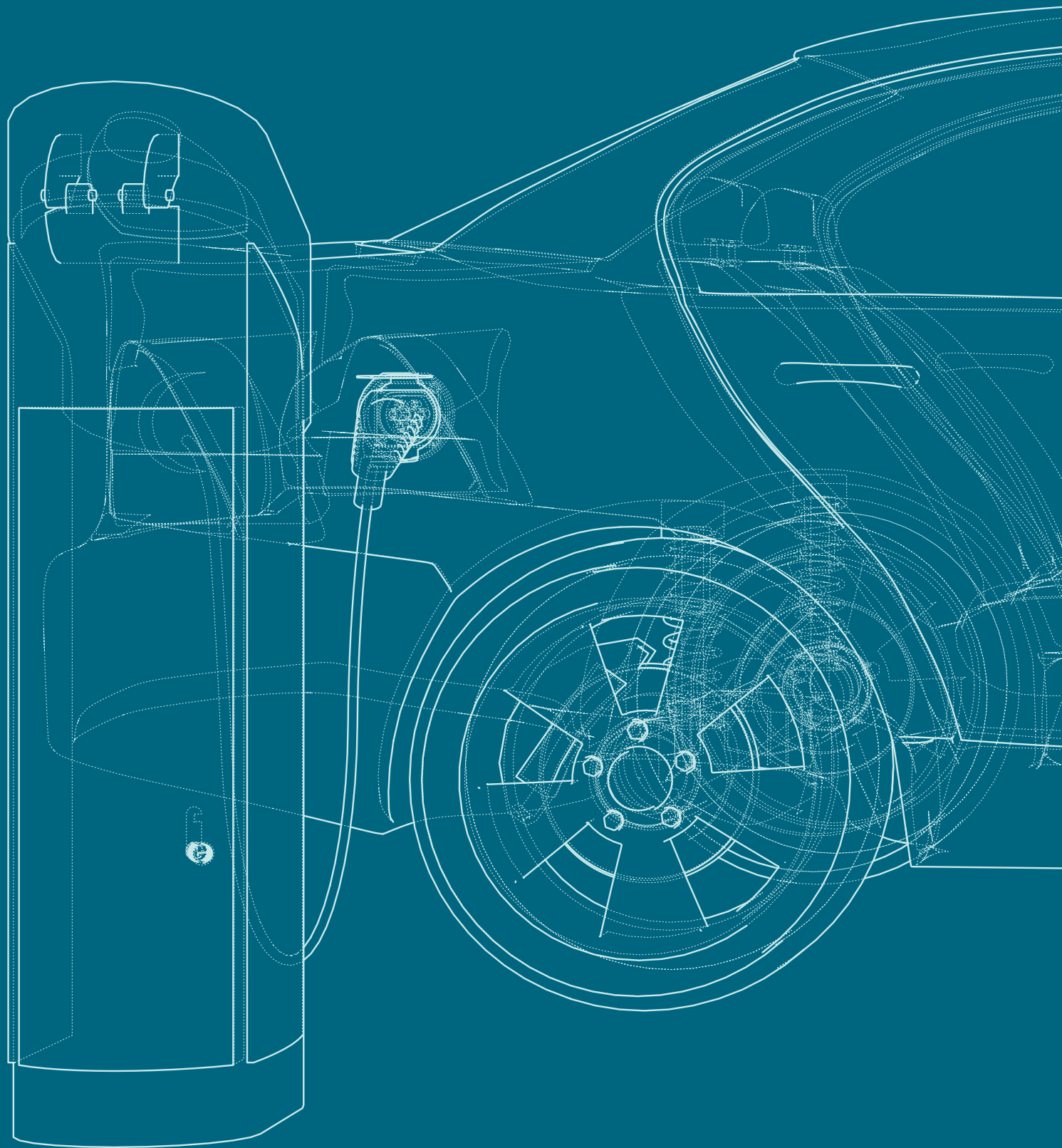
The fact check examines twelve questions along the battery value creation chain from raw material extraction, material/component manufacture, production of battery cells, modules and packs through their use in the vehicles up to closed-loop recycling concepts. Answers to these questions are found by comparing and evaluating relevant studies (meta literature analysis) and articles as well as some of Fraunhofer ISI's own scientific analyses. This leads to some fuzziness and ranges with regard to the assumptions and therefore the results. In fact, many of the studies used to answer the questions raised were conducted some time ago or rely on data and assumptions from the period 2010–2015.

More recent studies and assessments attempt to take the changed framework conditions into account. These include the accelerated market development since 2016-2018 compared to earlier estimations, better assumptions with regard to battery performance parameters and requirements, and greater clarity concerning their technical development (roadmap). Our analysis systematically considers the different time references of these studies.

## Core statements

When looking at the main questions along the entire battery value creation chain, it becomes clear that there is nothing to prevent the widespread market diffusion of battery-electric passenger cars, which represent the most important alternative to conventional cars with internal combustion engines, particularly in the period 2020-2030+. There are no „deal breakers“. However, there are still technological, economic, ecological, regulatory and social challenges that must be addressed in the next decade.

In general, a science-based comparison shows that battery cars perform better than passenger cars with internal combustion engines, even when selecting unfavorable parameters for the battery technology. The developments between 2020 and 2030 will increasingly improve the technology if the corresponding R&D efforts are made. The parallel expansion of renewable energy sources, market acceleration, and technical maturity of battery technology and electric vehicles will help electric cars evolve into a low-carbon, cost-effective and more sustainable alternative to conventional passenger cars, which also perform well in terms of range and have the relevant infrastructure. For this to become a reality, however, further action is required.



# The questions in more detail

## 01

### Do electric cars have a better environmental footprint than conventional passenger cars?

Manufacturing electric cars is much more energy-intensive than producing conventional passenger cars due to the battery production processes. Depending on the energy source used, the energy efficiency of production and the size of the battery, there are between 70 and 130 percent more greenhouse gas emissions than for producing gasoline or diesel vehicles. However, driving an electric car causes fewer greenhouse gas emissions, although this depends on the electricity used. Based on the standard German power mix and the assumption that the energy transition progresses as planned, i.e. the share of renewables continues to increase, an electric vehicle purchased today has 15 to 30 percent fewer greenhouse gas emissions in the overall balance of production, utilization and recycling over its entire service life than a comparable conventional passenger car [2–8]. This will continue to improve in future.

The energy transition and its continued progress is therefore very important for the life cycle assessment of electric cars. The greenhouse gas balance improves even more if mainly or solely renewable power is used to charge the vehicles - and almost 50 percent of electric car users in Germany have their own PV system at home, and a third of these their own battery storage.

The majority of studies in this field conclude that the recycling phase does not have a significant influence when comparing greenhouse gas balances. However, there are still uncertainties here. Secondary use of the vehicle batteries for stationary applications, for example, to store energy produced by PV, can further improve the greenhouse gas balance of EVs [3, 4].

It should be pointed out that the greenhouse gas balance can vary strongly from case to case. For instance, the greenhouse gas balance for an electric vehicle with a large battery

capacity and low mileage that is generally only charged using today's power mix in Germany is not much better than for the corresponding conventional vehicle.

Using renewable energies to produce the batteries, something several manufacturers are attempting to do and which can be economical, as well as making production more energy-efficient can further improve the greenhouse gas balance of EVs in the future [9]. This also applies to the development of secondary use concepts.

With regard to the greenhouse gas balance, the attempts being made by several manufacturers to increase the battery capacities of EVs should be critically reviewed. Tension exists here between environmental and economic issues. Due to range anxiety, larger batteries are often preferred to increase user acceptance.

In addition to greenhouse gas emissions, both conventional and electric passenger cars have other environmental impacts that occur not just during use, but also when extracting the raw materials, during production and disposal. Raw material extraction and production strongly influence the overall environmental footprint of electric cars. This is why, when considering the entire life cycle, electric cars currently have disadvantages in some environmental protection categories compared to conventional cars. These include the categories particulate emissions, water use, acidification (emissions of acid-forming gases that pollute ecosystems on land and in water) and human toxicity (emissions of substances that are toxic or carcinogenic for humans) [10, 11]. Electric cars have environmental advantages in terms of summer smog (formation of ozone close to the ground with its adverse health effects), overfertilization (emissions of nutrients like nitrates and phosphates that are a risk to ecosystems), land use and greenhouse gas emissions.

# The questions in more detail

Different studies of future scenarios for the year 2030 show that the negative environmental impacts of electric cars can be reduced in the future. Greening the power mix plays a major role here. In some fields, it is not yet clear how the comparison will develop by 2030. Compared to conventional cars, electric cars in 2030 will probably have advantages with regard to acidification, but still disadvantages in terms of human toxicity [10]. The latter is mainly due to the fact that battery production weighs so heavily in their environmental footprint. However, this also harbors huge potentials for improvement. It is only possible to reach a clear conclusion

when comparing the environmental balances of electric cars and conventional cars by prioritizing different environmental categories or assigning them different weights. Currently, top priority is given to the greenhouse gas balance.

As every drive technology has environmental impacts, in addition to alternative drives and fuels, we must also change our mobility behavior and reduce vehicle fleets and mileages. Suitable approaches here include incentive systems, for example, and innovative town and infrastructure planning with special consideration of local public transport [12].

## 02

### What measures can improve the social and environmental impacts?

The following section discusses measures to improve environmental and social impacts along the value creation chains of electric cars. To do so, individual environmental and social impacts are cited, but these are not suitable either for a comparison to other drive technologies, nor for an assessment of the environmental balance in general. These points are discussed in question 01.

Raw material extraction and production are particularly relevant for the negative environmental impacts of electric cars [10, 11], because of the large demand for resources and complex and costly production processes on the one hand. On the other hand, the corresponding impacts are enhanced by the often inadequate environmental, social and safety standards on location or the lack of control and regulation mechanisms to enforce them.

The raw materials relevant for batteries are cobalt, lithium, nickel, manganese and graphite. Electric cars also need the rare-earth elements of neodymium, praseodymium and dysprosium for the electric motor. Water shortages are the biggest concern when extracting lithium from salt lakes in Chile, Argentina and Bolivia given the existing water scarcity here,

although this requires more research. Closely connected with this issue are conflicts with local indigenous groups [13, 14].

60 percent of the world's mined cobalt comes from the Congo, and 15 to 20 percent of this from small-scale mining companies [15]. The lack of occupational health and safety measures in artisanal mining results in direct contact with heavy metals (especially uranium) in the rocks as well as fatal accidents. Children labor full-time in light work preparing the rocks to sell, but also in the most difficult and risky work. These terrible conditions are weighed against the fact that small-scale mining enables those involved to make a living wage [15].

Boycotting small-scale mining in the Democratic Republic of Congo will not improve the situation of those involved. It would be better to improve the conditions and formalize and regulate small-scale mining, for example, through the certified trading chain initiatives of the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) (German Federal Institute for Geosciences and Natural Resources). Among other things, these support artisanal mining cooperatives with the relevant formalization and the achievement of minimum standards.

In addition, they support the local authorities in establishing monitoring and control mechanisms.

Strong state institutions in the mining countries are the most important factor for improving environmental and social standards. From the perspective of the countries and companies processing the raw materials, establishing mandatory corporate due diligence is the most promising approach to combat the terrible conditions. These due diligence obligations require companies to identify, disclose and take measures to mitigate the social and environmental risks in their value chains. This can only be achieved on a broad

scale through legislation. The first legal requirements exist for the so-called conflict resources (gold, tin, tungsten, and tantalum from the DR Congo and neighboring countries) in the US-American Dodd Frank Act, the Chinese Due Diligence Guidelines and the EU Regulation 2017/821. Besides this, there are several international initiatives involving companies that are trying to increase compliance with corporate due diligence obligations (for example, Responsible Cobalt Initiative, Initiative Drive Sustainability). Overall, developments are moving in the right direction, but require substantial additional efforts and commitment on the part of the actors involved.

## 03

### Do we have enough global resources?

Studies from 2009 to 2015 already concluded that there are sufficient raw materials for batteries such as lithium, cobalt, nickel, manganese and graphite for global electric mobility needs [16–19]. The global reserves usually clearly exceed the predicted demand, even if the demand for resources continues to increase in parallel due to other applications. However, temporary shortages or price increases for individual resources cannot be ruled out, for example, if new production sites have to be developed, if the raw materials cannot be produced in line with demand for a certain period, or if exports from producer countries cannot always be guaranteed in sufficient quantities [20, 21].

In contrast to earlier studies, there was broad consensus in the period 2016-2019 about which specific battery technologies and cell chemistries should be developed, produced and installed in electric cars in the next ten years and longer. In line with this, it is considered unlikely that the weight proportion of lithium will be significantly reduced in high-energy batteries (about 72 grams of lithium per kilogram of battery cell), but it is very probable that the weight proportion of cobalt can be drastically reduced (from 200 grams per kilogram of

battery cell for NMC 111 to 60 grams per kilogram of battery cell for NMC 811). For example, switching to high-energy NMC batteries (lithium-rich materials with a high concentration of manganese), which are currently still being developed, could counteract the increased demand for nickel. Often, studies prior to 2016 did not consider this technology change nor the recently accelerated market ramp-up [22, 1, 21]. In last few years, actual demand has frequently overtaken the predicted growth in demand. This is taken into account in the basic statements of more recent studies [23, 24]. According to Fraunhofer ISI's own calculations, the primary material demand around 2030 is likely to be slightly higher for lithium than in previous studies, comparable for cobalt, and significantly higher for nickel [25]. For 2050, these calculations forecast a global demand for lithium of 1 to 1.3 million tonnes (more than in previous studies - cumulative 14 to 20 million tonnes by 2050), 150,000 to 250,000 tonnes for cobalt (much lower demand due to the use of materials with reduced cobalt content, cumulative 6 to 9 million tonnes by 2050) and 4 to 6 million tonnes for nickel (slightly lower due to the systems that may be available containing lower concentrations of nickel, cumulative 70 to 110 million tonnes by 2050).

# The questions in more detail

As the terrestrial lithium reserves amount to 14 million tonnes and lithium resources to 62 million tonnes according to current data [26], the availability of lithium does not pose a major threat, in principle. For cobalt, the reserves are 6.9 million tonnes and 25 million tonnes of land-based resources. A drop in the demand for cobalt can be expected in the longer term. For nickel, the reserves are 89 million tonnes and the resources are 130 million tonnes.

More than 90 percent nickel and cobalt can be recovered from used batteries [18]. As long as batteries are collect-

ed and recycled, this can help to secure the supply of raw materials in the future. However, there is still uncertainty about the role of the future used car market and therefore the whereabouts of many of the lithium-ion batteries from electric cars. For cobalt, it may even be possible to temporarily balance demand and supply using recycled materials because new cathode materials strongly reduce the amount of cobalt needed. If high collection rates can be guaranteed and 25 to 50 percent of the lithium can be recovered from used batteries, lithium from battery recycling could cover 10 to 30 percent of the annual demand until 2050 [27].

## 04

### What factors are important for competitive battery cell production?

Mass production of competitive battery cells in Europe has been discussed for several years. More and more Asian manufacturers, in particular, are announcing plans to develop battery production capacities in Europe. For instance, factories are planned in Hungary and Poland from 2020 with double digit GWh capacities/year. The Chinese company CATL has begun establishing cell production in Germany [28]. Other producers have made similar announcements: Between 2025 and 2030, production capacities of at least 250 to 300 GWh/year [29–36] are expected in Europe, mainly of Asian battery manufacturers, whose plans are matched on a similar scale by European cell producers [37–42]. This should result in total production capacities of 300 to 400 GWh/year by 2025 and around 500 to 600 GWh/year by 2030. The projects of Asian stakeholders are often already much more concrete and more advanced than those of the Europeans. They also have a clear roadmap scaled to the emerging demand in Europe, a large part of which is secured by close supplier relationships with local OEMs.

In particular, guaranteed demand through stable supplier relationships appears to be a decisive (stability) criterion for developing local production sites and the corresponding investments by Asian manufacturers. Spatial proximity to

customers from the automotive sector is obviously more important than possible (locational) disadvantages in terms of the production costs in Europe. In fact, location-independent material and equipment costs are the largest cost items in battery cells - together accounting for about 70 to 80 percent [43]. Due to the high and rising share of material costs in a battery cell, access to reasonably priced raw materials and components for batteries is a major element of competition both today and in the future. It is easier for well-established, large Asian battery producers with high demand to influence this access and they therefore have an advantage over every new and small cell manufacturer.

Costs for electricity (about 3 percent) [44, 45] and labor (5 to 10 percent) [43, 46] play a smaller but still significant role in battery production. A large proportion of labor costs today is still spent on research and development and this is likely to decline in the future as products and production are further optimized. The trend towards automated production will result in both lower labor cost shares and lower reject rates in the future. These developments should further reduce locational differences and significantly improve the competitiveness of individual producers. The reasons given by Asian

battery producers for locating production sites in Germany in particular include the demand for skilled workers, the geographical proximity to OEMs, and the importance of sustainably produced (using renewable energy) batteries.

From the viewpoint of a potential European or German manufacturer, it is important to minimize the locational disadvantages in production and at the same time, if possible, exploit the locational advantages resulting from the strong R&D landscape. The goal is to develop a technically superior prod-

uct at a competitive price. With regard to the possible unique selling points of a producer, the energy density of the current generation of lithium-ion batteries is already considered strongly optimized and predetermined by the available materials [47]. Alongside high energy density, therefore, unique selling points that are decisive for competition could be rapid charging capability, lower costs and sustainable production (for example by using renewable power in production). Sufficient security must be guaranteed at system level.

## 05

### Will the diffusion of electric mobility mean job losses?

An electric car is less complex and labor-intensive to produce than a conventional one due to the lower number of components involved. Many studies therefore expect significant job losses, and only a few anticipate a slight increase in employment [48–53]. The results here are determined by five factors: the assumed market acceleration (and especially the share of PHEVs), the market structures (ratio of exports/imports), the geographical limits of the study (e.g. EU, Germany, Baden-Wuerttemberg), the industries considered and their statistical demarcation as well as the consideration of productivity effects. Accordingly, the conclusions of these studies must be interpreted using these criteria. The IAB estimates that 114,000 jobs will be lost by 2035, but does not include hybrid vehicles [50]. For the automobile clusters in Baden-Wuerttemberg, this results in a loss of 31,000 jobs and 8,900 new jobs by 2030 depending on the diffusion assumed [54]. Production sites for powertrains are particularly badly affected here, with job losses between 10 and 46 percent [51]. The ifo Institute calculated a similar range for Bavaria [55]. Both studies conclude that these effects can be countered by active labor market policy measures and natural age-dependent job fluctuation.

The studies often state that cell production and production of the battery system will generate new jobs. However, when

looking at the announcements about the jobs being created in the planned German battery cell factories [56–59], it becomes clear that these can in no way compensate for the loss of jobs in conventional component sectors. The great significance of battery cell production is more the result of its role as an "enabler" of upstream value creation stages and the entire battery ecosystem. At European level, the demand for battery capacities around 2030 is likely to amount to 1 TWh. About 40 jobs are created per GWh of battery capacity [60, 61] directly in the production of battery cells and modules (when starting mass production, the demand may be twice as high because of the lack of economies of scale) and more than 200 additional jobs in the upstream value chain for materials, R&D, machinery and equipment manufacturers etc. [61]. Domestic cell production is very relevant, especially for machinery and equipment manufacturers, for example, to achieve references for the global market [61].

The employment effects due to electric mobility therefore extend beyond solely producing the vehicles. Purely electric cars require less servicing and maintenance than those with internal combustion engines [62], but create jobs in other areas such as the energy sector, charging infrastructure or digitalization that have a significant effect [52, 53, 63].



# The questions in more detail

## 06

### Will there be supply bottlenecks along the value creation chain?

There is no one answer to the question concerning existing supply bottlenecks for all the actors involved, and this may only affect individual companies. The causes of potential bottlenecks are also very heterogeneous. In the past few years, the global stock of (partially) electrified vehicles (PHEV, BEV) has risen from 1.4 million (2015) to more than 5.6 million (2018) [64]. Delivery delays of up to one year can be observed for individual models [65]. The main causes are likely to be structural, and can be traced back to the increase in demand as well as a lack of production capacities and long supply routes [66, 67, 68].

In addition to delayed deliveries to final customers, there are also reports of bottlenecks between vehicle manufacturers and the suppliers of cells and battery systems [69]. It is also speculated that some battery suppliers are attempting to assert their own interests over those of the OEM [70–72]. There are also isolated problems in procuring the raw materials [73, 74]. To avoid such dependencies, OEM are therefore pursuing a range of different strategies (some in parallel). Greater

diversification of suppliers can be observed [75–77], while at the same time companies are forging (some additional) strategic partnerships, for example, BMW with CATL, VW with Northvolt [78], BMZ with Samsung [79] or BASF with Nor-nickel [80]. It can also be seen that OEM are closing contracts directly with the suppliers of battery raw materials. Politicians have also recognized the relevance of German or European battery production and are backing its development. For instance, within the context of “Important Projects of Common European Interest” (IPCEI), funding is being provided for company consortia that aim to produce battery cells in Europe. The first consortium consists of Opel, Saft, BMW, VARTA and BASF, among others. Funding is planned for a second consortium [41, 42, 81, 82]. These measures are supported by other regulatory activities such as the ecodesign preparatory study for batteries [83] or the revision of the Batteries Directive (EU Directive 2006 / 66 / EC) [84]. Both aim at reducing raw material dependency and supply bottlenecks by designing, using and recycling batteries more efficiently.

## 07

### How will batteries develop and what ranges can we expect?

The automobile industry is pushing the optimization of vehicle batteries; the focus here is on a higher energy density to achieve greater ranges and simultaneous cost reduction. Standard dimensions have now been defined for the installation space that make the requirements for volumetric energy density even more stringent. This must be increased to accommodate a larger battery capacity in the same amount of space in the future. The cost reduction aims to lower the total costs of electric vehicles. In addition, vehicle batteries should have fast

charging capability in the future so that a BEV can be charged in just a few minutes using a DC charging cable. The minimum requirement for battery life is sufficient to cover 150,000 to 200,000 kilometers, roughly equivalent to 1,000 full cycles. Increasing battery capacities and large ranges per charge could lead to relaxing the requirements for battery cycle life in the future [47]. It is not yet possible to draw reliable conclusions about the calendar life of the battery beyond the typical warranty period of 10 years.

All types of battery formats (cylindrical, prismatic, and pouch) and all the main cell chemistries (NCA, NMC, LMO, LFP) are installed in today's electric cars. In the coming years, cell manufacturers worldwide plan to increasingly use nickel-rich high-energy cathodes and anodes (Si/C composite). In the medium term, high capacity NMC materials (for example, lithium-rich "integrated composites") or high-voltage materials promise even higher energy densities [47]. This should make it possible for conventional cells to increase up to 350 Wh/kg [85] or to over 800 Wh/l [86] (for example by pre-lithiating anode materials).

Lithium metal anodes could make the ultimate energy density increase feasible (more than 1,000 Wh/l or about 400 Wh/kg [87]). However, using these could require the application of solid electrolytes, and thus technologies which are not yet commercially available. On a laboratory scale, solid-state batteries are already achieving impressive energy densities that makes them very interesting for automobile applications. With regard to production processes and stability, however, major R&D efforts are still required on the path to large-scale commercialization. The fact that some important industrial and scientific players are demonstrating a high level of commitment to this field suggests that the first large-scale solid-state batteries could arrive on the market from about 2025 [47, 88–90], but probably not in cars to start with. So far, cylindrical cells lead the field in terms of energy density. However, the transition from conventional to solid-state batteries, in particular, could rob cylindrical batteries of their lead over pouch or

prismatic cells, especially if the use of solid electrolytes requires stacking the electrodes and cylindrical winding is no longer possible.

Depending on the cell format, losses of 8 to 18 percent of gravimetric energy density and 20 to 50 percent of volumetric energy density occur at the transition from cell to module. This loss continues at the transition to system level and is especially pronounced if, for example, fast charging capability places high demands on cooling and safety. Innovations outside the battery cell, such as merging modules and battery packs, for example, could improve the energy density transfer from the cells to the system level. This and further reducing the energy consumption of the vehicles (kWh/km), for example, by better insulation decreasing the need for heating, lowering energy consumption through electronics, lightweight construction etc., could double the range achieved with the same battery space requirement from today's 250 to 400 kilometers to 500 to 800 kilometers in the next ten years [47, 91, 92].

Higher energy densities and the associated ranges which may be cited in the literature based on alternative cell chemistries are usually still undergoing basic research, and are regarded as speculative from today's viewpoint. Issues concerning lifetime, safety and producibility, for example, make the use of these kinds of technologies in electric vehicles appear rather unlikely at present. In stationary applications, however, technologies such as sodium-ion batteries could play a role.

## 08

### How will charging infrastructure develop?

Sufficient charging infrastructure is frequently regarded as an essential prerequisite for the market success of electric vehicles [93, 94]. Charging possibilities at home are an important requirement for the acceptance and diffusion of EV, because public charging infrastructure was not widely available to start

with. The majority of charging takes place at home with a share of 50 to 75 percent [95]. The combination of an electric car and a photovoltaic system offers economic and environmental benefits. Almost 50 percent of the current EV users in Germany own such a system [96, 97].

# The questions in more detail

Financial support for private charging infrastructure is not absolutely necessary - but could be interesting if combined with mandatory participation in managed charging. Especially in the private sector, managed charging could relieve the pressure on the electricity distribution networks and avoid necessary investments [98, 99]. In addition, charging could be shifted to periods with cheaper electricity prices, which are usually linked to higher shares of renewable power being fed into the grid. This improves the carbon footprint of electric cars [5]. It is also important to make it legally simple to install home charging points, for example, in rental or jointly owned properties.

Another important option is being able to charge vehicles at the workplace [96]. On the one hand, this enables those with no access to private charging to drive an electric car. On the other hand, it could also be worth using an electric vehicle for longer commutes (beyond the vehicle's range), if there is the chance to recharge it at work. Charging at the workplace is also important to shift loads into daytime hours and be able to make direct use of photovoltaic power [100]. The fact that commercial electricity prices are sometimes significantly lower than the prices for private households can also result in an economic advantage [101].

It is advisable to differentiate the intended purposes when discussing public charging infrastructure. Public charging infrastructure can act as a substitute for missing private charging options at home. Fast-charging public hubs are currently being set up for this purpose, especially in Chinese megacities. In Germany, however, the availability of garages and designated parking spaces is very high (45 to 70 percent), depending on the size of the municipality, see [102]. As a result, the need for public charging infrastructure as a substitute for charging at home is of secondary importance in the medium term, although it is of particular interest to those who do not own a garage or have a designated parking spot, or who live in jointly owned or rental properties.

Rapid charging infrastructure is probably primarily needed in Germany for longer journeys exceeding the EV's range. These can already be operated economically with only small service charges and a low utilization of about two hours per day [103]. In Germany at present, there are about 50 electric cars (BEV) for each of the approx. 3,000 rapid charging points [104]. In the future, more BEVs per charging point can be assumed [105, 106], also due to larger ranges [107]. For comparison: in Norway, the ratio of BEVs to rapid charging points is already about 130 today [104]. This implies that fewer than 50,000 charging points would be needed for 5 million BEVs. The expansion of rapid charging infrastructure should therefore be determined by the market in order to guarantee cost efficiency and avoid creating overcapacities.

At present, as well as enlarging the infrastructure network, there is a focus on increasing the charging capacity from 50 up to 350 kW in order to significantly reduce charging times. However, this is associated with higher costs and lower charging efficiencies. With increasing battery capacities and charging power, the demand for rapid charging points will decrease proportionally, and this should be taken into account when planning further expansion.

Public charging with low capacity is probably less important, and business models without additional services are not likely to develop in the future [108]. In the long term, however, public charging infrastructure will also be needed for electric car users who do not have their own garage or designated parking space. An interesting substitute may be to install charging points at shopping centers like supermarkets or furniture stores as well as in multi-story car parks or leisure facilities.

# 09

## Are electric vehicles economical to run?

If the costs for purchasing an electric car today are compared with those for a comparable diesel or gasoline model, electric cars are more expensive at present [109–111]. In addition to range and infrastructure issues, the acquisition costs are a relevant decision factor for many buyers, which can explain the current reluctance to purchase electric vehicles.

The higher acquisition costs are due to the relatively high costs of the traction battery, which currently account for about 30 to 35 percent of total costs at vehicle level [112, 113]. The electric powertrain itself is much cheaper than a conventional engine [114].

According to numerous analyses, there has been a strong drop in battery costs in recent years, and this trend is expected to continue in the future [47, 115], so that cell production costs significantly below 100 euros per kWh could be achieved in the next ten years. This leads to price parity between electric cars and conventional cars. Earlier studies predicted this point would be reached between 2025 and 2030 [91, 116–118], whereas more recent analyses assume that electric cars will already draw level with conventional cars between 2022 and 2024 [92, 112, 119]. The accelerated market ramp-up of electric vehicles and associated learning and economies of scale effects in battery production are responsible for this.

While battery costs per kWh are falling, the average battery capacities of EVs are continuing to increase [120] to enable greater ranges and make the vehicles more suitable for everyday use and thus improve their acceptance. On the other hand, further cost reductions are also expected for the electric powertrain, whereas conventional internal combustion engines will tend to become more expensive due to increasingly ambitious pollutant emission limits and the necessary exhaust aftertreatment systems [121]. The acquisition costs for the

final customer are reduced even more when taking into account the environmental bonus for purely electric vehicles of up to 4,000 euros (planned to increase to 6,000 euros [122]). In addition, the electric vehicles announced for the next few years will achieve real ranges of 300 to 500 kilometers, which is more in line with customer requirements.

Any realistic cost comparison between alternative powertrains must be based on the Total Cost of Ownership (TCO). The TCO cover all the costs for acquiring and using a vehicle and thus also take into account the costs for fuel or power, maintenance and repairs as well as taxes and insurance. When considering the economic efficiency in Germany, the TCO of certain electric cars is already lower or only slightly higher than the TCO of conventional cars [110, 123].

The results of a TCO calculation depend strongly on the underlying assumptions. While the acquisition costs of electric vehicles and conventional vehicles are gradually converging, it is less clear how the electricity price will develop in relation to the prices for gasoline and diesel. Diesel and gasoline are taxed less heavily in Germany than in other European countries, but electricity is taxed more, which results in a relative disadvantage for electricity [124]. Due to the increasing shortage of oil, many studies assume rising fossil fuel costs in the coming years (see [125], for example). In contrast, several studies indicate that electricity prices in Germany are likely to decline after 2020 [126–128]. There have also been political announcements that the comparatively high tax burden on electricity will be lowered in the coming years and heavier taxes imposed on fossil energy sources [122]. The annual mileage also influences the economic efficiency of EVs. Due to their currently higher acquisition costs and simultaneously lower operating costs, electric vehicles have an advantage at medium to high annual mileages, whereas conventional vehicles perform better at low annual mileages.

# The questions in more detail

Electric vehicles have the potential to achieve significant economic advantages compared to conventional passenger cars. Much depends on whether the cost reduction potentials of electric cars are realized, especially those of the batteries.

Fiscal and taxation policy on fuels and electricity, which is currently unfavorable from the viewpoint of electric cars in Germany, will continue to have considerable influence as will the future funding policy.

## 10

### Will we have enough electricity and are the electricity networks equipped for e-mobility?

If all the passenger cars in Germany (roughly 45 million) were powered by batteries, electricity demand would increase by about 20 percent. Forecasts predict about 7 to 10 million EVs on German roads by 2030. This is driven mainly by the EU fleet-wide emission limits for CO<sub>2</sub>. This implies a more moderate electricity demand increase of 3 to 4.5 percent by 2030.

This will require adjustments to some electricity distribution networks and certain additional investments, but these will remain within manageable limits. The so-called diversity factor is around 30 percent, which means only 30 percent of electric vehicles plug in to charge at the same time. Considering that passenger cars are parked 95 percent of the time, the majority of them will charge at home or at the workplace (approx. 80 to 90 percent) and a power outlet is usually available there, managed charging is also feasible. This means that vehicles are charged at times when there is an electricity surplus. These are especially times with low electricity prices and high feed-in shares of renewable energies. This offers cost advantages on the one hand and contributes to a better integration of renewable energies into the system on the other hand. There is some uncertainty, however, about the extent to which users of electric vehicles will participate in such schemes [98].

Electric mobility continues to make an essential contribution to financing the expansion of the distribution networks

through the grid use fees that every electricity consumer pays. Electric mobility increases electricity sales and the revenue from grid use fees. In comparison, the investments in power lines and transformers do not increase to the same extent. This means that there could even be a decrease in the specific electricity prices for households as a result of electric mobility [98].

In addition, it is currently being researched whether bottlenecks might occur at public fast-charging points along highways during periods with heavy holiday traffic and how to overcome these. It remains open to what extent locally restricted network expansion will be needed here, or whether buffering provided by stationary battery storage is better suited to this purpose.

Overall, therefore, the increased investments in distribution networks caused by electric mobility will remain manageable. They can be financed using the higher revenues from electricity sales. Managed charging should continue to be promoted to significantly reduce the required investments. It should be made possible to charge vehicles everywhere, but especially at peoples' places of work and at their homes. Among other things, this will require a change to the tenancy and residential property law, which is currently hindering the expansion of charging infrastructure.

## What role is played by the secondary use of vehicle batteries?

Used traction batteries have not played a major role so far on the relatively young electric mobility market. They will only become available as recycled goods once the market ramp-up has progressed and after about 10 to 15 years delay. Beforehand, batteries that no longer deliver the desired range or acceleration in traction applications could still be used in stationary applications. Space restrictions and high-current capability are not as important in these applications [129]. This type of secondary use is attractive because, compared to new batteries, it significantly reduces the carbon footprint linked to battery production [3, 4, 130]. Reusing the batteries also appears interesting with regard to the potentially low costs of used batteries. This is only possible if used batteries still meet the safety, reliability and residual useful life requirements of the secondary application.

There are two conceivable scenarios for phased-out traction batteries: exchanging the battery because it has reached its end-of-life in the vehicle, or removing the battery from a decommissioned vehicle. In line with typical ramp-up scenarios, the battery capacity resulting from this could amount to 50 to 70 GWh annually in 2035 [83, 131, 132]. It remains open how many of these batteries will still be powerful enough to be reused in secondary applications. From a user perspective, it is also unclear at present typically when and why batteries reach their end-of-life in a vehicle. The warranties offered by OEMs suggest drivers can only claim a battery replacement if the range of the car drops to 70 to 80 percent of the nominal range in less than ten years or 150,000 km mileage. It is not yet possible to estimate what this means for vehicles older than ten years (which is the usual norm in Germany and the EU [133]). In view of the high expected costs for replacing the battery [134, 135] and the typical value development of used cars, it is entirely conceivable that drivers will continue to use them until the batteries are completely dead, at least for private short trips, which may be significantly below the 70 to 80 percent value of the nominal range. Such a battery

would then probably no longer meet the requirements of most secondary applications and could only be recycled. It can therefore be expected that only a fraction of the decommissioned traction batteries will actually be used in secondary applications.

There would certainly be a demand for such batteries. Depending on the speed of renewable energy expansion, an annual additional capacity of approx. 10 to maximum 30 GWh of stationary energy storage could be necessary or desirable in the EU by 2035 [136]. The underlying applications would be suitable for older batteries with low energy density. Compared to new batteries, however, higher battery failure rates are expected and possibly a higher fire risk as well. Having been used for 10 to 15 years in a car, the batteries could reach their end-of-life in their secondary application after only a few years, implying a high replacement rate.

This could disqualify small and decentralized battery storage systems for second-life battery use, as these systems, in particular, require high reliability and long maintenance intervals. This would rule out using second-life batteries for the rapidly growing home storage market. Larger industrial or grid-related [137] storage systems that are still rare today, but could become much more relevant in the future, are of a size that would permit redundant battery capacities and the occasional failure of individual battery modules. Second-life batteries would have to be cheap enough to pay for this redundancy (less than 50 percent of the costs of a new battery [138]). Unlike new batteries, the costs of such batteries are determined solely by the efforts required to integrate the used modules and systems into the new storage system. These costs increase with the increasing complexity of assessing and, where necessary, disassembling the used batteries. If different second-life batteries are to be controlled in one large storage, there may be compatibility problems due to individual and not yet standardized battery management

# The questions in more detail

systems. Potential business models are currently being tested in isolated pilot projects that generally only use one type of battery, for example, taken from a single vehicle model. From today's perspective, it is not yet possible to judge to what

extent it will become the norm that batteries get a second life in stationary applications after reaching the end of their useful life in vehicles [132, 139]. More research is needed here.

## 12

### What happens to the used batteries?

Within the European Union, the directives 2000/53/EC and 2006/66/EC regulate the recovery of lithium-ion batteries (LIB) from end-of-life vehicles. The former deals with end-of-life vehicles. It is mandatory to remove and handle parts with higher hazard potentials separately, such as the battery of an electric car. This is regulated in the Battery Directive 2006/66/EC, which stipulates an extended liability for battery producers. They must finance the costs for collecting, treating and recycling batteries. Vehicle batteries are listed under industrial batteries. Since 2016, Member States must achieve minimum collection rates of 45 percent. With regard to the recycling process, LIB fall under the category of "other batteries", for which only 50 percent of the average weight has to be recycled. Germany stated a collection rate of 48 percent for used batteries in 2018, and a recycling efficiency of 84 percent for the category of other batteries. The currently valid battery directive will not be suitable for the expected increase in the importance of LIB from the electric mobility sector. A revision is expected with specific regulations for vehicle batteries [20, 140, 141].

Recycling small lithium-ion batteries is already established in Europe. However, the LIB used in vehicles are much larger and heavier and store much more energy than the batteries used in electrical devices. This makes safe and environmentally-friendly recycling more complex and costly [142]. Alternative methods have been explored in various publicly funded R&D projects or are already offered commercially (for example, Umicore, Batrec, Duesenfeld, Retrie Technologies etc. [143, 144]). Recycling is considered technically feasible in principle. However, additional optimization is required

given the background of changing cell chemicals and battery designs. Regardless of the recycling method used, different safety aspects must be considered when dismantling, storing and transporting the batteries [142]. The most valuable assets are the metals cobalt and nickel followed by copper. To reach the required mass-based recycling rate for batteries, recovering iron/steel and aluminum is also very important [145].

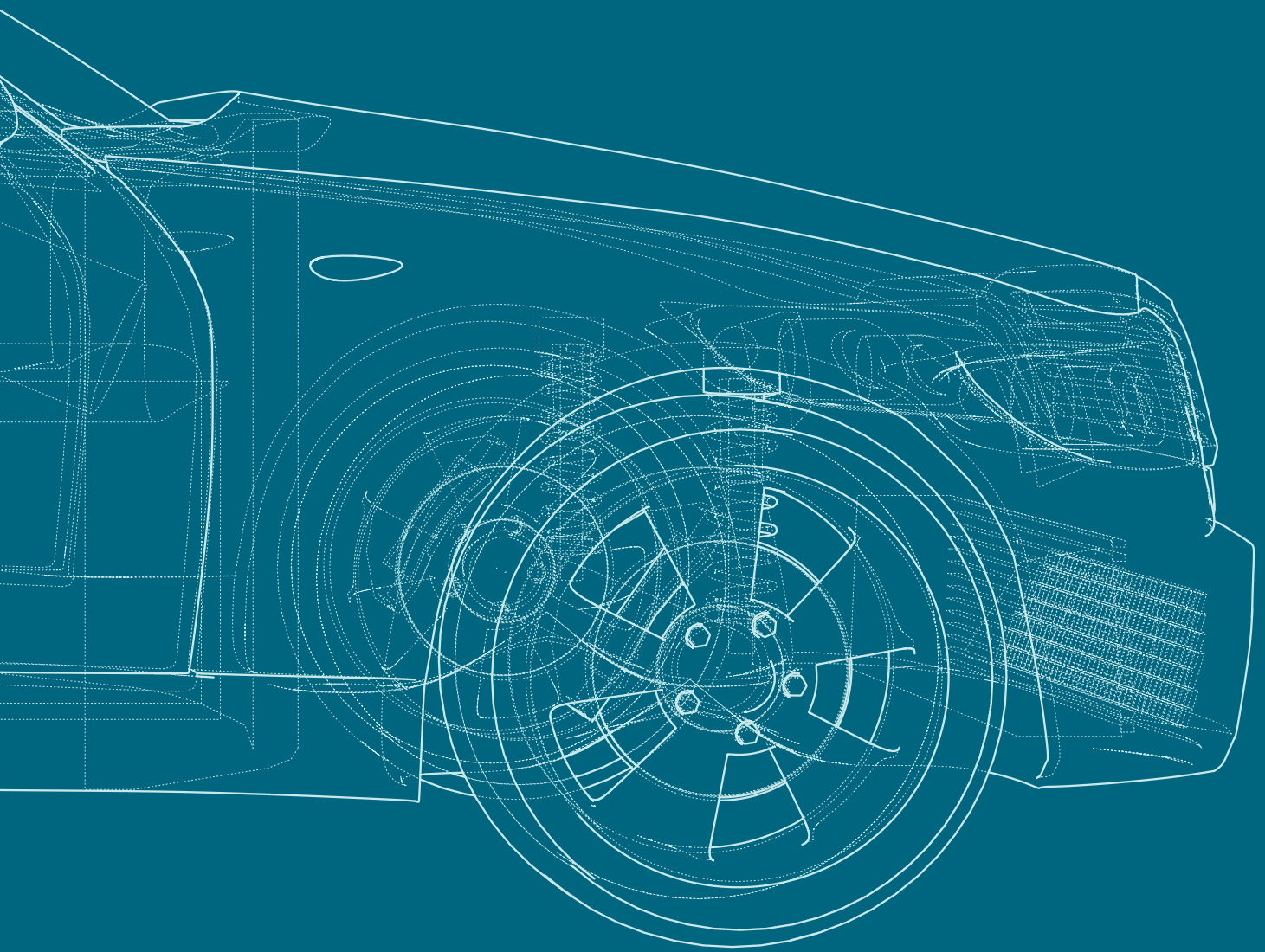
Umicore's LIB recycling installation on an industrial pilot scale can handle up to 7,000 tonnes per year. It is currently one of the largest plants in the world for recycling LIB [146, 147]. Copper, cobalt and nickel are recovered from the LIB modules/cells. Lithium is recovered subsequently using a lithium processor. The housing (copper wiring, steel, plastics etc.) and electronics (printed circuit boards) are also treated in separate processes [146, 148]. Other concepts rely on a stronger, mainly mechanical pretreatment of the LIB before the resulting fractions undergo further hydrometallurgical or pyrometallurgical treatment [140, 143]. There are no data available on the plant capacities of these alternative concepts.

At present, little is known about the economic efficiency of recycling automotive LIB. Many processes are still being operated on a small scale or are not specifically designed for these batteries. The revenue for dismantling is estimated at 210 to 240 euros per tonne batteries, half of which is for the aluminum contained, a quarter for steel and another quarter for the copper recycled from wires and circuit boards. Actually recycling the cells requires much more complex

processes, for which there is currently no cost data available from industry. In addition, the economic efficiency of cell recycling depends on the chemical composition of the battery. For example, the value of the metals contained in lithium iron phosphate-based cells (or lithium ferrophosphate LFP) is less than half of those in cobalt and nickel-based cells (NMC, NCA). The current trend towards decreasing amounts of cobalt contained in NMC batteries could make profitable recycling in the future even harder [140, 143].

Data on the environmental assessment of recycling processes are also very limited at present. Currently available assessments show an advantage of recycling in terms of the greenhouse gas potential, but are partially based on laboratory-scale data [140, 149, 150].





# References and comments

- [1] Thielmann, A.; Neef, C.; Fenske, C.; Wietschel, M. (2018): Energiespeicher-Monitoring 2018. Leitmarkt- und Leitanbieterstudie: Lithium-Ionen-Batterien für die Elektromobilität (Karlsruhe: Fraunhofer-Institut für System- und Innovationsforschung ISI)
- [2] Agora Verkehrswende (2019): Klimabilanz von Elektroautos: Einflussfaktoren und Verbesserungspotenzial
- [3] ICCT (2018): Effects of battery manufacturing on electric vehicle life-cycle greenhouse gas emissions. Briefing. International Council on Clean Transportation, <https://theicct.org/publications/EV-battery-manufacturing-emissions> (last checked 20 Nov 2019)
- [4] Joanneum Research (2019): Geschätzte Treibhausgasemissionen und Primärenergieverbrauch in der Lebenszyklusanalyse von Pkw-basierten Verkehrssystemen. (Graz: Joanneum Research)
- [5] Wietschel, M.; Kühnrich, M.; Rüdiger, D. (2019a): Die aktuelle Treibhausgasemissionsbilanz von Elektrofahrzeugen in Deutschland (Working Paper Sustainability and Innovation No. S 02/2019) (Fraunhofer ISI)
- [6] Wietschel, M.; Timmerberg, S.; Ashley-Belbin, N.; Moll, C.; Oberle, S.; Lux, B.; Neuling, U.; Kaltschmitt, M. (2019b): Klimabilanz, Kosten und Potenziale verschiedener Kraftstoffarten und Antriebssysteme für Pkw und Lkw: Endbericht, gefördert vom Biogasrat+ e.V. (Fraunhofer ISI)
- [7] Regett, A.; Mauch, W.; Wagner, U. (2019): Klimabilanz von Elektrofahrzeugen – Ein Plädoyer für mehr Sachlichkeit, <https://www.ffe.de/themen-und-methoden/ressourcen-und-klimaschutz/856-klimabilanz-von-elektrofahrzeugen-ein-plaedoyer-fuer-mehr-sachlichkeit> (last checked 21 Nov 2019)
- [8] VW (2019): Klimabilanz von E-Fahrzeugen & Life Cycle Engineering (VW Wolfsburg) (last checked 21 Nov 2019)
- [9] Emilsson, E.; Dahllöf, L. (2019): Lithium-Ion Vehicle Battery Production (C 444) (IVL Swedish Environmental Research Institute)
- [10] Bauer, C.; Hofer, J.; Althaus, H.-J.; Del Duce, A.; Simons, A. (2015): The environmental performance of current and future passenger vehicles: Life cycle assessment based on a novel scenario analysis framework, *Applied Energy* [157], 871–83
- [11] Helms, H.; Jöhrens, J.; Kämper, C.; Giegrich, J.; Liebich, A. (2016): Weiterentwicklung und vertiefte Analyse der Umweltbilanz von Elektrofahrzeugen (Texte 27/2016) (Umweltbundesamt)
- [12] Groneweg, M.; Weis, L. (2018): Weniger Autos, mehr globale Gerechtigkeit – Diesel, Benzin, Elektro: Die Antriebstechnik allein macht noch keine Verkehrswende (Misereor, Brot für die Welt & Powershift)
- [13] Boddenberg, S. (2018): Lithiumabbau in Chile – Fluch oder Segen? | DW | 28.04.2018, <https://www.dw.com/de/lithiumabbau-in-chile-fluch-oder-segen/a-43401781> (last checked 19 Nov 2019)
- [14] Frankel, T. C.; Whoriskey, P. (2016): Tossed aside in the »white gold« rush. Indigenous people are left poor as tech world takes lithium from under their feet (The Washington Post)
- [15] BGR – Die BGR-Commodity TopNews 53 (2017): Kobalt aus der DR Kongo – Potenziale, Risiken und Bedeutung für den Kobaltmarkt, [https://www.bgr.bund.de/DE/Gemeinsames/Produkte/Downloads/Commodity\\_Top\\_News/Rohstoffwirtschaft/53\\_kobalt-aus-der-dr-kongo.html](https://www.bgr.bund.de/DE/Gemeinsames/Produkte/Downloads/Commodity_Top_News/Rohstoffwirtschaft/53_kobalt-aus-der-dr-kongo.html) (last checked 19 Nov 2019)
- [16] Angerer, G.; Marscheider-Weidemann, F.; Wendl, M.; Wietschel, M. (2009): Lithium für Zukunftstechnologien. Nachfrage und Angebot unter besonderer Berücksichtigung der Elektromobilität (Karlsruhe: Fraunhofer ISI)
- [17] Umbrella-Arbeitsgruppe Ressourcenverfügbarkeit (2011): Ressourcenverfügbarkeit von sekundären Rohstoffen – Potenzialanalyse für Lithium und Kobalt: Umbrella-Arbeitsgruppe Ressourcenverfügbarkeit im Rahmen der durch das Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit geförderten Projekte LithoRec und LiBRi (BMUB)
- [18] Reuter et al. (2014): Conference on Future Automotive Technology (CoFAT), Future Ressource Availability for the Production of Lithium-Ion Vehicle Batteries, [https://www.researchgate.net/profile/Benjamin\\_Reuter/publica-](https://www.researchgate.net/profile/Benjamin_Reuter/publica-)

tion/263888647\_COFAT\_2014\_\_Future\_Resource\_Availability\_for\_the\_Production\_of\_Lithium-Ion\_Vehicle\_Batteries/links/53fdcd430cf2dca800039068.pdf (last checked 21 Nov 2019)

- [19] Thielmann, A.; Sauer, A.; Wietschel, M. (2015): Gesamt-Roadmap Lithium-Ionen-Batterien 2030 (Karlsruhe: Fraunhofer-Institut für System- und Innovationsforschung ISI)
- [20] Buchert, M.; Degreif, S.; Dolega, P. (2017): Strategien für die nachhaltige Rohstoffversorgung der Elektromobilität. Synthesepapier zum Rohstoffbedarf für Batterien und Brennstoffzellen: Studie im Auftrag von Agora Verkehrswende (Berlin, Darmstadt: Öko-Institut)
- [21] Öko-Institut e.V (2018): Elektromobilität – Faktencheck, <https://www.oeko.de/publikationen/p-details/elektromobilitaet-faktencheck/> (last checked 21 Nov 2019)
- [22] Comment: This is likely to lead to a global demand of 150-200 GWh for xEV in 2020 (250-350 GWh LIB in total), 700-1,200 GWh for xEV in 2025 (1,000-1,500 GWh LIB in total) and 2,000-4,000 GWh for xEV in 2030 (3,000-5,000 GWh LIB in total).
- [23] Dolega, P. (2019): Rohstoffszenarien für die Elektromobilität. Aktuelle Prognosen geben Aufschluss über den Rohstoffbedarf der Elektromobilität und das Recyclingpotential zur Bedarfsbefriedigung, ReSource, 9–15
- [24] Weil, M.; Ziemann, S.; Peters, J. (2018): The Issue of Metal Resources in Li-Ion Batteries for Electric Vehicles. Behaviour of Lithium-Ion Batteries in Electric Vehicles
- [25] Comment: The primary material demand around 2030 is likely to be 250,000-450,000 tonnes for lithium (only for electric cars) (higher than in previous studies), 250,000-420,000 tonnes for cobalt (comparable, because the effects of demand development and cobalt reduction offset each other) and 1.3-2.4 million tonnes for nickel (much higher because of the combined effect of demand development and nickel-rich systems).
- [26] USGS (2019): Lithium: <https://www.usgs.gov/media/files/lithium-mcs-2019-data-sheet>; Cobalt: <https://www.usgs.gov/media/files/cobalt-mcs-2019-data-sheet>; Nickel: <https://www.usgs.gov/media/files/nickel-mcs-2019-data-sheet>
- [27] Comment: Fraunhofer ISI calculations assuming a future recycling rate of up to 25-50 percent.
- [28] Schwierz, P. (2019): CATL legt Erfurter Batteriewerk für bis zu 100 GWh aus, <https://www.electrive.net/2019/02/04/catl-legt-erfurter-batteriewerk-fuer-bis-zu-100-gwh-aus/> (last checked 21 Nov 2019)
- [29] Comment: CATL 100GWh, LG Chem 70 GWh, Samsung SDI 20 GWh, SKI 7,5+X GWh, Envision/ AESC 8,2 GWh, Tesla with cells possibly from CATL or LG, SVOLT 24 GWh, Farasis 10 GWh, Microvast 6 GWh as well as other less specific announcements by BYD and GS Yuasa.
- [30] Eckl-Dorna, W. (2019): Sechs Antworten zu Teslas deutschem Riesenwerk, <https://www.manager-magazin.de/unternehmen/autoindustrie/elon-musk-6-antworten-zu-teslas-elektroauto-werk-in-gruenheide-bei-berlin-a-1296315-4.html> (last checked 21 Nov 2019)
- [31] Werwitzke, C. (2019): SK Innovation baut in Ungarn zweites Batteriezellwerk, <https://www.electrive.net/2019/02/27/sk-innovation-baut-in-ungarn-zweites-batteriezellwerk/> (last checked 21 Nov 2019)
- [32] Benchmark Mineral Intelligence | Price Reporting Agency (2018): Lithium Ion Battery Megafactory Assessment, <https://www.benchmarkminerals.com/> (last checked 21 Nov 2019)
- [33] Schaal, S. (2019): Europa-Werk: Tesla baut Gigafactory 4 nahe Berlin, <https://www.electrive.net/2019/11/12/tesla-baut-gigafactory-4-nahe-berlin/> (last checked 21 Nov 2019)
- [34] SVOLT: SVOLT will in Europa zwei Milliarden Euro in 24-GWh-Batteriefabrik investieren | photon.info, <https://www.photon.info/de/news/svolt-will-europa-zwei-milliarden-euro-24-gwh-batteriefabrik-investieren> (last checked 10 Dec 2019)
- [35] Farasis: Farasis, global führender Li-Ionen-Batteriekonzern, will Batterie-Fabrik in Bitterfeld-Wolfen errichten, <https://www.investieren-in-sachsen-anhalt.de/Farasis-Batterie-Fabrik-Bitterfeld-Wolf> (last checked 10 Dec 2019)
- [36] Microvast: Microvast collaborates with FPT Industrial to develop and offer battery power solutions through its new gigawatt factory in Ludwigsfelde, Microvast | Fast-Charging | Electric Vehicle | Energy Storage | Thinking Forward. Powering

Now, <http://microvast.com/de/index.php/news/info/106> (last checked 10 Dec 2019)

- [37] **Comment:** Northvolt up to 150 GWh, Freyr 32 GWh, PSA/Saft 32+32 GWh, VW with Northvolt 24 GWh, TerraE 8 GWh, other manufacturers like LeClanché, Saft and other smaller ones with a few GWh.
- [38] **electrive.net (2019):** Northvolt will Produktionskapazität drastisch erhöhen – [electrive.net](https://www.electrive.net/2019/11/26/northvolt-will-produktionskapazitaet-drastisch-erhoehen/), <https://www.electrive.net/2019/11/26/northvolt-will-produktionskapazitaet-drastisch-erhoehen/> (last checked 10 Dec 2019)
- [39] **Freyr (2019):** FREYR AS announces plans to build a 32 GWh battery cell production facility in Mo I Rana, Norway – European Battery Alliance, <https://www.eba250.com/freyr-as-announces-plans-to-build-a-32-gwh-battery-cell-production-facility-in-mo-i-rana-norway/> (last checked 10 Dec 2019)
- [40] **Michaelis, S.; Rahimzei, E.; Kampker, A.; Heimes, H.; Lienemann, C.; Offermanns, C.; Kehrer, M.; Thielmann, A.; Hettesheimer, T.; Neef, C. (2018):** VDMA Roadmap Batterieproduktionsmittel 2030 – Update 2018, <https://battprod.vdma.org/viewer/-/v2article/render/26974821> (last checked 21 Nov 2019)
- [41] **electrive.net (2019):** EU-Kommission genehmigt Förderung von Batterieforschung – [electrive.net](https://www.electrive.net/2019/12/09/eu-kommission-genehmigt-foerderung-von-batterieforschung/), <https://www.electrive.net/2019/12/09/eu-kommission-genehmigt-foerderung-von-batterieforschung/> (last checked 10 Dec 2019)
- [42] **Bundesministerium für Wirtschaft und Energie Altmaier:** »Großer Erfolg für den Automobilstandort Deutschland und Europa!«, <https://www.bmwi.de/Redaktion/DE/Pressemitteilungen/2019/20191209-altmaier-grosser-erfolg-fuer-automobilstandort-deutschland-und-europa.html> (last checked 10 Dec 2019)
- [43] **Thielmann et al. (2018):** Cost Development, Cost Structure & Cost Reduction Potentials of Electric Vehicle Batteries (Graz)
- [44] **Comment:** Germany ranges from 9 to 14 ct /kWh for industrial enterprises, Norway and Sweden around 6 ct /kWh; Poland and Hungary (factory locations) around 8 ct /kWh, <https://www.enerdata.net/about-us/company-news/energy-prices-and-costs-in-europe.pdf> 2017
- [45] **Comment:** China 10 ct /kWh (2018), Japan similar prices to Germany, South Korea 8 ct /kWh, <https://www.statista.com/statistics/267068/industrial-electricity-prices-in-europe/>; [https://www.globalpetrolprices.com/South-Korea/electricity\\_prices/](https://www.globalpetrolprices.com/South-Korea/electricity_prices/)
- [46] **Comment:** Industry without construction 2018 DE 40; Hungary, Poland 10, [https://ec.europa.eu/eurostat/statistics-explained/index.php/Wages\\_and\\_labour\\_costs](https://ec.europa.eu/eurostat/statistics-explained/index.php/Wages_and_labour_costs); <https://ec.europa.eu/eurostat/de/web/labour-market/labour-costs/database>
- [47] **Thielmann, A.; Neef, C.; Hettesheimer, T.; Döscher, H.; Wietschel, M.; Tübke, J. (2017):** Energiespeicher-Roadmap (Update 2017). Hochenergie-Batterien 2030+ und Perspektiven zukünftiger Batterietechnologien (Karlsruhe: Fraunhofer-Institut für System- und Innovationsforschung ISI)
- [48] **Welt am Sonntag (2019):** Elektromobilität kostet bis 2030 fast 125.000 Jobs: Veröffentlichung von Studienergebnissen des Center for Automotive Research (CAR) der Universität Duisburg-Essen, <https://www.welt.de/wirtschaft/article201106910/Autoindustrie-Elektromobilitaet-kostet-bis-2030-fast-125-000-Jobs.html> (last checked 8 Nov 2019)
- [49] **Bauer, W.; Riedel, O.; Herrmann, F.; Borrmann, D.; Sachs, C. (2018):** ELAB 2.0: Wirkungen der Fahrzeugelektrifizierung auf die Beschäftigung am Standort Deutschland (Fraunhofer IAO)
- [50] **Institut für Arbeitsmarkt- und Berufsforschung (2018):** Elektromobilität 2035: Effekte auf Wirtschaft und Erwerbstätigkeit durch die Elektrifizierung des Antriebsstrangs von Personenkraftwagen
- [51] **DLR; IMU Institut; bridging IT (2019):** Strukturstudie BWemobil 2019: Transformation durch Elektromobilität und Perspektiven der Digitalisierung (e-mobil BW GmbH)
- [52] **European Climate Foundation (2018):** Low-carbon cars in Europe: A socio-economic assessment (Cambridge Econometrics)
- [53] **Wietschel, M.; Thielmann, A.; Plötz, P.; Gnann, T.; Sievers, L.; Breitschopf, B.; Doll, C.; Moll, C. (2017):** Perspektiven des Wirtschaftsstandorts Deutschland in Zeiten zunehmender Elektromobilität (Fraunhofer ISI)

- [54] **Berger, M.; Boockmann, B.; Felbermayr, G. (2017):** Strukturanalyse und Perspektiven des Wirtschaftsstandortes Baden-Württemberg im nationalen und internationalen Vergleich
- [55] **Falck, O.; Koenen, J. (2019):** Fahrzeugbau – wie verändert sich die Wertschöpfungskette? (Bayerischer Industrie- und Handelskammertag e. V.)
- [56] **Comment:** VW expects 700 jobs in production in the medium term in Salzgitter and an additional 300 in the development center and CATL up to 2.000 jobs in Erfurt. Tesla announced up to 10.000 jobs for its planned factory in Brandenburg, but without stating in which field these will be created.
- [57] **Voigtmann, S. (2019):** Batterie-Hersteller CATL beginnt Bau von Fabrik bei Arnstadt, <https://www.mdr.de/thueringen/mitte-west-thueringen/arnstadt-ilmkreis/batterie-hersteller-catl-legt-in-arnstadt-grundstein-fuer-fabrik-100.html>
- [58] **manager magazin (2019):** VW beginnt mit eigener Batteriezellenfertigung, <https://www.manager-magazin.de/unternehmen/autoindustrie/volkswagen-ag-startet-in-salzgitter-mit-produktion-von-batteriezellen-a-1288170.html>
- [59] **Metzner, T. (2019):** Elon Musk plant neues Werk bei Berlin, <https://www.tagesspiegel.de/berlin/gigafactory-von-tesla-soll-10-000-jobs-bringen-elon-musk-plant-neues-werk-bei-berlin/25220356.html>
- [60] **Comment:** This figure of about 40 employees per GWh already includes economies of scale due to production. The employment effects are even higher at the outset of mass production, and are likely to be about 125 employees /GWh.
- [61] **Hettesheimer, T.; Thielmann, A.; Neef, C. (2018):** VDMA Kurzgutachten: Beschäftigungsauswirkung einer Batteriezellproduktion in Europa (VDMA)
- [62] **UBS Evidence Lab (2017):** Electric car Teardown – Disruption Ahead?
- [63] **Sievers, L.; Grimm, A.; Doll, C. (2019):** Transformation der Mobilität: Bestimmung der Beschäftigungseffekte in 2035 mit einem Input-Output-Modell: Arbeitspapier im Auftrag der Hans-Böckler-Stiftung (Karlsruhe)
- [64] **Nieder, T.; Püttner, A. (2019):** Datenservice Erneuerbare Energien, <https://www.zsw-bw.de/mediathek/datenservice.html#c6840>
- [65] **mdr (2019):** Lange Wartezeiten auf Elektro-Autos, <https://www.mdr.de/nachrichten/wirtschaft/inland/lange-lieferzeiten-elektroautos-100.html>
- [66] **ecomento (2019):** Hyundai verspricht kürzere Elektroauto-Lieferzeiten, <https://ecomento.de/2019/09/04/hyundai-verspricht-kuerzere-elektroauto-lieferzeiten/>
- [67] **manager magazin (2019):** Tesla hat Lieferprobleme – und verklagt Ex-Mitarbeiter
- [68] **Schwarzer, C. (2019):** Gezielte Auslieferungsverzögerung: Danke, dass Sie gewartet haben! <https://www.electrive.net/2019/12/08/gezielte-auslieferungsverzoegerung-danke-dass-sie-gewartet-haben/>
- [69] **Setzer, P. (2018):** Wie CATL BMW, VW und Daimler das Fürchten lehrt, <https://www.manager-magazin.de/unternehmen/autoindustrie/contemporary-ampere-technology-catl-blamiert-bosch-byd-und-tesla-a-1212966-2.html>
- [70] **Germis, C. (2019):** Batteriedeal zwischen VW und Samsung in Gefahr, <https://www.faz.net/aktuell/wirtschaft/diginomics/elektroautos-batterie-deal-zwischen-vw-und-samsung-in-gefahr-16209015.html>
- [71] **Kane, M. (2019):** Audi E-Tron Production Stalls Out, E-Tron Sportback Delayed, <https://insideevs.com/news/345863/audi-e-tron-production-stalls-out-e-tron-sportback-delayed/>
- [72] **Eisert, R. (2019):** Batterie-Nachschub für SUV in Brüssel hakt: Audi kämpft mit Produktionsproblemen beim e-tron, <https://www.automobilwoche.de/article/20190326/NACHRICHTEN/190329937/batterie-nachschub-fuer-suv-in-bruessel-hakt-audi-kaempft-mit-produktionsproblemen-beim-e-tron>
- [73] **Desai, P. (2017):** RPT-Volkswagen's talks with cobalt producers end without deal
- [74] **Moses, C. (2019):** Bolivien stoppt Lithiumprojekt mit deutscher Firma, <https://www.faz.net/aktuell/wirtschaft/unternehmen/bolivien-stoppt-lithiumprojekt-mit-deutscher-firma-16468047.html>

- [75] **Volvo (2019)**: Volvo Car Group signs multi-billion dollar battery supply deals with CATL and LG Chem, <https://www.media.volvocars.com/global/en-gb/media/pressreleases/252485/volvo-car-group-signs-multi-billion-dollar-battery-supply-deals-with-catl-and-lg-chem>
- [76] **Schaal, S. (2019)**: Porsche und CATL verhandeln über Batteriezellen-Lieferung, <https://www.electrive.net/2019/09/06/porsche-und-catl-verhandeln-ueber-batteriezellen-lieferung/>
- [77] **Daimler AG (2019)**: Liefervereinbarung mit CATL. Batteriemodule für elektrische Lkw, <https://www.daimler.com/investoren/berichte-news/finanznachrichten/20190918-catl-belieferung-batteriemodulen.html>
- [78] **Northvolt (2019)**: Volkswagen and Northvolt form joint venture for battery production (Northvolt)
- [79] **Industry Europe (2018)**: BMZ Group and Samsung SDI form electromobility partnership (Industry Europe)
- [80] **BASF (2018)**: BASF and Nornickel join forces to supply the battery materials market, <https://www.basf.com/global/en/media/news-releases/2018/10/p-18-336.html>
- [81] **Löhr, J.; Gropp, M. (2019)**: Der Startschuss für die europäische Batteriezelle
- [82] **Stratmann, K.; Hoppe, T. (2019)**: Zweites Großprojekt für Batteriezellfertigung steht – Vier deutsche Konzerne dabei, <https://www.handelsblatt.com/politik/deutschland/eu-industriepolitik-zweites-grossprojekt-fuer-batteriezellfertigung-steht-vier-deutsche-konzerne-dabei/24986594.html?ticket=ST-3991204-VyeYkQjWCDr2Ls5Xf7b-ap3>
- [83] **Ecodesign preparatory study for batteries**, <https://ecodesignbatteries.eu/welcome> (last checked 21 Nov 2019)
- [84] **EU Directive 2006/66/EC (2019)**: Batteries – Environment – European Commission, <https://ec.europa.eu/environment/waste/batteries/evaluation.htm> (last checked 21 Nov 2019)
- [85] **Comment**: 18650 cylindrical cells may reach 300 Wh/kg in the future from today's maximum of 270 Wh/kg. Larger 21700 cells are expected to reach 350 Wh/kg. Today large pouch and prismatic cells are about 180 Wh/kg (pouch) and 140 Wh/kg (prismatic) and may also reach 350 Wh/kg in the long term.
- [86] **Comment**: A limit of around 800 Wh / l is expected at cell level for 18650 cells, whereas larger 21700 cells might reach around 800–1.000 Wh / l. Large pouch and prismatic cells today are at 450 Wh / l (pouch) and 350 Wh / l (prismatic) and might reach 800–900 Wh/l in the longterm.
- [87] **Thielmann, A.; Neef, C. (2019)**: Dresden Battery Days
- [88] **Comment**: Probably in the form of polymer electrolytes to start with, later hybrid or ceramic-only electrolytes.
- [89] **Schmuck, R.; Wagner, R.; Hörpel, G.; Placke, T.; Winter, M. (2018)**: Performance and cost of materials for lithium-based rechargeable automotive batteries, *Nat Energy* [3], 267–78
- [90] **Manthiram, A.; Yu, X.; Wang, S. (2017)**: Lithium battery chemistries enabled by solid-state electrolytes, *Nat Rev Mater* [2], 294
- [91] **Thielmann, A. (2016)**: Battery Roadmap for Electric Mobility: CTI Symposium Berlin
- [92] **Thielmann, A. (2018)**: Battery Roadmap for Electric Mobility: CTI Symposium Berlin
- [93] **NMP AG 1 (2019)**: Wege zur Erreichung der Klimaziele 2030 im Verkehrssektor: Zwischenbericht 03/2019 (Berlin: Nationale Plattform Zukunft der Mobilität. Arbeitsgruppe 1 »Klimaschutz im Verkehr«)
- [94] **NPE (2015)**: Ladeinfrastruktur für Elektrofahrzeuge in Deutschland: Statusbericht und Handlungsempfehlungen (Berlin: Nationale Plattform Elektromobilität)
- [95] **Hardman, S. et al (2018)**: A review of consumer preferences of and interactions with electric vehicle charging infrastructure Transportation Research Part D: Transport and Environment [629, 508–23
- [96] **Scherrer, A.; Burghard, U.; Wiestchel, M.; Dütschke, E. (2019)**: Early Adopter von E-Fahrzeugen: Ladeleistungen, Eigenerzeugung und Einstellungen zum Lagemanagement Energiewirtschaftliche Tagesfragen
- [97] **Frenzel, I.; Jarass, J.; Trommer, S.; Lenz, B. (2015)**: Erstenutzer von Elektrofahrzeugen in Deutschland. Nutzerprofile,

Anschaffung, Fahrzeugnutzung (Berlin: Deutsches Zentrum für Luft- und Raumfahrt e. V.)

- [98] Wietschel, M.; Kühnbach, M.; Stute, J.; Gnann, T.; Marwitz, S.; Klobasa, M. (2018): Auswirkung der Elektromobilität auf die Haushaltsstrompreise in Deutschland (Working Paper Sustainability and Innovation) (Fraunhofer ISI)
- [99] Navigant, K. E.; RE-xpertise (2019): Verteilnetzausbau für die Energiewende – Elektromobilität im Fokus: Studie im Auftrag von Agora Verkehrswende, Agora Energiewende und The Regulatory Assistance Project (RAP)
- [100] Gnann, T.; Klingler, A.-L.; Kühnbach, M. (2018): The load shift potential of plug-in electric vehicles with different amounts of charging infrastructure, *Journal of Power Sources* [390], 20–9
- [101] BDEW (2019): BDEW-Strompreisanalyse Juli 2019 – Haushalte und Industrie (Berlin: BDEW Bundesverband der Energie- und Wasserwirtschaft e.V.)
- [102] Gnann, T. et al (2017): Öffentliche Ladeinfrastruktur für Elektrofahrzeuge: Ergebnisse der Profilregion Mobilitätssysteme Karlsruhe (Karlsruhe: Fraunhofer-Institut für System- und Innovationsforschung ISI, Institut für Industriebetriebslehre und Industrielle Produktion (IIP) am KIT, Institut für Verkehrswesen (IfV) am KIT and Karlsruhe Service Research Institute (KSRI) am KIT)
- [103] Gnann, T.; Funke, S.; Jakobsson, N.; Plötz, P.; Sprei, F.; Bennehag, A. (2018): Fast charging infrastructure for electric vehicles: Today's situation and future needs *Transportation Research Part D, Transport and Environment* [62], 314–29
- [104] eafo (2019): The total number of normal and fast public charging points, <https://www.eafo.eu/alternative-fuels/electricity/charging-infra-stats>
- [105] Robinius, M.; Linßen, J.; Grube, T.; Reuß, M.; Stenzel, P.; Syranidis, K.; Kuckertz, P.; Stolten, D. (2018): Comparative analysis of infrastructures: Hydrogen fueling and electric charging of vehicles Institut für Elektrochemische Verfahrenstechnik (IEK-3), Forschungszentrum Jülich: *Energy & Environment (FuelCellsWorks)* 408
- [106] NPE (2018): Fortschrittsbericht 2018 – Markthochlaufphase (Berlin: Nationale Plattform Elektromobilität)
- [107] Funke, S. Á.; Plötz, P.; Wietschel, M. (2019): Invest in fast-charging infrastructure or in longer battery ranges?: A cost-efficiency comparison for Germany, *Applied Energy* [235], 888–99
- [108] Ensslen, A.; Gnann, T.; Jochem, P.; Plötz, P.; Dütschke, E.; Fichtner, W. (2018): Can product service systems support electric vehicle adoption? *Transportation Research Part A: Policy and Practice*
- [109] Wietschel, M.; Moll, C.; Oberle, S.; Lux, B.; Timmerberg, S.; Ashley-Belbin, N. (2019): Klimabilanz, Kosten und Potenziale verschiedener Kraftstoffarten und Antriebssysteme für Pkw und Lkw: Endbericht: Gefördert vom Biogasrat+ e.V. (Karlsruhe: Fraunhofer ISI)
- [110] Agora Verkehrswende (2018): Ein Kostenvergleich zwischen batterieelektrischen und verbrennungsmotorischen Pkw als Klimaschutzoption für das Jahr 2030 (Öko-Institut e.V.)
- [111] Gnann, T. (2015): Market diffusion of plug-in electric vehicles and their charging infrastructure (Dissertation Karlsruhe Institute of Technology (KIT) (Karlsruhe))
- [112] Global X (2019): What's Driving the Electric Vehicle, Lithium, and Battery Markets in 2019? <https://www.globalxetfs.com/whats-driving-the-electric-vehicle-lithium-and-battery-markets-in-2019/> (last checked 30 Oct 2019)
- [113] BCG (2018): The Future of Battery Production for Electric Vehicles, <https://www.bcg.com/publications/2018/future-battery-production-electric-vehicles.aspx> (last checked 30 Oct 2019)
- [114] Özdemir, E. D. (2012): The Future Role of Alternative Powertrains and Fuels in the German Transport Sector: A model based scenario analysis with respect to technical, economic and environmental aspects with a focus on road transport (Forschungsbericht, Universität Stuttgart, Institut für Energie-wirtschaft und Rationelle Energieanwendung 108)
- [115] Bloomberg (2019): A Behind the Scenes Take on Lithium-ion Battery Prices, <https://about.newenergyfinance.com/blog/behind-scenes-take-lithium-ion-battery-prices/> (last checked 30 Oct 2019)

- [116] **Bloomberg (2017)**: Electric Cars to Reach Price Parity by 2025, <https://about.bnef.com/blog/electric-cars-reach-price-parity-2025/> (last checked 30 Oct 2019)
- [117] **McKinsey (2017)**: Electrifying insights: How automakers can drive electrified vehicle sales and profitability
- [118] **Thielmann, A.; Sauer, A.; Wietschel, M. (2015)**: Produkt-Roadmap Energiespeicher für die Elektromobilität 2030 (Karlsruhe: Fraunhofer-Institut für System- und Innovationsforschung ISI)
- [119] **Bloomberg (2019)**: Electric Car Price Tag Shrinks Along With Battery Cost, <https://www.bloomberg.com/opinion/articles/2019-04-12/electric-vehicle-battery-shrinks-and-so-does-the-total-cost> (last checked 30 Oct 2019)
- [120] **ICCT (2018)**: Power play: How governments are spurring the electric vehicle industry: White Paper (The International Council on Clean Transportation)
- [121] **Meszler, German, Mock, Bandivadekar (2012)**: Summary of the EU cost curve development methodology: ICCT Working paper 2012–5.
- [122] **Bundesregierung (2019)**: Eckpunkte für das Klimaschutzprogramm 2030, <https://www.bundesregierung.de/ > 2019-09-20-klimaschutzprogramm-data>
- [123] **Runkel, M.; Stubbe, R. (2019)**: Elektroautos und Verbrenner im Gesamtkostenvergleich. Forum Ökologisch-Soziale Marktwirtschaft (Policy Brief). [According to Runkel and Stubbe (2019), the TCO of a VW e-Golf are currently €32,880 compared to €39,240 for a similar gasoline Golf model, assuming a typical ownership period of 5 years, 15,000 km/year and considering the environmental bonus from 2020. Other electric cars like the VW e-up!, BMW i3s, Hyundai IONIQ or Tesla Model 3 also have advantages in terms of their TCO compared to their conventional alternatives. The calculations of Runkel and Stubbe (2019) are based on ADAC (2019): Autokostenrechner Auswahlseite (ADAC e.V. Online verfügbar unter <https://www.adac.de/infotestrat/autodatenbank/autokosten/autokostenrechner/default.aspx>). These calculations are supported by [109], for example.]
- [124] **Münzel, C.; Plötz, P.; Sprei, F.; Gnann, T. (2019)**: How large is the effect of financial incentives on electric vehicle sales? – A global review and European analysis Energy Economics 104493
- [125] **IEA (2018)**: World Energy Outlook 2018 (International Energy Agency)
- [126] **Schade, W.; Perez, E.; Berthold, D.; Wagner, U.; Krail, M.; Waßmuth, V. (2018)**: Gestaltung des Referenzszenarios zur Nutzung in der MKS 2017+: Arbeitspapier im Auftrag des Bundesministeriums für Verkehr und digitale Infrastruktur (Karlsruhe)
- [127] **Pfluger, B.; Testeegen, B.; Franke, B. (2017)**: Langfristszenarien für die Transformation des Energiesystems in Deutschland: Modul 3: Referenzszenario und Basisszenario
- [128] **Gerbert, P.; Herhold, P.; Buchardt, J.; Schönberger, S.; Rechenmacher, F.; Kirchner, A.; Kemmler, A.; Wünsch, M. (2018)**: Klimapfade für Deutschland (The Boston Consulting Group and Prognos AG)
- [129] **Bobba, S.; Podias, A.; Di Persio, F.; Messagie, M.; Tecchio, P.; Cusenza, M. A.; Eynard, U.; Mathieux, F.; Pfrang, A. (2018)**: Sustainability Assessment of Second Life Application of Automotive Batteries (SASLAB): JRC Exploratory Research (2016–2017) (Luxembourg: Publications Office of the European Union)
- [130] **Hettesheimer, T.; Durand, A.; Lam, W. C.; Mulder, G. (2019)**: Task 6 Report Design options: Preparatory Study on Ecodesign and Energy Labelling of rechargeable electrochemical batteries with internal storage under FWC ENER/C3/2015-619-Lot 1 (Brussels: European Commission)
- [131] **BNEF Report on Second-Life EV Battery Storage**: NGT News (2016), <https://ngtnews.com/bnef-report-on-second-life-ev-battery-storage>; Comment: StorageBNEF expects 25 GWh end-of-life batteries in 2025 and 10 GWh of these as potential second-life batteries for use in stationary storages (last checked 21 Nov. 2019).
- [132] **McKinsey (2019)**: Second-life EV batteries: The newest value pool in energy storage, <https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/second-life-ev-batteries-the-newest-value-pool-in-energy-storage> (last checked 21 Nov 2019)



- [133] ACEA: ACEA – European Automobile Manufacturers' Association, Average Vehicle Age, <https://www.acea.be/statistics/tag/category/average-vehicle-age> (last checked 21 Nov 2019)
- [134] How much does it cost to replace a hybrid battery?: <https://auto.howstuffworks.com/fuel-efficiency/hybrid-technology/hybrid-battery-cost.htm> (last checked 21 Nov 2019)
- [135] ICCT (2019): Update on electric vehicle costs in the United States through 2030, [https://theicct.org/sites/default/files/publications/EV\\_cost\\_2020\\_2030\\_20190401.pdf](https://theicct.org/sites/default/files/publications/EV_cost_2020_2030_20190401.pdf) (last checked 21 Nov 2019)
- [136] Neef, C.; Thielmann, A. (2019): TASK 2 Markets – For Ecodesign and Energy Labelling, Preparatory Study on Ecodesign and Energy Labelling of Batteries under FWC ENER/C3/2015-619-Lot 1 (Brussels: European Commission)
- [137] Comment: Primary balancing power, for example.
- [138] Publisher: Begleit- und Wirkungsforschung Schaufenster Elektromobilität (2016): Studie: Second-Life-Konzepte für Lithium-Ionen-Batterien aus Elektrofahrzeugen
- [139] Comment: 250 new EV models are expected by 2025, each with different battery packs.
- [140] Elwert, T.; Römer, F.; Schneider, K.; Hua, Q.; Buchert, M. (2018): Recycling of Batteries from Electric Vehicles Behaviour of Lithium-Ion Batteries in Electric Vehicles: Battery Health, Performance, Safety, and Cost (Green Energy and Technology), Publisher: Pistoia, G; Liaw, B.(Cham: Springer) pp. 289–321
- [141] Umweltbundesamt (2019): Altbatterien, <https://www.umweltbundesamt.de/daten/ressourcen-abfall/verwertungsentsorgung-ausgewaehlte-abfallarten/altbatterien#textpart-1> (last checked 18 Nov 2019)
- [142] Umicore; Daimler; Öko-Institut; TU Clausthal (2011): Entwicklung eines realisierbaren Recyclingkonzeptes für die Hochleistungsbatterien zukünftiger Elektrofahrzeuge: Lithium-Ionen Batterierecycling Initiative – LiBRi (Hanau)
- [143] Hanisch, C.; Diekmann, J.; Stieger, A.; Haselrieder, W.; Kwade, A. (2015): Recycling of Lithium-Ion Batteries Handbook of clean energy systems, Publisher: Yan, J. (Chichester: Wiley) pp. 1–24
- [144] Hettesheimer, T.; Thielmann, A.; Neef, C.; Durand, A. (2019): Task 4 Technologies – For Ecodesign and Energy Labelling: Preparatory Study on Ecodesign and Energy Labelling of Batteries under FWC ENER/C3/2015-619-Lot 1 (Brussels: European Commission)
- [145] TU Braunschweig; ACTIA I+ME; Hosokawa Alpine; Electrocyling; Volkswagen; Audi; Solvay Fluor; Universität Münster; Rockwood Lithium, H. C. Starck (2016): Recycling von Lithium-Ionen-Batterien – LithoRec II: Abschlussberichte der beteiligten Verbundpartner
- [146] Hagelüken, C. (2019): Recycling von Lithium-Ionen Batterien (6. Fachkonferenz Elektromobilität vor Ort) (Stuttgart)
- [147] Marscheider-Weidemann, F.; Langkau, S.; Hummen, T.; Erdmann, L.; Tercero Espinoza, L.; Angerer, G.; Marwede, M.; Benecke, S. (2016): Rohstoffe für Zukunftstechnologien 2016 (DERA Rohstoffinformationen 28) (Berlin: Deutsche Rohstoffagentur (DERA) in der Bundesanstalt für Geowissenschaften und Rohstoffe)
- [148] Hagelüken, C. (2019): Closing the loop: Why recycling is crucial to secure a sustainable metals supply (Frankfurt: E-Waste World Conference & Expo)
- [149] Buchert, M.; Sutter, J. (2016): Aktualisierte Ökobilanzen zum Recyclingverfahren EcoBatRec für Lithium-Ionen-Batterien: (Stand 09/2016) (Berlin, Darmstadt: Ökoinstitut)
- [150] Buchert, M.; Sutter, J. (2016): Aktualisierte Ökobilanzen zum Recyclingverfahren LithoRec II für Lithium-Ionen-Batterien: (Stand 09/2016) (Berlin, Darmstadt: Öko-Institut)

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## Graphic design

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## Printed by

Stober GmbH  
Druck und Verlag 2020

[www.isi.fraunhofer.de](http://www.isi.fraunhofer.de)

## Picture credits

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Lithium-ion battery  
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(based on a template from Audi)

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Electric car with lithium-ion battery  
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Charging station with electric car  
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Electric car  
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## Acknowledgements

We would like to thank Prof. Martin Winter,  
Prof. Dirk Uwe Sauer and Dr. Peter Lamp for  
their critical review of this Policy Brief and  
their feedback.

