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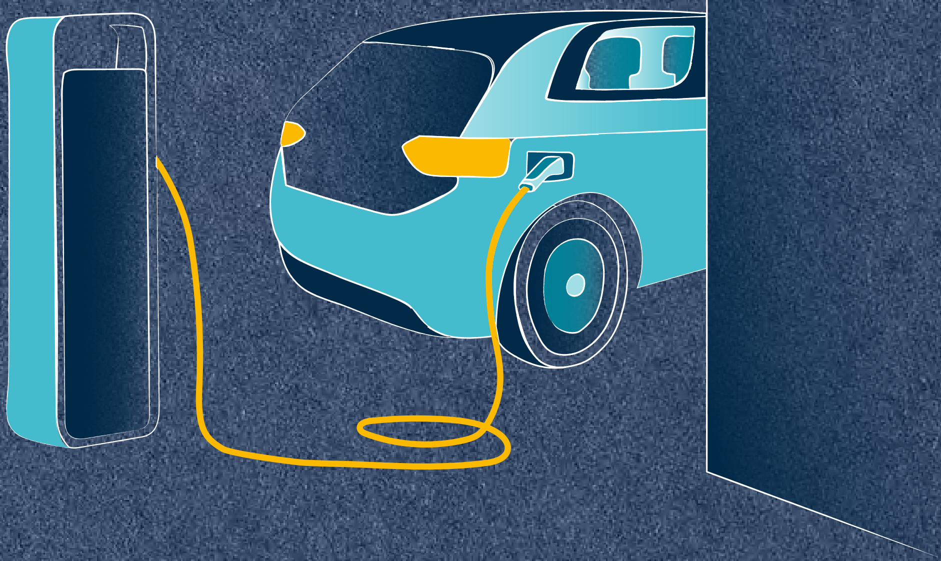

Batteries for Electric Cars: Fact Check and Need for Action – An Update

perspectives

policy brief

Fraunhofer ISI

Batteries for Electric Cars: Fact Check and Need for Action – An Update

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

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Further information

The policy brief: "Batteries for Electric Cars: Fact Check and Need for Action – An Update" is part of Fraunhofer ISI's series "perspectives – policy briefs" and draws on findings and study results from our battery research and our cross-departmental topic of electric mobility.

More information using the following links:

- **Policy briefs**
- **Battery research**
- **Electric mobility**

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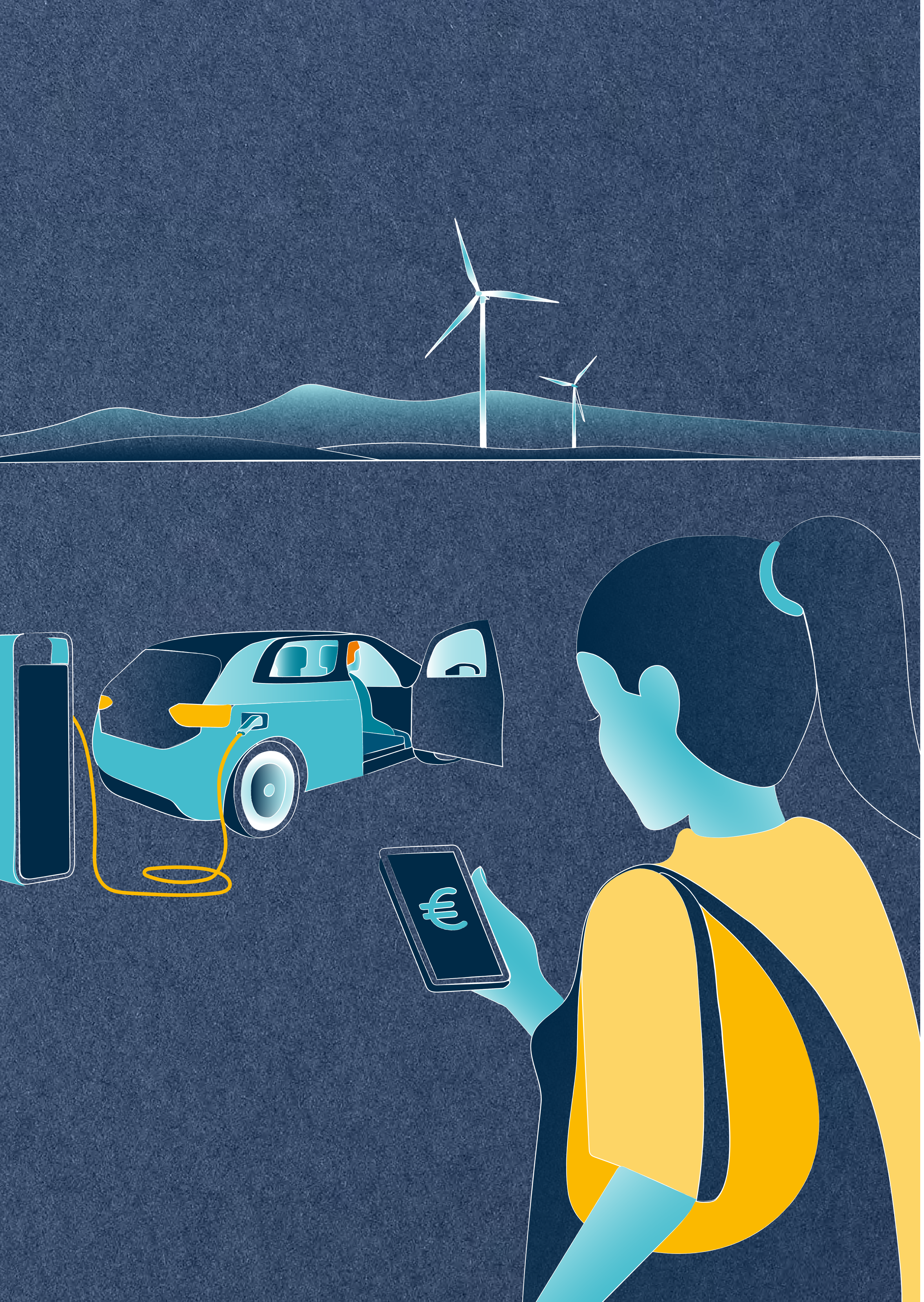

Overview and core statements

There is widespread agreement in politics and industry that battery-electric cars will play a major role in the future.

When looking at the key issues along the entire battery value chain, it becomes clear that there are no insurmountable obstacles to the continued widespread market diffusion of battery-electric cars. However, there are still several technical, economic, environmental, regulatory and social challenges to address in the coming years. These challenges can be overcome, provided there is the political will to do so. The most important findings are summarized below and discussed in greater detail in the sections on the individual questions.

Note: This policy brief was published under the same title in 2020, but its content has been completely revised, and new aspects have been added. It reflects the state of research as of February 2025.

01

How are electric mobility and the demand for batteries developing worldwide and in Germany?

Globally, the demand for electric cars has risen sharply over the last few years and currently accounts for just under 20 percent of new registrations, with a growth trend in many markets. This trend is being driven by China in particular, the world's largest car market, but figures are continuing to rise in the US and Europe as well. According to international studies, the global share of new electric vehicles could grow from just under 20 percent today to 40 percent by 2030 and more than 50 percent by 2035. Compliance with ambitious climate targets is one of the main drivers. Until 2023, the number of new registrations also climbed steadily in Germany and was even higher than the global market development. However, the numbers dropped in 2024 for various reasons, such as the abrupt withdrawal of purchase subsidies and high electricity prices, especially as far as battery-electric cars are concerned. It remains to be seen whether this is only a temporary effect and whether factors such as the EU fleet limits and falling prices for electric cars will reverse it. The global development of electric cars is still driving the demand for battery capacities upwards. Demand will increase by a factor of 4 to 6 by 2030 compared to 2023 and by a factor of 7 to 11 by 2035. When looking at the total battery capacity demand, road traffic applications will dominate the market with around 85 to 90 percent in 2030.

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02

Are electric cars economical?

Without subsidies, electric cars are still more expensive to buy than conventional vehicles. However, purchasing costs have recently decreased significantly due to falling battery prices and growing international competition. Supported by the EU's fleet-wide CO_2 emission targets to be achieved in 2025, this trend is likely to continue in Germany as manufacturers want to sell their vehicles. Within the next few years, the purchase prices for many electric vehicles are expected to even out at a similar level to comparable gasoline or diesel models. Due to their lower running costs, electric vehicles already perform better than conventional ones in terms of total costs in some cases, although there are currently still uncertainties regarding their resale value. This positive economic trend will continue. For example, controlled and bidirectional charging will have a significantly positive impact on the economic efficiency of electric cars in the future (see questions 09 and 11).

The advantages in terms of total costs should be clearly communicated to customers, who often focus on acquisition costs when making purchasing decisions. Government funding policies should therefore focus more on reducing the purchasing price.

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Overview and core statements

03

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

Electric cars purchased in Germany today have a clearly positive greenhouse gas balance compared to conventional cars when looking at their entire lifetime from manufacturing and use to disposal (40 to 50 percent emission reduction for a mid-range car and average mileage). The higher emissions when manufacturing the electric vehicles are more than offset during their use phase. Battery production focused on energy-efficient and renewable energy sources, more renewable electricity when charging, controlled charging (see question 11) and a closed resource cycle (see question 10) have the potential to further improve the climate and environmental footprint of electric vehicles. However, as with every other form of motorized private transport, using an electric car is also associated with significant environmental pollution, so transforming transport must also involve changes in our mobility behavior (including fewer and smaller vehicles and fewer car trips). Electric cars have negative environmental impacts including acidification, over-fertilization and the use of critical raw materials, although new types of battery and recycling (see questions 04, 05 and 09) are having an effect on reducing the use of at least some critical raw materials or even avoiding them completely in some cases. Regulations should be set accordingly.

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04

How has battery performance improved?

Batteries will continue to evolve in the future in terms of materials, battery cell designs, and pack designs at the vehicle level. For example, another major improvement in energy density of up to 30 percent is expected by 2030. This will make batteries lighter and smaller or increase the range of a vehicle. This is backed by innovations such as nickel-rich, high-energy cathode materials, silicon anodes, and new cell and pack designs for better system integration. As well as optimizing space requirements, the latter will also optimize the thermal management and safety of battery systems (see question 13). These advances will also change the fast-charging options for batteries. Charging times of 10 to 20 minutes will be feasible with simultaneously long lifetimes of at least 15 years – important factors for improving user acceptance.

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05

Do we have enough global resources?

Globally, there are sufficient quantities of critical raw materials for batteries such as lithium, cobalt, nickel, manganese and graphite, but temporary supply bottlenecks or price increases cannot be ruled out in the medium term. This is related to the dynamics of battery demand on the one hand and, on the other hand, to the high market concentration and Germany's and the EU's import dependency due to low or no domestic production of these raw materials. The core challenges here are the financing required, the rapid implementation of mining projects and the acceptance of these projects in the home country, as the majority of the raw materials required will have to be supplied from primary sources. To mitigate this problem on the demand side, there are new lithium-ion battery chemistries (based on iron or manganese, or cobalt-free) and alternative technologies such as sodium-ion batteries. In addition, recycling in Europe can help supplement the supply of raw materials from mining. By expanding its own mining projects and processing facilities, and increasing recycling, Europe could cover a significant share of its growing demand for raw materials in the long term. However, dependency on raw material imports cannot be completely avoided.

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06

What factors are important for competitive battery cell production?

Vehicle batteries now account for a significant proportion of the value creation in electric cars (about one-third in medium-sized cars). The international competitiveness of battery cell production in Germany and Europe depends on different factors such as investments, operating costs, the technological expertise available, access to supply chains, and last but not least, the political framework and funding initiatives. The US and Asia are Europe's main competitors. Although Europe is strong in basic research, it faces major challenges in terms of high energy prices, longer construction times, mainly due to bureaucratic obstacles, and less experience with scaled production. For instance, problems with ramp-up processes and lengthy approval procedures are currently hindering or delaying several European projects. Politicians have introduced several regulatory and supportive measures intended to cushion the high investments required and address issues such as research and development, and training skilled workers.

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07

Are there supply shortages and risks along the value chain?

The declining sales figures for electric vehicles in Germany after 2023 (see question 01) are not due to supply bottlenecks affecting the vehicles. This is also clearly shown by the shorter average vehicle delivery time of four months. Nevertheless, the ramp-up in the production of electric cars poses a challenge for procuring the traction batteries. Although battery cell production and its upstream supplier industry have sufficient capacity, the vast majority of the production facilities are in Asia. China, in particular, dominates large parts of the value chain. Geopolitical crises can have a major impact on the resilience of supply chains.

European and American manufacturers are therefore backing multi-sourcing strategies that accompany the development of their own domestic production capacities. In the long term, the dependence on Asian battery cells is therefore likely to decline. However, the complexity of global supply chains for electric cars remains challenging.

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08

What challenges does the labor market face?

Despite varying assessments of the employment effects in the automobile industry and its suppliers, the majority of studies reckon with a significant reduction in the number of jobs in this important branch of the economy in Germany. Battery cell production itself is highly automated, which is why positive job effects here are limited. However, if the upstream and downstream value chains are included in the analysis, for example, in electricity generation, charging infrastructure and digitalization, the resulting employment effects are significant and could compensate negative effects within the automotive industry or even create jobs in newly emerging sectors. However, they are heavily dependent on whether and where German and European companies will be able to position themselves competitively in the long term.

It is important to set the system boundaries carefully and understand these when assessing such employment effects because the automotive industry and its suppliers are undergoing transformation. Completely new fields of activity and therefore jobs are emerging within the automotive industry, but also outside it. This structural transformation across industries and regions should be shaped to be as socially compatible as possible through active industrial and labor market policies in conjunction with natural age-related fluctuations. This requires the implementation of retraining and further training measures in and for companies. It is important to train and to retain skilled workers with battery-specific expertise because there is the risk of a growing shortage of highly trained battery experts in this future industry, who function as multipliers for upstream and downstream jobs.

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09

What ranges can we expect, and how is the charging infrastructure developing?

Today's top electric car models offer a range of at least 400 km, while some future models are aiming to exceed 1,000 km, thanks to advanced battery systems (see question 04). While battery technology allows for correspondingly longer ranges, the costs and environmental impacts associated with increasing range (see questions 03 and 12) are arguments in favor of using smaller batteries. Since many drivers consider a range of 400 km to be sufficient in practice, especially with ever faster charging times, the average increase in range is expected to be moderate.

The expansion of charging infrastructure and the increase in charging capacity are crucial for the use of smaller batteries. The charging infrastructure at home or at work is and will remain important for charging electric cars. Load management can help avoid additional costs in the power distribution grid and support the integration of renewable energies. The legal framework is promoting the expansion of charging infrastructure in semi-public spaces, such as supermarkets, for users who do not have private parking. The public fast-charging network, which is important for long-distance journeys, is already well developed, but needs to be continuously expanded in line with demand as the number of electric vehicles increases. Bidirectional charging will be established in the future and will help to reduce charging costs (see question 11) and improve the overall economic efficiency of electric cars. The existing statutory regulations should be further developed, and users' awareness of this issue should be increased.

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10

What happens to the used batteries?

The Battery Regulation (Regulation (EU) 2023/1542) governs the collection and recycling of used batteries, particularly in view of the growing market for electric vehicles. Forecasts assume that sufficient recycling capacities will be available in the long term for end-of-life batteries and manufacturing waste. By 2035, up to 30 percent of the lithium, nickel, and cobalt required for battery cell production could be covered by recycled materials.

Battery recycling involves processes such as collection, discharge, dismantling, mechanical processing, and high-temperature melting. These processes allow the recovery of valuable materials such as cobalt, nickel, and lithium. The profitability of battery recycling depends heavily on the chemical composition of the battery and the current market prices for the raw materials. The residual value of current electric vehicle batteries at the end of their service life is generally estimated at 10–20 percent of the original price.

In addition to recycling, repair, refresh, and second-use concepts are currently the main options for batteries that are still usable to extend their effective battery life and reduce their ecological footprint. Studies suggest that a combination of second use and recycling can reduce the ecological footprint of batteries by 35–80 percent.
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11

Does it make sense to use car batteries as mobile storage devices?

Bidirectional charging (with energy feedback) for electric cars will offer advantages for both the power grid and their users in the future, provided the right conditions are created. This will integrate renewable energies better, reduce grid overloads, and lower overall system costs. In Germany, this can achieve considerable financial savings in the energy system. There is also a large saving potential for car users, depending on factors such as driving behavior, location, battery size, and availability of a photovoltaic system. Possible negative effects on battery aging are usually not a problem (anymore). The future spread of smart meters, bidirectionally chargeable vehicles and infrastructure, and dynamic electricity tariffs will increase the technical potential and economic attractiveness of electric cars. Home applications are easy to implement in regulatory terms. There are still bigger obstacles to grid applications, such as double financial burdens for charging and discharging, and a lack of compatibility between vehicles and charging infrastructure. A high degree of user acceptance is also essential.
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12

What measures could improve the social and environmental effects along the global value chains of batteries?

Regardless of the drive technology involved, there are environmental and social risks in global value chains associated with extracting raw materials and manufacturing technical components (for example, toxic emissions or human rights violations), which are more severe the weaker the laws and state institutions in the respective country. Legal stipulations regarding corporate due diligence create uniform conditions for greater transparency and improve the social and environmental conditions along the value chains. Since boycotting regions with environmental and social risks often makes it worse for those affected, the focus should be on improving conditions through monitoring and support.
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13

Do electric cars have a high fire risk?

The current state of knowledge is that electric cars do not catch fire more frequently than conventional cars. Some international studies even assume a significantly lower fire risk. The new battery types currently entering the market have a much lower fire risk than conventional LIB batteries (see question 02). Extinguishing fires in electric cars is more complex and takes longer, but there are now different options available to do so. According to current knowledge, parking electric cars in garages or on ferries does not lead to a significant increase in risk compared to the hazards that already exist.
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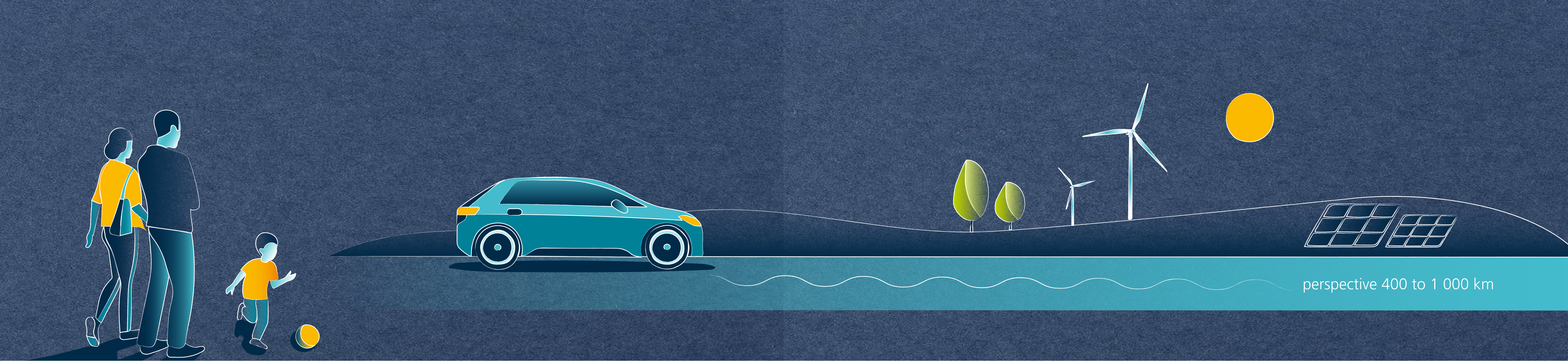
14

Who wants an electric car and how stable is the interest in electric mobility?

Interest in electric cars among the German population remained stable between 2020 and 2024 despite the current drop in sales figures (see question 01). Around one-third of those questioned have a positive attitude toward this technology. The group of electric car users has become more diversified with a rising proportion of women, but electric cars are still most prevalent among people with higher levels of education and income. Important framework conditions such as purchase subsidies and charging infrastructure influence sales figures and social acceptance. In addition, positive media coverage has a favorable effect on attitudes, while inconsistencies in comparative assessments of drive technologies can reinforce uncertainties.
→ **More information on page 30**



Introduction

In 2020, Fraunhofer ISI published the policy brief "Batteries for Electric Cars: Fact Check and Need for Action", which has been widely cited.

Background

The topics have evolved over the past five years, which is why we decided to update the policy brief by revising individual topics and addressing new ones related to batteries for electric mobility.

Climate change is one of the biggest challenges facing humanity. The new IPCC report [1] sounds a clear alarm: Human activities, mainly through the emissions of greenhouse gases, are the indisputable cause of global warming. As a result, the global surface temperature in the period 2011–2020 was 1.1°C above that of 1850–1900. Human-induced climate change is already responsible for many weather and climate extremes in all regions of the world. This has led to widespread adverse impacts and associated losses and damage to nature and people (see [1]).

According to the International Energy Agency (IEA), the return to normal levels of passenger and freight transport after the coronavirus pandemic led to a three percent increase in transport-related CO_2 emissions in 2022 compared to the previous year. From 1990 to 2022, transport emissions increased at an average annual rate of 1.7 percent, faster than in all other end-use sectors except industry. To achieve the IEA's net-zero emissions scenario by 2050, the CO_2 emissions of the transport sector must decrease by more than three percent per year by 2030. Achieving this reduction in emissions requires strict regulations, economic incentives and considerable investments in infrastructure to enable the operation of low-emission and zero-emission vehicles [2].

There is now widespread agreement in science and industry that electric cars are the most important drive technology of the future for reducing greenhouse gas emissions and that batteries are the key to this. There has already been a significant recent rise in their sales worldwide, which is set to continue based on current trends. Other fuels and drive technologies, such as synthetic fuels in international aviation and shipping, will also play a role in the future.

In spite of obvious global market success, many buyers in Germany, as well as some segments of the public and the media, politicians, corporate decision-makers and experts are still questioning the sustainability, economic viability, practicality and technological maturity of battery technology and of electric mobility in general. At the same time, the market ramp-up of battery-electric cars is an integral part of the national and European mobility transformation. It is also a key component in the relevant recommendations of national and international studies (see, for example, [3], [4] and [115]), in policy goals, and in the transition to climate neutrality in many countries (see [4]).

Against this backdrop, it is necessary to take another scientific and analytical look at the developments, potential and obstacles relating to the market ramp-up of battery-electric cars and to update the recommendations for action. These should serve the political goal of a ramp-up that is socially acceptable, makes environmental sense, and benefits the economy for Germany and Europe. In this context, the following questions take a scientific perspective when checking the facts for batteries for electric cars and electric mobility in general and identifying the areas of action required. This policy brief is aimed equally at policymakers, experts and the general public and summarizes the current state of knowledge and latest findings with a focus on "Batteries for electric cars".

Approach and methodology

The fact check examines fourteen questions along the entire battery chain from raw material extraction, material/component manufacturing, the production of battery cells, models and packs, their use in vehicles, to recycling from a German perspective. The relevant studies and articles and some of Fraunhofer ISI's own scientific analyses are compared and evaluated to answer these questions.

Key statements

When looking at the main questions along the entire battery chain, it becomes clear that there are no longer any fundamental obstacles standing in the way of the continuing market diffusion of battery-electric cars, which are likely to make up the majority of new vehicle sales after 2030 if climate protection continues to advance. Many of the technical hurdles have been overcome in recent years, and rapid progress is being made in many areas. In Germany, however, there are still economic challenges such as cheaper internal combustion vehicles and insufficient government incentives. The German automotive industry is also currently facing fierce international competition. Electric vehicles are generally already significantly better than conventional internal combustion vehicles in terms of overall greenhouse gas emissions, but their environmental performance needs to be further improved, for example through appropriate regulation. There is still insufficient acceptance of electric vehicles, and further awareness-raising is needed.

The questions in more detail

In the following sections, we provide more detailed answers to the fourteen questions along the battery value chain by comparing and evaluating the relevant studies and articles, and some of our own scientific analyses.

01

How are electric mobility and the demand for batteries developing worldwide and in Germany?

Sales of electric cars – including purely battery-powered vehicles (BEVs) and plug-in hybrids (PHEVs) – are currently continuing to rise worldwide and could reach around 17 million in 2024 [3]. This corresponds to more than one in five new cars sold worldwide. In 2024, the market share of electric cars could be as high as 45 percent in China, 25 percent in Europe, and more than 11 percent in the United States, boosted by competition between manufacturers, falling battery and vehicle prices, and continued political support (see [3]).

It is clear that this trend must continue if ambitious climate protection targets are to be met. Their global share could rise to 40 percent of new vehicles by 2030 and more than 50 percent in 2035, driven in part by low-cost vehicles from China. Assuming the goal of zero greenhouse gas emissions by 2050, the share could even grow to 90 percent in 2035 (see [5]).

New registrations of electric vehicles in Germany also rose significantly to 30 percent by 2022 [6, 3]. However, numbers dropped again in 2024 (to 23 percent, mainly due to a decline in battery-only vehicles) [7]. The European market is also weakening, with a three percent decline in the market share of electric cars [8]. As a result, Europe, and Germany in particular, is losing some of its momentum.

There are several reasons for this development in Germany: The purchase price subsidies expired at the end of 2023, comparatively high acquisition costs (significantly higher than prices in China), the rise in electricity prices due to the war in Ukraine (even though these have since fallen again), comparatively low gasoline and diesel prices, discussions about the lack of charging infrastructure (even though Germany is in a good position here by international standards), and weak overall economic development. Furthermore, the debate about synthetic fuels (which are produced from renewable electricity) and, in particular, the debate about technology openness may have unsettled market participants and led to a reluctance to buy electric.

It remains to be seen whether there will be a reversal of this trend in the short term, partly due to the EU CO_2 fleet limits that must be met by 2025 and the arrival of new, cheaper models [7]. Taking into account the current market development, it seems unlikely that the political target of 15 million electric vehicles on the road in Germany by 2030 will be reached [9], which could contribute to Germany missing its greenhouse gas reduction targets [10]. The current framework conditions in the EU, which include a ban on new fossil fuel-powered vehicles with internal combustion engines from 2035, and the various announcements by international car manufacturers, some of which have ambitious sales targets for electric cars, paint a slightly positive picture.

It should also be noted that German car manufacturers (OEMs) lost market shares in electric cars last year compared to their international competitors (see Figure 1). This sends a clear signal to one of Germany's most important industries.

Figure 2 calculates the battery capacity required for two scenarios involving the market diffusion of electric cars, which correlate with the above-mentioned market growth figures in electric cars.

There is a clear upward trend in the demand for battery capacity, driven mainly by demand in China. Europe accounts for around 20 percent of global demand. According to forecasts, road transport applications could account for around 85 to 90 percent of demand in 2030. This means that they are well above the forecast demand for stationary energy storage and other applications.

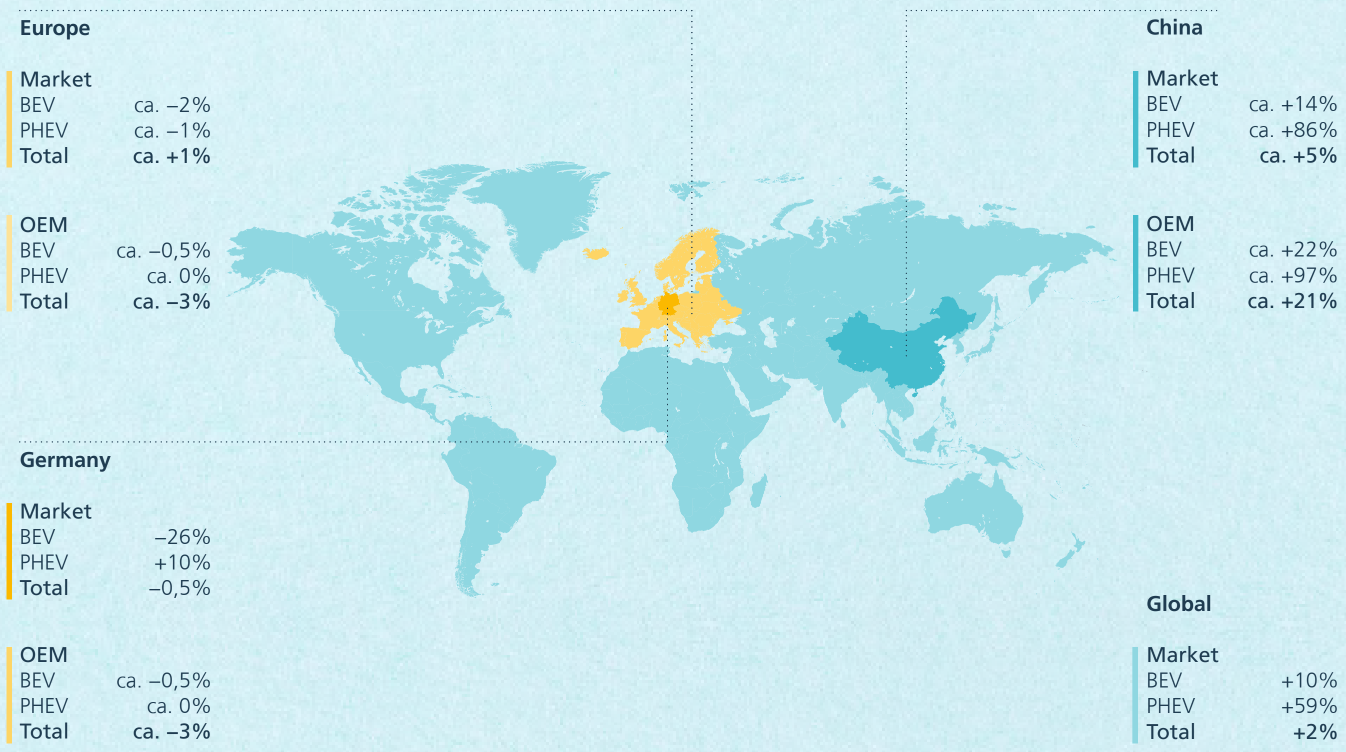


Figure 1 Comparing the registrations of electric cars and the car market as a whole in 2023 (January–November) and 2024 (January–November) for national markets and national car manufacturers (OEMs) based on their global sales in the previous year. Source: own analysis

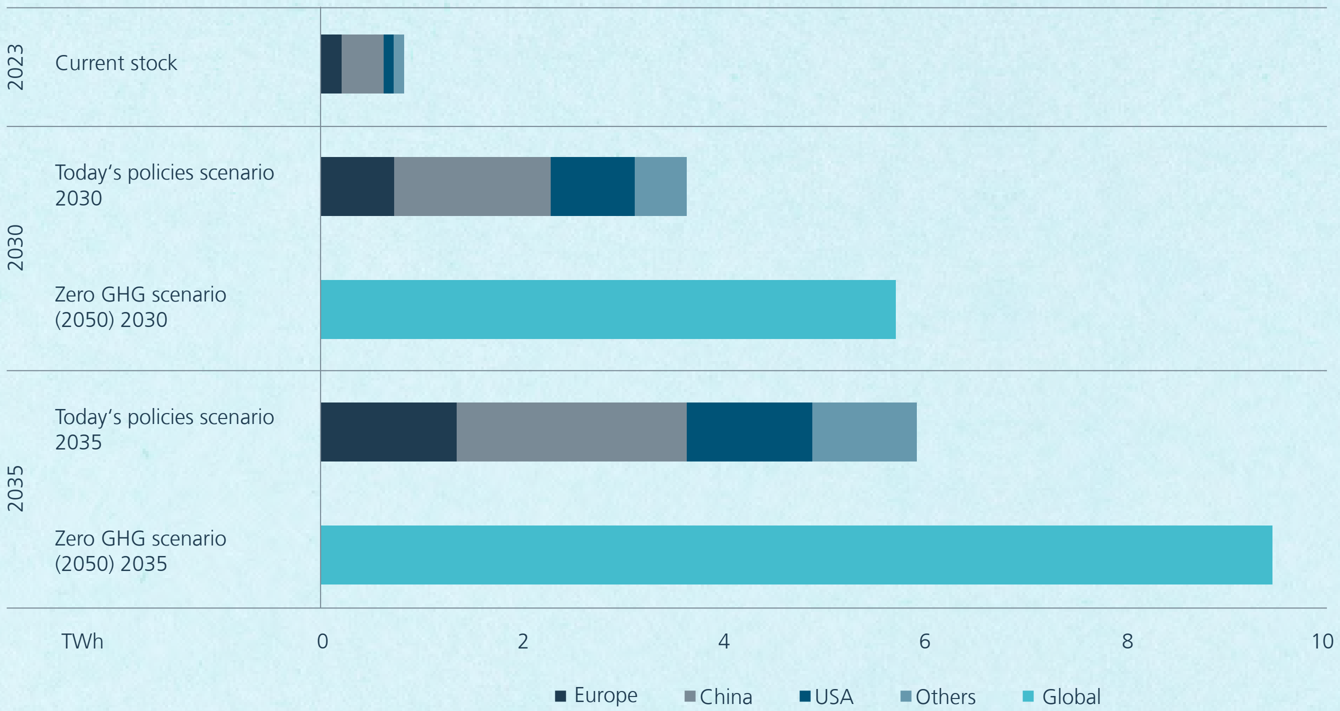


Figure 2 Development of the demand for battery capacity by region and for two scenarios (figures from [3])

02

Are electric cars economical in Germany?

Looking at the total cost of ownership (TCO) of conventional and battery-electric vehicles (BEVs), similar costs are already being recorded for average mileage in the mid-range segment. The current higher purchase costs of BEVs are offset by their lower running costs. On the one hand, this is due to lower energy costs as a result of the more efficient drive system. On the other hand, maintenance and repair costs are also lower than those for internal combustion engines [11]. This is mainly due to the absence of motor and transmission components that are subject to wear and tear [12]. In comparison, tire wear costs are slightly higher for BEVs due to the vehicles' greater weight, but this does not raise the overall costs above those of an internal combustion engine vehicle. Maintenance and repair costs are still relatively high due to the lack of experience and the limited number of workshops that service and repair electric vehicles [13]. Access to charging infrastructure also plays an important role in terms of economic efficiency. If this is available privately or at work, electric vehicles can be more economical than comparable internal combustion engine vehicles after just three years [14]. In the future, the cost-effectiveness of electric vehicles compared to conventional combustion engine cars will improve even further, partly due to falling vehicle prices, improved and cheaper vehicle batteries (see question 04), and the use of controlled and bidirectional charging (see question 11).

However, the higher price of the vehicles is still proving to be an obstacle, as this is a decisive factor for many buyers, especially since they do not take the overall costs into account. When compared with equivalent diesel or gasoline-powered cars, electric vehicles are still more expensive in Germany and many other countries [15, 16, 17, 18, 19]. The higher purchase costs are due to the relatively high cost of the traction battery. However, following the expiry of the environmental bonus in Germany at the end of 2023, many electric vehicle manufacturers are responding with price reductions as the share of electric vehicles among new registrations in Germany has since stagnated at a low level of 13 percent (see question 01). The price reductions observed are the result of battery overproduction in China, sharply falling cell prices, consumer reluctance on the German market, and the CO_2 fleet limits for cars and light commercial vehicles to be achieved in the EU by 2025. According to analyses by Bloomberg [20], prices for lithium iron phosphate (LFP) and nickel manganese cobalt (NMC) battery cells have fallen from USD 151/kWh at the beginning of 2023 to below USD 100/kWh and in some cases even to USD 75/kWh due to the easing of the raw materials situation. New battery technologies and production processes offer further potential for cost reductions (see questions 04 and 06). However, there are also risks associated with pricing, particularly in relation to raw materials, supply chains, and batteries (see questions 05, 06, and 07). Since private customers tend to base their purchasing decisions on the purchase price rather than total costs, the total cost advantages of electric cars need to be emphasized much more strongly. This should also be taken into account when designing incentive systems.

The CO_2 fleet limits to be achieved in the EU by the end of 2025 are an additional factor that could contribute to further price reductions for electric vehicles in 2025. According to a study by the ICCT [119], manufacturers must achieve an electric vehicle average share of 28 percent of all new registrations to avoid penalties. This means that the price parity between electric vehicles and internal combustion engine vehicles, which was predicted in earlier studies between 2025 and 2030 [120, 121, 122, 123], seems achievable in the near future.

In addition to the purchase price, range and access to (fast) charging infrastructure are important factors for many buyers when deciding what to purchase. While battery costs per kWh will continue to fall, the average battery capacity of electric vehicles has continued to increase in the past [21], enabling longer ranges and thus greater everyday usability and acceptance. However, there are indications that the trend toward ever greater battery capacities is declining (see question 09).

There are also indications that range improvements will tend to be achieved through efficiency improvements in the powertrain [12]. Fast charging after a long journey can also significantly increase the vehicle's effective range.

Various institutions offer calculators to compare the cost-effectiveness of different options (see [22], for example).

03

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

The chief driving force behind electric cars is the reduction of greenhouse gas emissions. Compared to conventional cars, manufacturing purely battery-powered vehicles is significantly more energy-intensive due to the production processes required for the battery. Depending on the energy source, the energy efficiency of production, and battery size, greenhouse gas emissions are between 60 and 130 percent higher than for manufacturing gasoline or diesel vehicles. However, depending on the electricity used, BEVs cause fewer greenhouse gases during their use phase. Assuming the German electricity mix is used and that the energy transition goes as planned, i.e., among other things, that the share of renewables continues to increase, a BEV purchased today will have 40 to 50 percent lower greenhouse gas emissions over its lifetime in the overall balance of the manufacturing, use, and recycling phases than a comparable modern, conventional mid-range car with average mileage (see studies in [3, 23, 24, 25, 26, 27]. This will continue to improve in the future as the energy transition progresses. If predominantly or exclusively renewable electricity is used for charging – and in Germany, just under 50 percent of electric vehicle users currently have their own PV system, and a third of those have their own battery storage – the greenhouse gas balance is even more positive [26, 25].

Another factor is the time at which charging takes place. Low electricity prices and a high share of renewable electricity production are usually positively correlated. Moreover, electric cars can be charged in a very controlled manner, as they are mostly stationary and often have a charging point available (see questions 09 and 11). In addition to charging with renewable energies, future efforts should focus on the potential for reducing greenhouse gas emissions in battery production [29], which includes new battery technologies (see question 04) and recycling (see question 10). Reusing batteries for stationary applications, for example, to store energy from PV systems, can also significantly improve the greenhouse gas balance of electric vehicles (see also question 10).

However, the greenhouse gas balance can vary greatly from case to case. If a heavy, inefficient electric vehicle with a large battery capacity and low annual mileage is taken into account, which is usually only charged using the current German electricity mix, its greenhouse gas balance is hardly any better than that of a comparable conventional vehicle.

In addition to greenhouse gas emissions, electric cars, like conventional cars, have other environmental impacts that arise not only during use but also during raw material extraction, manufacturing, and disposal. Raw material extraction and manufacturing have a significant impact on the overall environmental balance of electric cars. Therefore, when considering their entire life cycle, the electric cars currently purchased in Germany also have disadvantages in some areas of environmental protection compared to conventional cars. These include particulate matter emissions, acidification (emissions of acid-forming gases that pollute ecosystems on land and in water), and eutrophication (emissions of nutrients such as nitrate and phosphate that endanger ecosystems) [27]. With regard to particulate matter emissions, those caused by tire wear have recently come under particular scrutiny. There are developments here in tire technology that can significantly reduce abrasion, driven in part by legal regulations.

Since all forms of motorized private transport have a high environmental impact compared to other modes of transport, in addition to alternative drive systems and fuels, mobility behavior must change, for example, through greater use of public transport, and vehicle fleets and mileage must be reduced. Suitable approaches include incentive systems and innovative urban and infrastructure planning with a special focus on local public transport [30].

04

How has battery performance improved?

The performance of batteries at the vehicle level is expressed, for example, by the range, fast-charging capability, service life, or performance at low temperatures. In the past, the automotive industry focused on range and thus on a high energy density of batteries, which led to the introduction of battery materials with ever higher specific capacities. Today's electric cars are equipped with batteries of all formats (cylindrical, prismatic, pouch) and all major cathode material classes (NCA, NMC, LFP). To achieve maximum energy densities, manufacturers are planning to use high-nickel NMC cathodes and silicon-carbon anodes. This should enable conventional cells to be increased to up to 350 Wh/kg or over 800 Wh/l [12] (for example, through pre-lithiation of anode materials). An ultimate increase in energy density would be conceivable with lithium metal anodes (over 1,000 Wh/l or around 400 Wh/kg) [31].

However, this could require the use of solid-state electrolytes and thus technologies that are not yet commercially available. Solid-state batteries are currently being developed by a large number of industrial players. As of 2024, solid-state batteries can be produced in small series and are currently being tested by car manufacturers. Significant R&D efforts will likely continue to be necessary on the road to industrial-scale production. The high level of commitment shown by some key industrial and scientific players suggests that the first solid-state batteries could be launched on a larger scale before 2030. This may initially take the form of so-called semi-solid concepts, i.e., batteries that are a kind of hybrid of today's liquid electrolyte-based and solid electrolyte-based cells.

The requirements of the high-energy cells and solid-state cells described above for the battery pack in the vehicle are relatively high in terms of temperature control, safety, and management, which is why losses of 30 to 40 percent in gravimetric energy density occur during the transition from the cell to the pack level [32]. This makes high-energy batteries relatively expensive, not only because of the valuable materials in the battery cells, but also because of the effort required to integrate them into the vehicle. Inexpensive, iron-based LFP cells have therefore established themselves as a second important pillar in battery

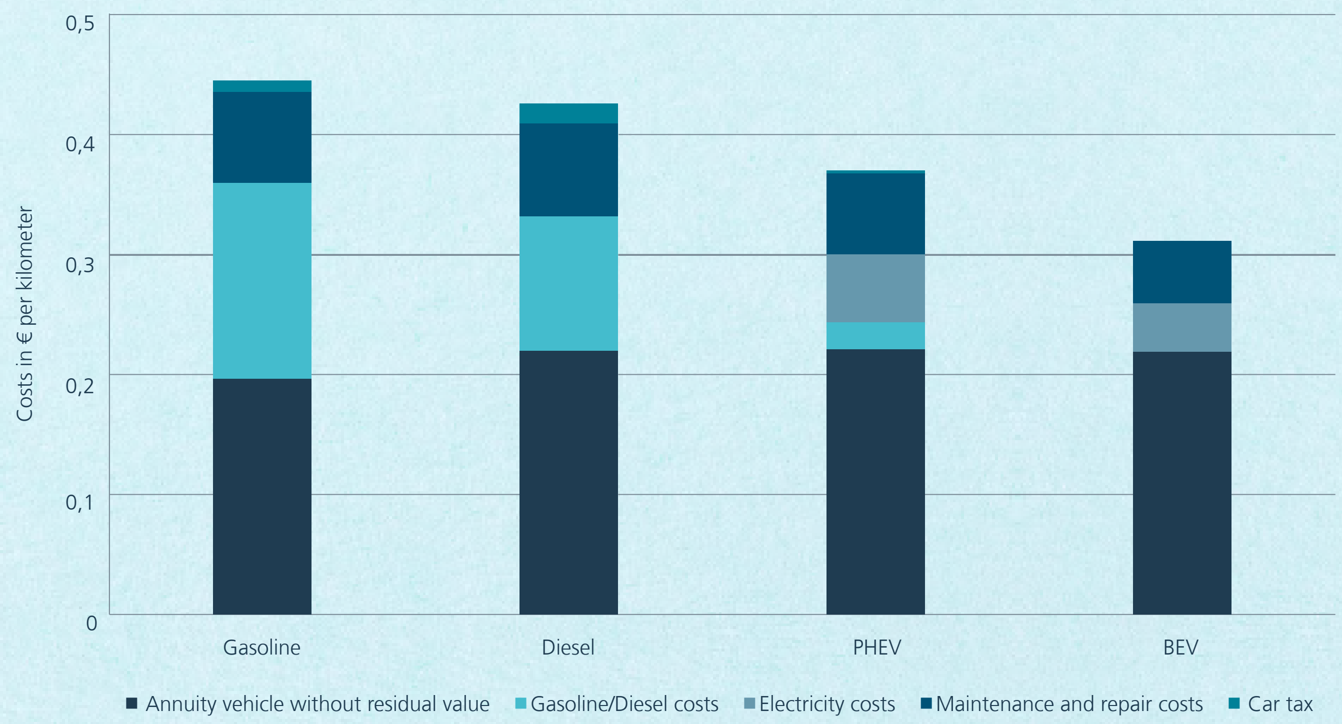


Figure 3 Comparison of the economic efficiency of conventional mid-range cars with battery electric vehicles (BEVs) and plug-in hybrids (PHEVs) in 2025 (source: Own representation based on [4])

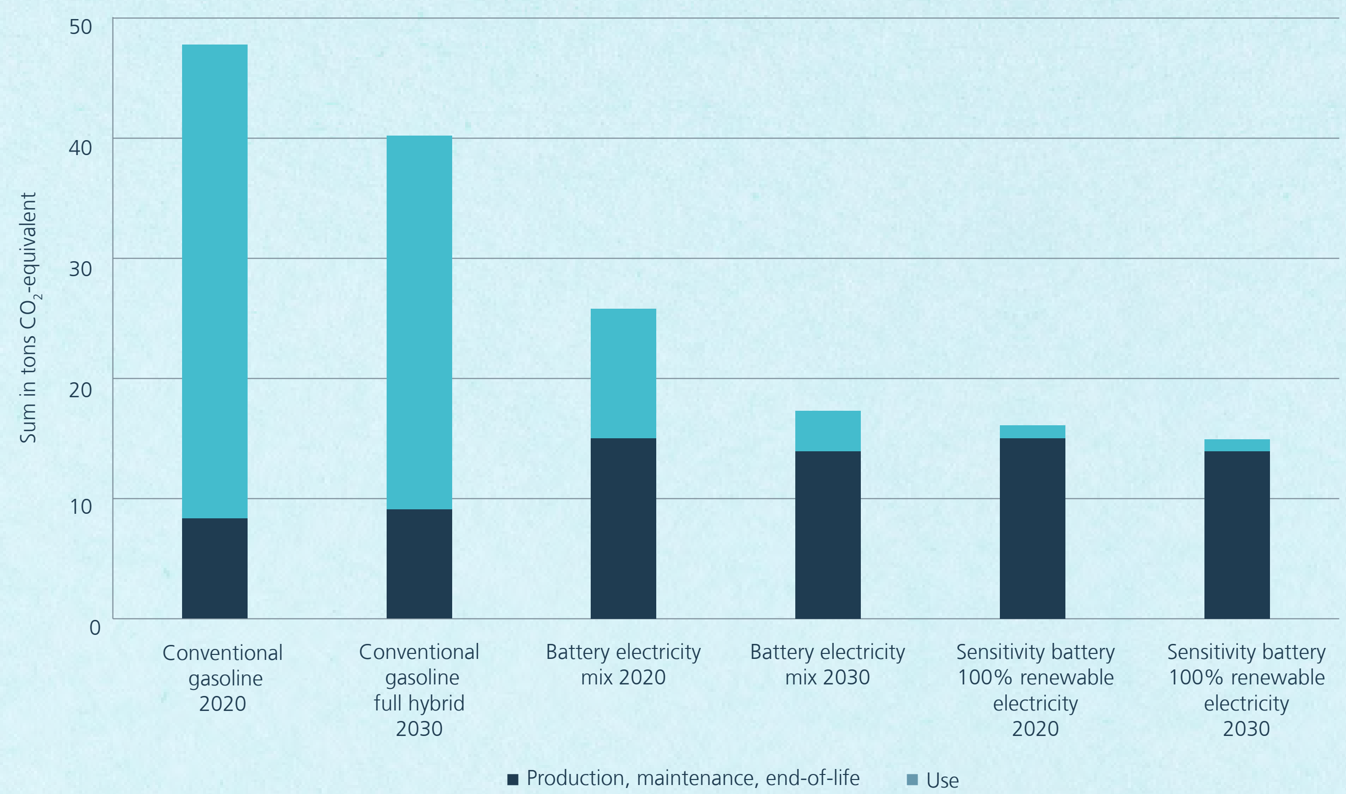


Figure 4 Greenhouse gas emissions from battery electric cars compared to conventional cars (compact class) over the entire life cycle for Germany for cars purchased in 2020 or 2030 [28]

technology. Although they have a lower energy density than nickel-rich cells, they are favorable in terms of safety and are highly robust, meaning they can be integrated into vehicles with significantly less effort. The intermediate level of the module is no longer necessary, and these are referred to as cell-to-pack batteries. The losses at the transition from cell to pack are only 15 to 30 percent in terms of gravimetric energy density. This alternative battery cell variant is also being further developed. For instance, substituting iron with the less expensive manganese promises to increase gravimetric energy density to more than 200 Wh/kg and volumetric energy density to more than 500 Wh/l (comparison: LFP approx.>140 Wh/kg and >350 Wh/l).

An alternative approach to increasing the vehicle's range through battery energy density is to develop very fast charging batteries. Typically, today's vehicles can be recharged from 10 percent to 80 percent in about 30 minutes. New fast-charging batteries promise to do this in only ten minutes [33, 34] and are likely to enter the vehicle market in the coming years. This should further increase the acceptance of electric cars.

The changes described in battery chemistry affect their costs as well as performance. The example often given here is the reduction in the proportion of expensive cobalt in NMC batteries. LFP batteries are a technology whose costs, at least from the perspective of the materials required, are only dependent on the price of lithium. Since raw material prices, especially for battery materials, are subject to large fluctuations, it is unclear how these will develop in the coming years. After a phase of especially expensive raw materials in 2022, the prices in 2024 fell to a very low level. For example, lithium carbonate, an important battery material, costs only one-fifth of what it did in 2022. The main factors influencing price are the ratio of production capacity to demand and market expectations for electric vehicles in the coming years. This applies not only to raw materials but also to battery production itself. In recent years and especially in China, large material and cell production capacities have been developed that are only partially demanded at present. These excess capacities are resulting in high price pressure. In 2024, LFP batteries were available for just over 50 USD/kWh [35]. Prices could go up again if the ratio of supply and demand were to even out. At the same time, work is ongoing to continuously improve production processes, to make these more energy-efficient and faster, and to minimize production waste, which should continue to have a favorable effect on battery prices.

In addition to the approaches described above to improve lithium-based vehicle batteries, research is being carried out on other chemistries. These new battery technologies should be drop-in capable and are only likely to become widely accepted if they offer tangible advantages compared to the technologies mentioned above in terms of cost, performance and sustainability. That there are indeed many promising alternatives to lithium-ion batteries is shown by the example of sodium-ion batteries, which are particularly suitable for smaller vehicles. Although these are only produced on a much smaller scale at present, they are commercially available and are being used in the first electric vehicles. They promise especially low prices and a low environmental footprint due to the substitution of lithium with readily available sodium. Other battery technologies may play a role in the more distant future and supplement lithium-ion batteries in both mobile and stationary applications, ensuring a greater variety of battery technologies [36].

05

Do we have enough global resources?

Which specific materials will be required depends on the cell chemistry of the lithium-ion battery (LIB), with large differences between the available cathode materials: (1) Materials containing nickel, cobalt and manganese (NMC), (2) Materials with a high nickel content but only low amounts of manganese and cobalt, and (3) Iron-based or manganese-based cathode materials (see question 04). The market is moving away from cathodes containing cobalt and toward materials with high nickel content as well as cathodes based on iron or manganese [37].

Figure 5 shows the material footprint for a standard LIB with 80 kWh, differentiated according to cathode chemistry. This indicates that LIBs need 7-10 kg lithium and 56-84 kg graphite, while the use of cobalt, nickel and manganese varies greatly depending on the chemistry chosen.

In principle, the raw materials needed are available worldwide. This was confirmed by various studies more than a decade ago [38, 39, 40, 41], and the basic assessment has not changed since then [42]. The practical availability of raw materials depends on timely investment and the geographic distribution of usable mineral deposits. This has geopolitical and local implications and requires strategic decisions based on economic, social and environmental aspects of the extraction and processing of the different materials [43] (see question 12). The EU currently classifies most of the raw materials needed for LIB as critical (Al, Co, Li, natural graphite, phosphate rock, Si, Mn) and/or strategic (Al, Co, Li, Mn, Cu, Ni).

The rising demand for batteries in Europe, which is expected to reach between 1.5 and 2 TWh per year by 2035, is likely to lead to a substantial increase in the overall demand for key raw materials. Compared to 2025, battery production in Europe will need about five times more lithium and nickel and about six times more graphite and manganese per year [37, 44]. Together with the increase in European battery cell production compared to imports (Europe is likely to cover at least 50 percent of its battery cell demand from domestic production by 2030), this will require an environmentally compatible, ethical and competitive supply of raw materials for the EU.

In view of the current global distribution of production and currently known mineral deposits, a large proportion of these raw materials will still have to be imported into the EU in the future, leading to various dependencies. The provisions of the Critical Raw Materials Act [24] aim at increasing the share of domestic procurement of critical and strategic raw materials, with both mining and recycling contributing to this. In the next few years, most of the raw materials will have to be procured from primary sources (especially from mining) due to the rapid growth in battery demand. There are considerable reserves of lithium, manganese and natural graphite available in Europe, but primary cobalt and nickel are scarce. Estimates of the potential for European self-sufficiency point to the progress made in establishing European value chains (mining and refinery facilities), but the startup phase has to be extremely quick. The key challenges here are the financing needed and the acceptance of mining projects in the EU.

While cobalt and nickel imports will probably still be necessary to meet European demand, some lithium and most manganese can probably be sourced and refined domestically. Natural graphite will probably have to be sourced locally, but imported as well. Although the global diversification of mining and refineries is expected to reduce the overall risks of dependency, the geographic concentration on specific regions will still be high in most cases, with China, in particular, continuing to play a major role beyond 2030 [25, 26, 22].

In principle, circular economy and recycling can help reduce dependencies and further improve sustainability within the battery ecosystem, thereby ensuring the availability of materials beyond 2050 [45, 46, 47]. In practice, current estimates of the quantities of returned batteries strongly indicate that the number available for recycling (excluding production waste) or for second-life/repurposing will be low until the early 2030s, but will rise sharply by 2040 so that, in the long term, 10–30 percent of Europe's demand for lithium and nickel and up to 50 percent of its demand for cobalt could be met by processing these used batteries [48, 49]. The rest (>50 percent) must come from primary sources inside and outside Europe.

Alternative battery technologies, e.g., sodium-ion batteries, need different raw materials and are much less dependent on critical and strategic raw materials. These are currently at the beginning of large-scale commercialization [36].

06

What factors are important for competitive battery cell production?

Various factors are decisive for competitive battery cell production, including investment and operating costs, technical expertise, strategic partnerships and political framework conditions. A fundamental aspect is the availability of capital and the speed with which factories can be constructed. Government subsidies can play an essential role here in accelerating the construction of new plants and cushioning the initial high investments in buildings, machinery, and infrastructure. Optimizing operating expenses is equally important. These are influenced by the costs for energy and labor, among other things. While low energy costs are crucial in production, the importance of skilled workers is increasingly being recognized as a key factor. Without enough specialized workers, efficient production cannot be guaranteed, which is why the location must be attractive in terms of the workers available and, of course, the wage costs.

Another important factor is creating reliable conditions along the supply chain. Access to essential raw materials (see question 05) and components must be ensured, as bottlenecks or unreliable supply chains can jeopardize production and drive costs up.

Additional competitive criteria are battery cell technology and design, including proprietary, exclusively usable designs not restricted by other manufacturers' patents. Exclusively accessible technologies have the advantage that no license fees are incurred, and manufacturers can offer technologically leading products that exceed the usual market standard. Another element is upstream technology, which is often developed in close cooperation with material manufacturers. This allows cell manufacturers to own the rights to specific material developments and thus strengthen their position. If, on the other hand, only materials available on the global market are used, the technology design often remains state of the art, which can quickly become outdated in a dynamic market. An independent R&D network in collaboration with international partners is therefore vital to be able to offer innovative, exclusive solutions.

In addition to design, mastering the manufacturing process is an important competitive factor, as otherwise high costs can be incurred due to production rejects. Efficient production processes developed using specific know-how are often a unique selling point and crucial for product quality and cost efficiency. This knowledge can either be built up through internal expertise or purchased from specialists. Work has to start now on the next generation beyond today's cell and plant technology. Access to R&D partners from industry and research is therefore extremely important for the competitiveness of a location.

Figure 5 Average raw material requirements of a lithium-ion battery (gross capacity: 80 kWh) for different clusters of battery chemistries, in kilograms, excluding the demand for electrolytes and binders. [own, averaged calculation according to Fraunhofer ISI eEV database]

Both European and established Asian companies are building up production capacities for battery cells in Europe. Both groups share some competitive factors but are distinguished by others. For example, energy costs, import duties on components such as cathode materials, and government support mechanisms such as the EU's Innovation Fund or the Temporary Crisis and Transition Framework often apply regardless of where a company is from. As a location, Europe is currently competing with the US, in particular, and with countries that benefit from the Inflation Reduction Act (IRA) due to free trade agreements with the US. This is equivalent to a subsidy on running costs and is complemented in the US by investment grants. On the demand side as well, the development and competitiveness of the battery industry is influenced by political decisions, such as planning security with regard to the ramp-up of electric mobility and the phase-out of combustion engine vehicles.

Compared to China as a production location for especially low-cost battery cells, the costs for many upstream products and plant technology are currently significantly higher in Europe. This applies in particular to new European manufacturers. Although these are able to access the same technology using Asian suppliers, installation and commissioning times, as well as investment volumes per production capacity, are significantly longer and higher in Europe. This is only partially due to permit procedures, but also to the lack of experience of European companies with building gigafactories and, when compared to the structure of Asian industry, a still very young network of suppliers (process engineering, infrastructure) and cell manufacturers. For example, several European projects suffered from ramp-up problems in 2024 related to production processes, and thus to both process control and process technology. Asian companies are clearly at an advantage here because of their networks in their home countries.

As far as the next generation of batteries is concerned (see question 04), Europe wins points as a location due to its strong research landscape. However, this concerns more basic and applied research. At present, important steps toward commercializing emerging technologies are often being taken by start-ups outside Europe (for example, solid state batteries, silicon-anodes, see [12], [31]).

07

Are there supply shortages and risks along the value chain?

As already indicated by question 01, the demand for electric vehicles rose steadily until 2023. The drop in sales in 2024 in Europe, and especially in Germany, can be explained by the effects already described and was not due to any supply bottlenecks for electric vehicles or their upstream components, such as batteries. This is underpinned by analyzing the delivery times for current electric vehicle models: These have become steadily shorter over the past few years and are currently 4.3 months on average in Germany. This puts them in the same range as conventional internal combustion cars [50].

Nevertheless, procuring traction batteries for electric cars, which account for about 30 to 40 percent of vehicle costs, is still a major strategic challenge, especially for European and North American OEMs. At present, cell production capacity exceeds the demand for cells so that average factory utilization has decreased over the last few years and is not likely to exceed 60 percent in the future. While this may pose economic challenges, there are unlikely to be any structural capacity bottlenecks. There are also surplus capacities in the upstream stages of the value chain, such as materials production for battery components, especially anode active materials [12]. However, the ramp-up in production capacities has led to a regional decoupling of battery production and demand. It is therefore not assumed that there will be supply bottlenecks in the future due to the lack of production capacities, but rather that there may be limited access to the battery supply chain. China has the largest market share in battery production, with more than 70 percent, followed by Korea and Japan [51]. In addition, individual enterprises in China hold very large market shares (for example, CATL or BYD). It is not only cell production itself that is mainly located in Asia, and especially in China, but also the corresponding suppliers of the raw materials for batteries [52]. In addition, the raw materials for the most important battery active materials, especially lithium, manganese, cobalt and graphite, are primarily processed in China [53]. Recent political events, such as the trade dispute between the US and China, but also the war in Ukraine with its related geopolitical impacts, are drawing attention to the potential consequences of one-sided dependency and underlining the relevance of resilient supply chains.

The scope of action for European producers includes multi-sourcing strategies in addition to potentially setting up their own cell production and thus gaining direct access to the supply chain. Another advantage is their geographical proximity to automobile manufacturers, as this makes contact, access and logistics much simpler. One consequence of this strategy has been the large number of new production facilities announced in Europe, especially in recent years.

Even when taking into account the medium-term dependency on imported battery cells from Asia, it is unlikely that there will be a shortage of batteries in Europe. In the future, this dependency will be reduced more and more through European cell production. This is supported by regulations like the Critical Raw Materials Act (CRMA) and funding programs to develop European cell production (IPCEI projects). Weakening market demand has brought about the cancellation of individual construction projects, but it can still be assumed that import dependency will be reduced in the long term.

An upstream supply industry could be established in Europe with a slight time lag. The first sites have already been announced or are under construction. In addition to accessing cell production, manufacturers are increasingly trying to gain direct access to raw materials. There are a large number of publicly announced purchase agreements between vehicle manufacturers and various raw material producers [54]. This also helps to make the entire supply chain more robust and enables greater control over the costs of battery cells. However, completely decoupling Europe from global supply chains is not realistic given the quantities of raw materials and components required.

Disrupted parts production at the start of the war in Ukraine and interrupted trade following the accident with the container ship Ever Given, which blocked the Suez Canal, demonstrate again and again the complexity of global supply chains and illustrate the planning difficulties involved.

08

What challenges does the labor market face?

Producing a battery-electric car is less complex and labor-intensive than a conventional car due to the lower number of components involved. According to a recent study, roughly one in four jobs in the automotive industry could be lost [Bertelsmann Foundation/Prognos for VDA]. The study states that the loss of 190,000 jobs cannot be completely offset by age-dependent changes and retraining/further training measures. Many other studies also anticipate a significant reduction in employment. The results are determined by several factors: the assumed market ramp-up, global market structures and shares, geographical scope, the industries and supply chains examined, and the consideration of productivity effects. Accordingly, the studies' findings must be interpreted based on these criteria.

Particular attention must be paid to the underlying system boundaries, as the shift toward electric mobility not only affects jobs in vehicle manufacturing. For example, new jobs are created in the energy sector, charging infrastructure and digitalization that also have a significant effect [55], [56], [57], [58].

Cell production and battery system manufacturing are often cited as new job generators. However, the relevance of battery cell production does not result from directly generated jobs but rather from its role as an "enabler" of upstream value creation stages and the entire battery ecosystem. This has the effect of creating completely new value-added structures and the associated jobs in many areas (such as battery raw materials, battery components, charging infrastructure and control, second-life battery use, etc.).

The extent to which German OEMs, battery producers and suppliers are able to compete, especially against China, is of crucial importance. There is a limited market for electric vehicles and their components, so location factors are decisive for where jobs are created or lost.

Human capital is an important location factor. Prior to 2010, there were only a few hundred qualified battery experts in Europe, but this figure has since increased to between 30,000 and 40,000, of which 15,000 have been trained in Germany alone. They are especially needed in research and development and production. In the whole of industry across the EU, around 40,000 to 60,000 experts were needed in the past few years, and it is expected that this figure will rise to around 200,000 by 2030. There is a risk that only half of the jobs required can be filled.

When considering the entire value chain, including the integration of battery systems into electric cars and other applications, and indirect employment effects, up to 1.5 million jobs across the EU could be linked to the battery value chain by 2030. However, most of these jobs do not necessarily require highly qualified battery experts. There are also positions for workers in areas such as production, service, logistics and sales, who could be trained, retrained, or further trained by battery experts in a relatively short time. If a battery ecosystem can be successfully established in Europe, this could be linked to four to five million jobs in the long term. Domestic cell production is also very relevant for machinery and equipment manufacturers, for example, to gain credentials on the global market [59].

A potential lack of experts and skilled workers is therefore critical in two respects: First, any direct shortage has the effect of reducing the attractiveness of the location and leads to lower productivity. Second, it weakens the above-described multiplier effect of training additional workers.

Overall, the electric mobility value chain can help to cushion the impacts of structural change and transformation in the automotive sector. However, for the domestic labor market to benefit, it is vital to establish these value creation chains in Germany. At present, however, many projects are being delayed or even canceled due to declining domestic sales of electric vehicles (see question 01).

09

What ranges can we expect and how is charging infrastructure developing?

Two key aspects for potential buyers are the vehicle range and the availability of private and public charging infrastructure. However, surveys show that both are usually viewed much more positively after purchasing a vehicle than before [60]. Despite this, vehicle range and charging infrastructure are still relevant criteria for buyers.

Today's top models have at least 80 kWh of usable battery capacity and enable nominal ranges of at least 400 km [61]. The real range depends on individual driving behavior and is usually slightly lower. In the medium term, manufacturers have announced ranges of more than 1000 km, not least due to the use of solid-state batteries. Today's medium vehicles (C-Segment) are usually equipped with 45 kWh to 75 kWh [62]. Recently, the spectrum has increased. Figure 6 shows the development of battery capacity per vehicle segment in recent years. Battery size is frequently being determined by the trade-off between the cost of a larger battery with better cells and the resulting additional benefit in the form of extended range [63]. Technical limitations are becoming increasingly negligible.

It can be assumed that battery size will continue to diversify in the future to reflect different purposes and that battery technology developments will open up additional options (see question 04). There could be only moderate increases in the average battery size, especially because 95 percent of drivers consider a range of 300 to 400 km to be sufficient [64], and more attention is being paid to environmental aspects (see question 02). Well-developed charging infrastructure makes it possible to use smaller batteries and is an essential prerequisite for the success of electric vehicles, especially on the mass market [65, 66].

Most charging – 50 to 75 percent – is done at home [63]. About three-quarters of the drivers in Germany own a garage or a private parking space [60, 64, 65]. Approximately half of the current electric vehicle users in Germany also have a solar power system and benefit from low-cost charging [60, 66, 67]. The German Energy Industry Act (EnWG) includes the provision that grid operators are permitted to reduce the power of private charging points to a minimum of 4.2 kW in the event of grid overload. Users are compensated for this through reduced grid fees, regardless of whether such a reduction actually occurs. Financial support for private charging infrastructure is no longer necessary, but may be of interest in conjunction with mandatory participation in controlled charging. Controlled charging could ease the burden on the distribution grid, avoid high investments and increase the use of low-cost electricity from renewable energies [68, 69] (see also the comments in question 11 on bidirectional charging).

Charging at work represents one option for users who cannot charge at home and can make longer commutes possible. Workplace charging is also important for the direct use of solar-generated power [67]. This can also have an economic benefit, as commercial electricity prices are significantly lower than household prices in some cases [68].

Users currently have a positive perception of how public charging infrastructure is developing [60]. Charging at public points is usually possible without waiting; it is rare for all the charging points to be occupied. Public charging infrastructure can be a substitute for those who lack the possibility to charge at home. It can be expected that more users without private parking will have to rely on public charging points in the future. This is why Germany's Electric Mobility Infrastructure in Buildings Act (GEIG) has set the framework conditions for expanding charging infrastructure in residential blocks and public buildings, such as supermarkets [69]. While legal requirements in semi-public spaces can be met using AC charging infrastructure, supermarket operators are increasingly turning to fast-charging infrastructure that promises faster turnover and better economic efficiency [70, 71].

However, fast-charging infrastructure in Germany is mainly needed for long-distance trips. Economically viable operation is already possible at low surcharges and utilization rates of about two hours per day [70]. In Germany, there are currently about 50 electric cars (BEV) for each of the approximately 30,000 fast-charging points [72]. Even if several thousand fast-charging stations were added each year, it can be assumed that there will be more vehicles per charging point in the future [73, 74], also due to longer ranges [75]. The deployment of fast-charging infrastructure should therefore be market-driven to ensure cost efficiency and avoid creating surplus capacities. More than 80 percent of the public charging infrastructure is already being operated by the private sector today [72].

As well as expanding the infrastructure network, there is a focus on increasing the charging power from 50 up to 350 kW to further shorten the time needed for charging, which is roughly 30 minutes (from 10 to 80 percent) today. With increasing battery capacities and higher charging speeds, however, there will be a proportional decrease in the demand for fast-charging points, which should be taken into account when planning further deployment. Public charging at low power will still be needed in the future for users without private parking options, as described above.

10

What happens to the used batteries?

How used batteries should be treated and how end-of-life batteries should be recycled are the subject of the so-called "Battery Directive" (Directive (EU) 2023/1542). This regulates important aspects such as collection points and processes, collection rates, recycling efficiencies for individual materials such as cobalt, and the use of recycled materials. This directive aims to introduce better sustainability, recycling and safety requirements and improve the availability of raw materials in Europe. This is extremely important, especially in view of the market ramp-up of electric vehicles and the time-lagged return of used batteries resulting from this (10–15 years) [76], [77].

Battery recycling is also becoming more important in Europe with the ramp-up of the electric vehicle market (see question 01) [78]. Its growth will be driven by production rejects from gigafactories up to the early 2030s and then mainly by used batteries from electric cars. Pre-treatment processes include collecting the batteries, discharging and disassembling them, and initial processing steps. These involve either mechanical processing (crushing and shredding) to produce so-called "black mass" or high-temperature melting to produce metal alloys without combustible elements. This mass contains the cathode and anode active materials that incorporate most of the valuable metals. Various separating processes are used on black mass (based on size, density and magnetism) to extract different materials. This black mass is subsequently refined using hydrometallurgical or polymetallurgical methods, which can recover valuable materials such as cobalt, nickel and lithium [45]. Research is continuing on new direct recycling methods to reuse or regenerate battery components without breaking down their chemical structures. Based on the announcements made up to mid-2024, recycling capacities for LIBs in Europe could increase to 330 kilotons per year by 2026 [78]. However, by January 2025, it had become clear that these announcements would not be implemented to the extent cited or would be postponed. Nevertheless, in theory, there will be sufficient production capacities available for recycling used batteries as well as production rejects in the future. By 2035, 30 percent of the demand for lithium, nickel and cobalt in battery cell production could be met using recycled materials. The economic viability of battery recycling depends mainly on the chemical composition of the batteries, which is determined by the prices and availability of primary materials, and there are large differences between batteries with relatively low material costs such as LFP and higher-priced ones with NMC/NCA chemistries [79, 80]. In addition to this, profitability depends heavily on the current stock market prices for raw materials, which have fluctuated greatly in recent years. The typical residual value of current end-of-life EV batteries is usually estimated at 10–20 percent of the original price and will depend, in particular, on the value of the materials in the future [81].

Alongside recycling, there are also repair-and-refresh and second-use concepts for still usable batteries to extend their lifetime and therefore reduce their ecological footprint. This involves either treating and reusing entire modules or dismantling the modules and making new batteries from them. Stationary energy storage systems for private households, commercial and industrial companies, and the energy sector are the main fields of application. These types of application already exist, for example, in local combinations with solar or PV to provide primary balancing power to stabilize the grid ([82], to supply emergency power, or to use battery-supported EV charging infrastructure for load shifting and reduce the demand for mains power/energy [83]. However, second-use concepts are still the exception rather than the rule.

With regard to reducing CO_2 emissions, studies assume that combining second-use and recycling can reduce the environmental footprint of batteries by 35–80 percent [84, 85].

11

Does it make sense to use car batteries as mobile storage devices?

The expansion of renewable energies means that power storage is increasingly needed in the electricity system. In addition to their function as a mode of transport, electric cars can also be used as mobile energy storage devices, i.e., they are not only charged but also discharged. This so-called bidirectional charging is an attractive option, as cars are parked about 95 percent of the time on average [67]. The stored energy can be used in various applications, for example, to supply electric appliances (vehicle-to-load, V2L), a house (vehicle-to-home, V2H), a commercial building (vehicle-to-building, V2B), or even to feed energy back into the grid (vehicle-to-grid, V2G).

Various advantages for the electricity system as a whole result from using vehicle batteries as mobile storage devices. For example, they can relieve pressure on the grid and postpone or avoid grid expansion, conserve back-up capacities from other power stations and enable the integration of more renewable energy. In addition to reducing greenhouse gas emissions, this can also reduce system costs. Bidirectional charging could already lower

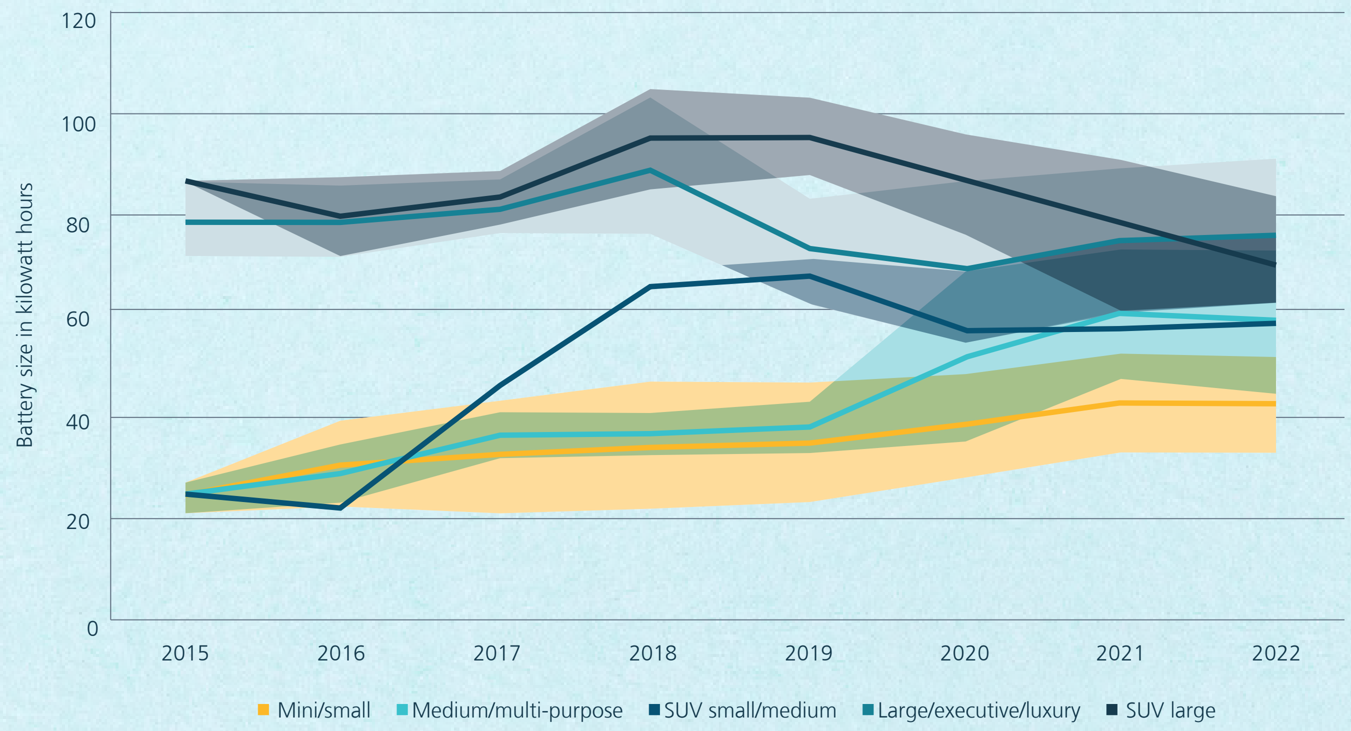


Figure 6 Average sales-weighted battery capacity in Europe from 2015 to 2022 shown by segment. The coloring indicates standard deviation. Own illustration, based on [44]

Figure 7 Roadmap of current and future ranges of electric vehicles and the energy density development of lithium-ion batteries [12], Note: WLTP stands for "Worldwide Harmonized Light-Duty Vehicles Test Procedure" and describes a test procedure to determine the fuel consumption of vehicles.

the total costs of the electricity system by between approximately 2.5 and up to 13 percent annually by 2040 [86, 87], depending on factors such as the diffusion of bidirectional vehicles and infrastructure.

Car owners can also benefit economically from using their electric cars as mobile storage devices. For instance, charging costs can be minimized and/or additional revenue generated. According to studies, around 300–730 EUR per year can be saved in a medium-sized household with a PV system when using the battery to power home applications (for example [86, 87]). Such savings are heavily dependent on factors such as vehicle use and charging location, the size of the vehicle battery and PV system, and whether additional price-optimized charging is possible. If power is additionally fed back into the grid and price differences on the wholesale market are exploited (arbitrage), revenues of more than 1,000 EUR per year and vehicle can be generated [87, 88]. These earnings are offset by the additional costs for bidirectional home charging points, which experts estimate to be around a maximum of 100 EUR more expensive than conventional charging points in the long term [86].

Fears that using vehicle batteries as mobile storage devices would not be economical due to negative impacts on the battery's lifetime have receded in recent years. Batteries now last significantly longer, usually longer than the typical warranties and even the cars themselves [89], and the first car manufacturers are already offering longer warranties for the battery than those common for combustion engines. Furthermore, in many cases, smart charging control can have a positive effect on battery life [90, 86]. However, more practical experience needs to be gained with battery usage, such as the number of fast-charging cycles or permanent charging and discharging.

The framework conditions for using car batteries as mobile storage devices are improving in Germany. At present, bidirectionally chargeable vehicles and infrastructure are not readily available. However, many car and charging station manufacturers have announced models for some or all of the applications mentioned, albeit with some restrictions on their usage as mobile storage devices [91]. It is important for the future that the industry standardizes its technical approaches so that different vehicle types and charging points are compatible. In addition, from 2025, it will be mandatory to install smart meters above a specific electricity consumption level, usually reached by a household with an electric car, or above a specific amount of power fed into the grid, which is also often reached by today's more modern PV systems, and approximately 50 percent of electric car owners already have their own PV system [92, 93]. Larger energy suppliers in Germany are also obliged to introduce dynamic tariffs from 2025, which can make using the car battery as a mobile storage device even more profitable. There are already several providers with dynamic prices on the market. There are hardly any regulatory obstacles to V2H and V2B, but some still need to be removed for V2G. For example, it is important to reduce financial double burdens when charging and discharging, and the relevant standards should be harmonized to ensure compatibility between different vehicles and charging points. User acceptance is also essential for widespread diffusion. Existing concerns must be addressed, for example, regarding possible range limitations or the disclosure of data, and attractive tariffs offered.

12

What measures can improve the social and environmental impacts in the value chain?

The following section discusses measures to improve the environmental and social effects along the value chain of electric cars. Individual impacts are described that are, however, not suitable in this form for a comparison with other drive technologies, nor for an assessment of the overall environmental balance. These points are addressed in question 03. This section does not address the harmful environmental impacts of conventional cars, such as the extraction and transportation of crude oil and accidents involving oil, all of which can cause significant damage to ecosystems, nor does it consider the social impacts of corruption or the destruction of the basis for food security in mining regions.

Raw material extraction and manufacturing are particularly relevant for the negative environmental impacts of electric cars [94, 95]. This is due, on the one hand, to the high demand for raw materials and how complex and costly these are to produce. On the other hand, the related impacts are enhanced by the often inadequate environmental, social and safety standards on site, or the lack of control and regulation mechanisms to enforce compliance with standards.

In the following, we discuss current social and environmental impacts in the battery value chain, which could change in the future, especially due to changes in battery technology. The relevant raw materials for NMC batteries are cobalt, lithium, nickel, manganese and graphite, while LFP batteries do not contain cobalt (and use iron instead). Electric cars also require the rare-earth elements neodymium, praseodymium and dysprosium for the electric motor, as well as copper.

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 populations [96, 97].

60 percent of the world's mined cobalt comes from the Democratic Republic of the Congo, and 15 to 20 percent of this from artisanal small-scale mining [98], although this proportion fluctuates strongly each year, because small mines can react particularly quickly to changes in demand [99]. 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 are employed full-time for light work preparing the rocks to sell, but also for the most difficult and dangerous work. In addition, the expansion of large-scale cobalt mining projects has led to the forced relocation of entire communities [100]. These deplorable conditions are weighed against the fact that artisanal small-scale mining enables those involved to earn a living wage [98].

Boycotting artisanal small-scale mining in the Congo does not improve the situation of those affected. Instead, conditions must be improved, and mining supported and monitored. To do so, in a long-standing collaboration, the German Federal Institute for Geosciences and Natural Resources (BGR) and the DRC Ministry of Mines have developed the Certified Trading Chains (CTC) certification scheme. In 2024, the first audits were conducted in small-scale cobalt mines [99, 101].

Strong state institutions in the mining countries are the most important factor for improving environmental and social standards. There is no simple solution to these problems, which are often linked to poverty and people's way of life [102]. From the perspective of the countries and companies processing the raw materials, establishing mandatory corporate due diligence is the most promising approach to combating deplorable conditions. These due diligence obligations require companies to identify, disclose and take measures to mitigate the social and environmental risks in their value chains. Legal requirements create a level playing field for all companies. In Germany, the Supply Chain Act on Corporate Due Diligence Obligations in Supply Chains applies across sectors for companies with more than 1,000 employees [103]. At the EU level, an agreement was reached on the European Corporate Sustainability Due Diligence Directive [104]. However, these legal developments are meeting with strong resistance from business associations, which see the complex and costly verification checks involved as putting them at a disadvantage compared to international competitors. Nevertheless, from the viewpoint of sustainability research, corporate due diligence obligations represent a key lever for improvement, as consumers do not have an overview of the complex supply chain structures involved and can only influence these to a very limited extent through their decisions [105].

13

Do electric cars have a high fire risk?

Current information does not indicate a higher fire risk when comparing the frequency of fires in electric cars with those in conventional ones [106, 107, 108]. There are even a number of recent studies that assume a significantly lower fire risk in battery-electric vehicles [109, 108, 110]. However, there is still a limited data basis for this and there may be distortions due to the discrepancy in the age of electric cars compared to conventional ones [111].

When lithium-ion batteries catch fire, toxic gases, harmful combustion products and residues are released in significant quantities, as is the case with other fires. LIB fires can be triggered by mechanical damage, and internal and external events (e.g., exposure to flames or short circuits). If a LIB catches fire, thermal runaway can occur, a chain reaction in which one cell after another burns out.

New battery types are currently lowering the risk of fire. For instance, the proportion of lithium-iron phosphate batteries (LFP batteries) has increased in recent years (see question 04). Their chemical composition and thermal stability mean they have a much lower fire risk than LIBs [112]. The currently emerging sodium-ion batteries also pose a lower fire risk. These developments could foster the acceptance of electric cars.

If an electric car does catch fire, it is not possible to extinguish the individual cells directly, but the battery as a whole can be cooled with water to prevent thermal runaway. A larger fire can be extinguished by conventional fire engines using water or, alternatively, the vehicle can be left to burn out in a controlled manner. It is very unlikely that emergency personnel will be exposed to electrical dangers from the high-voltage system in hybrid or electric vehicles due to their construction design (among other things, in the event of an accident, the high-voltage batteries are disconnected from the vehicle's electrical system).

One drawback is that significantly more water is needed to extinguish a burning electric car. Work is ongoing on solutions to inject water directly into the battery via access points (so-called water mist lances). Putting a vehicle into a container filled with water is also possible, but this is not usually necessary and is considered impractical. Work is also ongoing to develop an extremely heat-resistant fire blanket to prevent fire spreading to adjacent vehicles or objects. This is important in underground car parks, for example.

One problem with battery fires in electric cars can be the time lag that occurs between the actual accident and the fire. Even if the initial fire has been extinguished by firefighters, for example, a defective battery continues to pose a risk for much longer. This is why an electric car should be monitored after the fire has been extinguished to prevent the fire from breaking out again, and certain precautionary measures should be taken when removing the vehicle from the scene and storing it. There is an extensive set of rules for this [113].

At present, there are recurring debates and isolated cases regarding banning electric cars from multi-storey car parks or on ferries. Fires that have occurred so far and fire experiments with electric vehicles in enclosed infrastructures such as tunnels or garages do not indicate that the risk is significantly higher than the hazards that exist here anyway [114]. In a garage constructed in accordance with building regulations, parking and charging an electric vehicle using a certified charging system is not in conflict with the applicable building regulations law [114].

14

Who wants an electric car and how stable is the interest in electric mobility?

There is a direct correlation between the declining share of electric vehicles in new registrations in 2024 and the cancellation of the purchase subsidies for these vehicles (see question 01). This also raises questions about whether the German population is interested in electric vehicles to the degree needed for a renewed increase in vehicle sales and whether there are different expectations or uncertainties when choosing a vehicle drive system.

Surveys show that a large proportion of the population is generally interested in electric cars. Between 2020 and 2024, survey results repeatedly show a positive attitude toward electric cars [115, 92, 116]. Around one-third of those questioned displayed a general interest in this technology during this period and were open to using it in the future [117]. In addition, about 10 percent of those surveyed said they wanted to purchase an electric car in the next few years [115, 117]. Therefore, it can be concluded that there is a consistent, general interest in electric cars among one-third of the German population.

Electric cars are now being bought and driven by women more often than before, but they have not yet been adopted across all education and income groups. While the so-called “first adopters” in early studies were predominantly male (around 90 percent in [93]), a more differentiated picture is now emerging (about 62 percent in [92], and 52 percent in [118]). Survey data also show that most electric car users are still more highly educated and have a higher income than the average population. The group of electric car owners is therefore becoming increasingly similar to the general population, but those with lower incomes are still more likely to buy combustion engine cars.

These results show how important the framework conditions are. Sales figures depend directly on whether the more than 40 percent of the respondents who stated they want to buy and use electric cars in the future, or are interested in this, actually do so. The important aspect of acquisition costs (see question 02) explains why, so far, mainly those with a higher income have purchased an electric car. This is backed by the positive rating given to a purchase subsidy for electric cars by the majority of respondents [117]. Another important framework condition, according to the respondents, is charging infrastructure. In general, empirical studies show that the availability of public and semi-public charging infrastructure, for example at people’s workplaces, has a positive effect on social acceptance (see question 09). In addition, the visibility of charging infrastructure in people’s daily lives can lead to increased acceptance [116]. Deployment of such charging infrastructure is continuously supported by a majority of the population [117].

The media also influences how confident people are about their decisions concerning electric mobility and how clearly they perceive the facts and political guidance regarding the available technologies. Frequent, mainly positive and consistent reporting on electric cars in German daily newspapers had on average a positive effect on readers’ attitudes toward them [115]. On the other hand, there were often inconsistent results in the media from direct comparisons of alternative drive technologies, such as electric cars and fuel cell cars [115]. It became clear in the 2020 survey that, on average, respondents not only rated electric cars positively but fuel cell vehicles and e-fuels as well (synthetic fuels produced using renewable electricity). Around half of those surveyed expected several alternatives to be successful in the future, even though, unlike electric cars, fuel cell vehicles and e-fuels are not yet widely available on the market. Inconsistent comparisons of technologies in the media can reinforce these uncertainties, which can stand in the way of continued public interest in electric mobility. These uncertainties could be reduced by more effective communication clearly stating that industry and politics expect a predominantly electric car fleet in the future.

References

[1] **IPCC**: AR6 Synthesis Report Climate Change 2023, accessed on: December 12, 2024. Available [online]: https://www.ipcc.ch/report/ar6/syr/

[2] **IEA**: Transport – Energy System – IEA, accessed on: December 12, 2024. Available [online]: https://www.iea.org/energy-system/transport

[3] **IEA**: Global EV Outlook 2024, Moving towards increased affordability. Accessed on: December 12, 2024. Available [online]: https://www.iea.org/reports/global-ev-outlook-2024

[4] **T. Gnann, D. Speth, M. Krail and M. Wietschel**: Langfristszenarien für die Transformation des Energiesystems in Deutschland 3, 045-Szenarien, Modul Verkehr, Fraunhofer ISI, Karlsruhe, 2024, doi: 10.24406/w34244.

[5] **IEA**: World Energy Outlook 2024, accessed on: December 13, 2024. Available [online]: https://iea.blob.core.windows.net/assets/efba04ce-2472-4df1-9873-fb170c055259/WorldEnergyOutlook2024.pdf

[6] **Statistisches Bundesamt (Destasis)**: Neuzulassungen: Anteil von Elektroautos bleibt gering. Accessed on: December 12, 2024 Available [online]: https://www.destatis.de/Europa/DE/Thema/Verkehr/E_PKW_Neuzulassungen.html

[7] **ADAC**: Pkw-Neuzulassungen im Februar 2025: E-Autos deutlich erholt. Available [online]: https://www.adac.de/news/neuzulassungen-kba/

[8] **P. Keller and T. Wicke**: Verkaufszahlen von Elektroautos: Flaute oder anhaltende Trendumkehr? Accessed on: December 12, 2024. Available [online]: https://www.isi.fraunhofer.de/de/blog/themen/batterie-update/elektroautos-verkaufszahlen-hybrid-flaute-deutschland-europa.html

[9] **Agora Verkehrswende und BCG**:15 Millionen Elektrofahrzeuge bis 2030: Wege zum Ziel und die Rolle chinesischer Automobilhersteller, 2024 Available [online]: https://www.agora-verkehrswende.de/fileadmin/Projekte/2024/15-Millionen-Ziel-China_mit-BCG/20240726_15M_Ziel_Wege_und_Rolle_China_Publikationsversion.pdf

[10] **R. O. Harthan et al.**: Technischer Anhang der Treibhausgas-Projektionen 2024 für Deutschland (Projektionsbericht 2024). Federal Environment Agency, 2024. Available [online]: https://publica.fraunhofer.de/handle/publica/475591

[11] **A. Burnham et al.**: Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains, United States, 2021, doi: 10.2172-1780970

[12] **T. Hettesheimer et al.**: Lithium-Ion Battery Roadmap – Industrialization Perspectives toward 2030, 2023, doi: 10.24406-Publica-2153. Available [online]: https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cct/2023/Fraunhofer-ISI_LIB-Roadmap-2023.pdf

[13] **DEKRA**: Sind Elektrofahrzeuge teurer bei Reparaturen? Accessed on: November 28, 2024. Available [online]: https://www.dekra.de/de/sind-elektrofahrzeuge-teurer-bei-reparaturen/

[14] **M. Krail and P. Plötz**: Factsheet TCO – Ein Wirtschaftlichkeitsvergleich von Antriebsarten bei Pkw, 2023. Available [online]: https://www.now-gmbh.de/wp-content/uploads/2023/03/NOW_Factsheet_Vergleich-Antriebsarten-Pkw.pdf

[15] **M. Wietschel, C. Moll, S. Oberle, B. Lux, S. Timmerberg and N. Ashley-Belbin**: Klimabilanz, Kosten und Potenziale verschiedener Kraftstoffarten und Antriebssysteme für Pkw und Lkw: Final report, 2019. Funded by Biogasrat+ e.V.

[16] **Agora Verkehrswende**: Ein Kostenvergleich zwischen batterieelektrischen und verbrennungsmotorischen Pkw als Klimaschutzoption für das Jahr 2030. Accessed on: December 16, 2024. Available [online]: https://www.agora-verkehrswende.de/fileadmin/Projekte/2017/Die_Kosten_synthetischer_Brenn-_und_Kraftstoffe_bis_2050/Agora_Verkehrswende_Kostenvergleich_WEB.pdf

[17] **T. Gnann**: Market diffusion of plug-in electric vehicles and their charging infrastructure, 2015. Available: https://publica.fraunhofer.de/entities/publication/dc0394d7-75f9-48ea-9e04-dcbee64a1d72

References

[18] **Global X**: What's Driving the Electric Vehicle, Lithium, and Battery Markets in 2019? Accessed on: December 16, 2024. Available [online]: https://www.globalxetfs.com/whats-driving-the-electric-vehicle-lithium-and-battery-markets-in-2019/

[19] **BCG**: The Future of Battery Production for Electric Vehicles. Accessed on: December 16, 2024. Available [online]: https://www.bcg.com/publications/2018/future-battery-production-electric-vehicles

[20] **E. D. Özdemir**: 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, University of Stuttgart, Institute of Energy Economics and Rational Energy Use, 108, 2012, doi: 10.18419/opus-1976.

[21] **ICCT**: Power play: How governments are spurring the electric vehicle industry: White Paper, 2018. Available: https://theicct.org/publication/power-play-how-governments-are-spurring-the-electric-vehicle-industry/

[22] **ADAC**: Comment, https://assets.adac.de/Autodatenbank/Autokosten/E-AutosVergleich.pdf. e-drivers: https://efahrer.chip.de/kostenrechner, eStations: https://www.e-stations.de/elektroautos/kostenrechner or Websites of the sales portals: https://guide.autoscout24.ch/de/elektromobilitaet/kostenrechner-elektroauto/, https://www.evium.de/compare-calculator/compare-calculator.

[23] **Joanneum Research**: Geschätzte Treibhausgasemissionen und Primärenergieverbrauch in der Lebenszyklusanalyse von Pkw-basierten Verkehrssystemen, 2019. Available [online]: https://www.oeamtc.at/thema/autokauf/experten-tool-zeigt-erstmals-gesamtumweltbilanz-aller-pkw-antriebsarten-32522717

[24] **European Commission**: Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA, 2020. Available [online]: https://op.europa.eu/en/publication-detail/-/publication/1f494180-bc0e-11ea-811c-01aa75ed71a1

[25] **M. Wietschel, K. Biemann, S. Link and H. Helms**: Langfristige Umweltbilanz und Zukunftspotenzial alternativer Antriebstechnologien: Los 2 der Schwerpunktstudie Nachhaltige Mobilität für die Expertenkommission Forschung und Innovation. Studie unter Beteiligung des Ifeu-Instituts für Energie- und Umwelttechnik Heidelberg gGmbH, 2022.

[26] **VDI**: VDI-Analyse der CO_2äq-Emissionen von Pkw mit verschiedenen Antriebssystemen. Verein Deutscher Ingenieure e.V, 2023.

[27] **K. Biemann et al.**: Analyse der Umweltbilanz von Kraftfahrzeugen mit alternativen Antrieben oder Kraftstoffen auf dem Weg zu einem treibhausgasneutralen Verkehr. Accessed on: December 13, 2024. Available [online]: https://www.umweltbundesamt.de/sites/default/files/medien/11850/publikationen/13_2024_texte_analyse_der_umweltbilanz_von_kraftfahrzeugen_0.pdf

[28] **M. Wietschel, S. Link, K. Biemann and H. Helms**: Langfristige Umweltbilanz und Zukunftspotenzial alternativer Antriebstechnologien: Studie zum deutschen Innovationssystem, 9-2022, 2022.

[29] **Agora Verkehrswende**: Batteriestandort auf Klimakurs: Perspektiven einer klimaneutralen Batterieproduktion für Elektromobilität in Deutschland. Studie. Accessed on: December 13, 2024. Available [online]: https://www.agora-verkehrswende.de/fileadmin/Projekte/2021/Klimaneutrale-Batterieproduktion/59_klimaneutrale_Batterieproduktion.pdf

[30] **M. Groneweg and L. Weis**: Weniger Autos, mehr globale Gerechtigkeit – Diesel, Benzin, Elektro: Die Antriebstechnik allein macht noch keine Verkehrswende. Accessed on: December 13, 2024. Available [online]: https://power-shift.de/wp-content/uploads/2019/06/Studie-Weniger-Autos-mehr-globale-Gerechtigkeit.pdf

[31] **T. Schmaltz, T. Wicke, L. Weymann, P. Voß, C. Neef and A. Thielmann**: Solid-State Battery Roadmap 2035+, Fraunhofer ISI, 2021, doi: 10.24406- Publica -68

[32] **X.-G. Yang, T. Liu and C.-Y. Wang**: Thermally modulated lithium iron phosphate batteries for mass-market electric vehicles, Nat Energy, vol. 6, No. 2, p. 176–185, 2021: 10.1038/s41560-020-00757-7

[33] **CATL**: CATL Launches Superfast Charging Battery Shenxing, Opens Up Era of EV Superfast Charging. Accessed on: December 12, 2024. Available [online]: https://www.catl.com/en/news/6091.html

[34] **Gotion**: Gotion High-tech Unveiled New Products and New Technology_News_News_Gotion. Accessed on: December 12, 2024. Available [online]: https://en.gotion.com.cn/news/company-news-282.html

[35] **Bloomberg**: China's Batteries Are Now Cheap Enough to Power Huge Shifts, Bloomberg, July 9, 2024. Accessed on: December 12, 2024. Available [online]: https://www.bloomberg.com/news/newsletters/2024-07-09/china-s-batteries-are-now-cheap-enough-to-power-huge-shifts

[36] **A. Stephan et al.**: Alternative Battery Technologies Roadmap 2030+, 2023, doi: 10.24406- Publica -1342

[37] **F. Maisel, C. Neef, F. Marscheider-Weidemann and N. F. Nissen**: A forecast on future raw material demand and recycling potential of lithium-ion batteries in electric vehicles, Resources, Conservation and Recycling, Vol., p.106920, 2023, doi: 10.1016/ rec.2023.106920.

[38] **G. Angerer et al.**: Rohstoffe für Zukunftstechnologien: Einfluss des branchenspezifischen Rohstoffbedarfs in rohstoffintensiven Zukunftstechnologien auf die zukünftige Rohstoffnachfrage, 2009. doi: 10.24406/publica-fhg-294279. Available [online]: https://publica.fraunhofer.de/entities/publication/682cdacd-57af-4d4c-bb78-8abb2f701cc3

[39] **G. Angerer, F. Marscheider-Weidemann, M. Wendl and M. Wietschel**: Lithium für Zukunftstechnologien. Nachfrage und Angebot unter besonderer Berücksichtigung der Elektromobilität. Accessed on: December 12, 2024. Available [online]: http://www.isi.fraunhofer.de/isi-wAssets/docs/n/de/publikationen/Lithium_fuer_Zukunftstechnologien.pdf

[40] **M. Buchert, S. Degreif and P. Dolega**: Strategien für die nachhaltige Rohstoffversorgung der Elektromobilität: Synthesepapier zum Rohstoffbedarf für Batterien und Brennstoffzellen: Studie im Auftrag von Agora Verkehrswende, 2017.

[41] **Öko-Institut e.V.**: Elektromobilität – Faktencheck. Accessed on: November 21, 2019. Available [online]: https://www.oeko.de/publikationen/p-details/elektromobilitaetfaktencheck/

[42] **BGR**: DERA Rohstoffinformationen 50 (2021), 2022. Available [online]: https://www.deutsche-rohstoffagentur.de/DE/Gemeinsames/Produkte/Downloads/DERA_Rohstoffinformationen/rohstoffinformationen-50-en.pdf

[43] **European Commission**: Study on the Critical Raw Materials for the EU 2023. Final Report. Accessed on: December 12, 2024. Available [online]: https://single-market-economy.ec.europa.eu/publications/study-critical-raw-materials-eu-2023-final-report_en

[44] **S. Link, L. Schneider, A. Stephan, L. Weymann and P. Plötz**: Feasibility of meeting future battery demand via domestic production in Europe. Nature Energy – accepted for publication, 2024.

[45] **G. Harper et al.**: Recycling lithium-ion batteries from electric vehicles, Nature, Early Access, 2019. doi: 10.1038/s41586-019-1682-5.

[46] **J. Baars, T. Domenech, R. Bleischwitz, H. E. Melin and O. Heidrich**: Circular economy strategies for electric vehicle batteries reduce reliance on raw materials, Nat Sustain, Vol. 4, No. 1, p. 71–79, 2021. doi: 10.1038/s41893-020-00607-0. Available [online]: https://www.nature.com/articles/s41893-020-00607-0

[47] **N. Sharmili, R. Nagi and P. Wang**: A review of research in the Li-ion battery production and reverse supply chains, Journal of Energy Storage, Vol. 68, p. 107622, 2023, doi: 10.1016/j.est.2023.107622.

[48] **T. Schmaltz**: Recycling von Lithium-Ionen-Batterien wird in Europa stark zunehmen: Mengenszenarien von Lithium-Ionen-Batterien für das Recycling und deren Herkunft. Accessed on: December 12, 2024. Available [online]: https://www.isi.fraunhofer.de/de/blog/themen/batterie-update/recycling-lithium-ionen-batterien-europa-starke-zunahme-2030-2040.html

[49] **European Commission**: RMIS – Lithium-based batteries supply chain challenges. Accessed on: December 12, 2024. Available [online]: https://rmis.jrc.ec.europa.eu/analysis-of-supply-chain-challenges-49b749

[50] **carwow**: Aktuelle Lieferzeiten für Elektroautos. Accessed on: December 12, 2024. Available [online]: https://www.carwow.de/ratgeber/elektroauto/lieferzeiten-elektroautos#gref

[51] **Fraunhofer ISI**: Zellproduktion. Accessed on: December 12, 2024. Available [online]: https://metamarketmonitoring.de/de/zellproduktion/

[52] **T. Wicke**: Ausgangsmaterialien von Batterien – die asiatische Dominanz bei Batteriekomponenten. Accessed on: December 12, 2024. Available [online]: https://www.isi.fraunhofer.de/de/blog/themen/batterie-update/batterien-ausgangs-materialien-asiatsische-dominanz-bei-batteriekomponenten.html

[53] **VDI/VDE-IT**: Resilient Supply Chains in the Battery Industry, 2023. Available [online]: https://www.ipcei-batteries.eu/fileadmin/Images/accompanying-research/publications/2023-03-BZF_Studie_Lieferketten-ENG.pdf

[54] C. Neef and A. Balakrishnan: Price fluctuations of battery raw materials: How the automotive industry reacts and the impact of these price changes on cell costs. Accessed on: December 12, 2024. Available [online]: https://www.isi.fraunhofer.de/de/blog/themen/batterie-update/batterie-rohstoffe-preis-schwankungen-wie-reagiert-automobil-industrie-auswirkungen-zellkosten.html

[55] European Climate Foundation: Low-carbon cars in Europe: A socio-economic assessment, Cambridge Econometrics, 2018.

[56] M. Wietschel et al.: Perspektiven des Wirtschaftsstandorts Deutschland in Zeiten zunehmender Elektromobilität, 2017.

[57] L. Sievers, A. Grimm and C. Doll: Transformation der Mobilität: Bestimmung der Beschäftigungseffekte in 2035 mit einem Input-Output-Modell: Working paper on behalf of the Hans Böckler Foundation, Karlsruhe, 2019.

[58] IEA: World Energy Employment 2024. Accessed on: January 20, 2025. Available [online]: https://www.iea.org/reports/world-energy-employment-2024

[59] T. Hettesheimer, A. Thielmann and C. Neef: VDMA Kurzgutachten: Beschäftigungsauswirkung einer Batteriezellproduktion in Europa (VDMA), 2018

[60] Bdew: Zweite BDEW Umfrage: Elektromobilität und Laden aus Nutzersicht. Accessed on: December 12, 2024. Available [online]: https://www.bdew.de/service/publikationen/zweite-bdew-umfrage/

[61] EV Database: EV Database. Accessed on: December 12, 2024. Available [online]: https://ev-database.org/de/#group=vehicle-group&rs-pr=10000_100000&rs-er=0_1000&rs-fc=0_1500&rs-ac=2_23&rs-ts=100_350&rs-ub=10_200&rs-tw=0_2500&rs-ef=100_350&rs-sa=-1_5&s=1&p=0-10

[62] S. Link, L. Schneider, A. Stephan, L. Weymann and P. Plötz: Probabilistic feasibility of meeting future battery demand via domestic production in Europe., Nature Energy, 2025.

[63] S. Link, M. Stephan, L. Weymann and T. Hettesheimer: Techno-Economic Suitability of Batteries for Different Mobile Applications – A Cell Selection Methodology Based on Cost Parity Pricing, WEVJ, Vol. 15, No. 9, p. 401, 2024: 10.3390/wevj15090401.

[64] European Commission: Consumer Monitor 2023 EAFO: European aggregated report. Luxembourg: Publications Office, 2024. Accessed on: December 12, 2024. Available [online]: https://alternative-fuels-observatory.ec.europa.eu/system/files/documents/2024-06/EU%20Aggregated%20Report%202023_0.pdf

[65] NMP AG 1: Wege zur Erreichung der Klimaziele 2030 im Verkehrssektor: Interim report 03/2019. Accessed on: December 12, 2024. Available [online]: https://www.plattform-zukunft-mobilitaet.de/wp-content/uploads/2020/03/NPM-AG-1-Wege-zur-Erreichung-der-Klimaziele-2030-im-Verkehrssektor.pdf

[66] NPE: Ladeinfrastruktur für Elektrofahrzeuge in Deutschland: Statusbericht und Handlungsempfehlungen, 2015.

[67] T. Gnann, A.-L. Klingler and M. Kühnbach: The load shift potential of plug-in electric vehicles with different amounts of charging infrastructure, Journal of Power Sources, Vol. 390, p. 20–29, 2018, doi: 10.1016/j.jpowsour.2018.04.029.

[68] Bdew: BDEW-Strompreisanalyse Dezember 2024: Haushalte und Industrie. Accessed on: December 13, 2024. Available [online]: https://www.bdew.de/service/daten-und-grafiken/bdew-strompreisanalyse/

[69] M. Kühnbach et al.: Potenziale von Stellplätzen an Wohn- und Nichtwohngebäuden zur Bereitstellung privater Ladeinfrastruktur, Fraunhofer ISI und Fraunhofer ISE, Freiburg, Karlsruhe, 2024, doi: 10.24406/publica-2743.

[70] T. Gnann, S. Á. Funke, N. Jakobsson, P. Plötz, F. Sprei and A. Bennehag: Fast charging infrastructure for electric vehicles: Today's situation and future needs, Transportation Research Part D: Transport and Environment, Vol. 62, p. 314–329, 2018, doi: 10.1016/j.trd.2018.03.004.

[71] P. Jochem, T. Gnann, J. E. Anderson, M. Bergfeld and P. Plötz: Where should electric vehicle users without home charging charge their vehicle? Transportation Research Part D: Transport and Environment, Vol. 113, p. 103526, 2022, doi: 10.1016/j.trd.2022.103526.

[72] NOW GmbH: Verstehen | Nationale Leitstelle Ladeinfrastruktur. Accessed on: December 13, 2024. Available [online]: https://nationale-leitstelle.de/verstehen/

[73] M. Robinius et al.: Comparative analysis of infrastructures: Hydrogen fueling and electric charging of vehicles. Energie & Umwelt /Energy & Environment. Accessed on: December 13, 2024. Available [online]: ttps://juser.fz-juelich.de/record/842477/files/Energie_Umwelt_408_NEU.pdf

[74] NPE: Fortschrittsbericht 2018 – Markthochlaufphase. Accessed on: December 13, 2024. Available [online]: https://www.plattform-zukunft-mobilitaet.de/wp-content/uploads/2021/12/2018_Fortschrittsbericht_2018_Markthochlaufphase.pdf

[75] S. Á. Funke, P. Plötz and M. Wietschel: Invest in fast-charging infrastructure or in longer battery ranges? A cost-efficiency comparison for Germany, Applied Energy, Vol. 235, p. 888–899, 2019, doi: 10.1016/j.apenergy.2018.10.134.

[76] European Parliament and the Council of the European Union: Regulation (EU) 2023/1542 of the European Parliament and of the Council of July 12, 2023, concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC, 2023. Accessed on: December 13, 2024. Available [online]: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32023R1542

[77] Notes: The design, production and waste management of automotive lithium-ion batteries in Europe are influenced by Directive 2000/53/EG ("End-of-Life Vehicles Directive") and Regulation (EU) 2023/1542 ("Battery Regulation"). This regulation aims to introduce improved sustainability, recycling and safety requirements and to improve the availability of raw materials in Europe. It applies to all manufacturers, producers, importers and distributors of batteries and covers all types of battery (regardless of their origin) sold in the EU, including batteries for portable devices and light means for transport (LMT). To achieve these objectives, the use of certain substances harmful to humans or the environment will be restricted. In addition, the carbon footprint and other information must be declared, including the levels of recycled cobalt, lead, lithium and nickel contained in the battery. Minimum shares of recycled content will be set for specific materials: 16 percent for cobalt (26 percent), 85 percent for lead (85 percent), 6 percent for lithium (12 percent) and 6 percent for nickel (15 percent) by 2031 (by 2036). Large market participants that place batteries on the EU market are obliged to set up and implement due diligence policies that consider the social and environmental impacts along the supply chain. To obtain information about the condition of the battery and ensure compliance with requirements, a digital battery passport will be developed by 2027, providing information about battery capacity, performance, durability and chemical composition accessible via a QR code, for example. With regard to recycling and end-of-life concepts, minimum collection rates are set for portable and LMT batteries, which increase to 73 percent for portable and 61 percent for LMT batteries. Producers are responsible for collecting used batteries from vehicles and their improper disposal is prohibited. Collected batteries are to be recycled. The recycling efficiency for complete Li-based batteries should reach 65 percent in 2026 and increase to 70 percent by the end of 2030. Recycling targets for specific are also planned: The share of lithium recovered from a battery should rise to 80 percent by 2031 and a recovery rate of 90 percent is planned for cobalt, copper, nickel, and lead by 2027.
To facilitate the use of second-life concepts, the Battery Regulation also introduces requirements concerning the removability and replaceability of batteries. All battery management systems (BMS) must have a software reset function so the battery can be used in its second life or at its end-of-life. Such concepts and design strategies are intended to extend battery lifetime and support the re-use of electric vehicle batteries.

[78] M. Stephan: Batterierecycling in Europa nimmt weiter Fahrt auf: Recycling-Kapazitäten von Lithium-Ionen-Batterien in Europa. Accessed on: December 13, 2024. Available [online]: https://www.isi.fraunhofer.de/de/blog/themen/batterie-update/lithium-ionen-batterie-recycling-europa-kapazitaeten-update-2024.html

[79] R. Ma et al.: Pathway decisions for reuse and recycling of retired lithium-ion batteries considering economic and environmental functions, Nature communications, Early Access, 2024, doi: 10.1038/s41467-024-52030-0.

[80] J. Neumann et al.: Recycling of Lithium-ion Batteries – Current State of the Art, Circular Economy, and Next Generation Recycling, Advanced Energy Materials, Vol. 12, No. 17, 2022, Art. No. 2102917, doi: 10.1002/aenm.202102917.

[81] A. Burke and L. Fulton: Analysis of advanced battery-electric long-haul trucks: batteries, performance, and economics: Working Paper. Accessed on: December 13, 2024. Available [online]: https://ucdavis.app.box.com/s/cfpoywahc2so21hogykiga6h8r9rppxe

References

[82] **BMW Group, Vattenfall and Bosch**: Ein zweites Leben für Elektroauto-Batterien: Vattenfall, BMW und Bosch testen Stromspeicher in Hamburg . Hamburg, München, Stuttgart, 2016. Accessed on: December 13, 2024. Available [online]: https://www.press.bmwgroup.com/deutschland/article/detail/T0263968DE/ein-zweites-leben-fuer-elektroauto-batterien?language=de

[83] **H. H. Heimes et al.**: Potenziale von Second-Use-Anwendungen für Lithium-Ionen-Batterien, in Elektromobilität, A. Kampker and H. H. Heimes, ed., Berlin, Heidelberg: Springer Berlin Heidelberg, 2024, S. 655–668.

[84] **P. Li, X. Xia and J. Guo**: A review of the life cycle carbon footprint of electric vehicle batteries, Separation and Purification Technology, vol. 296, p. 121389, 2022, doi: 10.1016/j.seppur.2022.121389.

[85] **M. Gutsch and J. Leker**: Costs, carbon footprint, and environmental impacts of lithium-ion batteries – From cathode active material synthesis to cell manufacturing and recycling, Applied Energy, Vol. 353, p. 122132, 2024, doi: 10.1016/j.apenergy.2023.122132.

[86] **M. Kühnbach et al.**: Potential of a full EV-power-system-integration in Europe and how to realise it. Study on behalf of Transport & Environment (T&E) Europe. Fraunhofer Institute for Solar Energy Systems ISE, Fraunhofer Institute for Systems and Innovation Research ISI, 2024. Available: https://www.transport-environment.org/uploads/files/2024_10_Study_V2G_EU-Potential_Final.pdf

[87] **Ffe**: Bidirektionales Lademanagement – Abschlussbericht der FfE, 2023. Available [online]: https://www.ffe.de/wp-content/uploads/2023/03/BDL-Abschlussbericht.pdf

[88] **L. Schmidt, N. Waxmann, D. Reichert and K. V. Boesche**: Bidirektionales Laden in Deutschland – Marktentwicklung und Potenziale. Accessed on: December 13, 2024. Available [online]: https://www.e-mobilbw.de/fileadmin/media/e-mobilbw/Publikationen/Studien/Potenzialanalyse_bidirektionales_Laden.pdf

[89] **M. Hackmann, H. Knörzer and J. Pfeuffer**: Batteriealterung in der Praxis: Analyse von über 7.000 Fahrzeugen gibt tiefe Einblicke in Batterielebensdauer und Fahrzeug-Restwert. Accessed on: December 13, 2024. Available [online]: https://www.p3-group.com/p3-updates/batteriealterung-in-der-praxis/

[90] **J. Gong et al.**: Quantifying the impact of V2X operation on electric vehicle battery degradation: An experimental evaluation, eTransportation, Vol. 20, p. 100316, 2024, doi: 10.1016/j.etran.2024.100316.

[91] **Volkswagen**: Bidirektionales Laden | Laden und Reichweite | Volkswagen Deutschland. Accessed on: December 13, 2024. Available [online]: https://www.volkswagen.de/de/elektrofahrzeuge/laden-und-reichweite/smartes-laden.html

[92] **M. Helferich et al.**: Tariff option preferences for smart and bidirectional charging: Evidence from battery electric vehicle users in Germany, Energy Policy, Vol. 192: p. 114240, 2024, doi: 10.1016/j.enpol.2024.114240.

[93] **A. Scherrer, U. Burghard, M. Wietschel and E. Dütschke**: Early Adopter von E-Fahrzeugen: Ladeleistungen, Eigenerzeugung und Einstellungen zum Lademanagement, Energiewirtschaftliche Tagesfragen, No. 11, p. 23–26, 2019. Available [online]: https://publica.fraunhofer.de/handle/publica/259960

[94] **C. Bauer, J. Hofer, H.-J. Althaus, A. Del Duce and A. Simons**: The environmental performance of current and future passenger vehicles: Life cycle assessment based on a novel scenario analysis framework, Applied Energy, Vol. 157, p. 871–883, 2015, doi: 10.1016/j.apenergy.2015.01.019.

[95] **H. Helms, J. Jöhrens, C. Kämper, J. Giegrich and A. Lieblich**: Weiterentwicklung und vertiefte Analyse der Umweltbilanz von Elektrofahrzeugen: (Texte 27/2016). Accessed on: December 16, 2024. Available [online]: https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/texte_27_2016_umweltbilanz_von_elektrofahrzeugen.pdf

[96] **S. Boddenberg**: Lithiumabbau in Chile – Fluch oder Segen? Deutsche Welle, 27 April 2018. Accessed on: December 16, 2024. Available online: https://www.dw.com/de/lithiumabbau-in-chile-fluch-oder-segen/a-43401781

[97] **T. C. Frankel und P. Whoriskey**: Tossed aside in the "white gold" rush. Indigenous people are left poor as tech world takes lithium from under their feet, The Washington Post, 2016.

[98] **BGR**: Die BGR – Commodity TopNews 53. Kobalt aus der DR Kongo – Potenziale, Risiken und Bedeutung für den Kobaltmarkt. Accessed on: December 16, 2024. Available [online]: https://www.bgr.bund.de/DE/Gemeinsames/Produkte/Downloads/Commodity_Top_News/Rohstoffwirtschaft/53_kobalt-aus-der-dr-kongo.html

[99] **BGR**: Lieferketten und Abbaubedingungen im artisanalen Kupfer-Kobalt-Sektor der Demokratischen Republik Kongo, 2021.

[100] **Democratic Republic of the Congo**: Industrial mining of cobalt and copper for rechargeable batteries is leading to grievous human rights abuses, Amnesty International, 12. September 2023. Accessed on: December 16, 2024. Available online: https://www.amnesty.org/en/latest/news/2023/09/drc-cobalt-and-copper-mining-for-batteries-leading-to-human-rights-abuses/

[101] **BGR**: DR Kongo: BGR unterstützt Akkreditierung von nationalen Auditoren. Accessed on: December 16, 2024. Available online: https://www.bgr.bund.de/DE/Gemeinsames/Nachrichten/Aktuelles/2024/2024-03-15_dr-kongo-bgr-unterstuetzt-akkreditierung-von-nationalen-auditoren.html

[102] **DRC**: Why it's hard to make cobalt mining more transparent, Deutsche Welle, 19 March 2024. Accessed on: December 16, 2024. Available [online]: https://www.dw.com/en/drc-struggles-to-make-cobalt-mining-more-transparent/a-68610784

[103] **BMJ**: Gesetz über die unternehmerischen Sorgfaltspflichten zur Vermeidung von Menschenrechtsverletzungen in Lieferketten. Accessed on: December 16, 2024. Available [online]: https://www.gesetze-im-internet.de/lksg/index.html

[104] **European Union**: Directive (EU) 2024/1760 of the European Parliament and of the Council of 13 June 2024 on corporate sustainability due diligence and amending Directive (EU) 2019/1937 and Regulation (EU)2023/2859 (Text with EEA relevance), 2024. Accessed on: December 16, 2024. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32024L1760

[105] **M. Bodenheimer**: Behavioral transitions to social sustainability in global production networks, Dissertation, Fraunhofer IRB-Verlag and Fraunhofer ISI, 2019. Available online: https://publica-rest.fraunhofer.de/server/api/core/bitstreams/cbe179e7-3571-4ad0-a4df-dfb60d8f336d/content

[106] **ADAC**: E-Auto brennt: So löscht die Feuerwehr. Accessed on: December 13, 2024. Available [online]: https://www.adac.de/rund-ums-fahrzeug/elektromobilitaet/elektroauto/e-auto-loeschen/

[107] **GDV**: Brennen E-Autos wirklich öfter? Zahlen und Fakten. Accessed on: December 13, 2024. Available [online]: https://www.gdv.de/gdv/themen/mobilitaet/dossier-elektromobilitaet/e-autos-elektroauto-braende-statistik-182792

[108] **Wissenschaftliche Dienst**: Verhalten von Elektroautos im Brandfall. Accessed on: December 13, 2024. Available [online]: https://www.bundestag.de/resource/blob/891136/55c913be8b0207bcd76e911a66287f00/WD-8-002-22-pdf-data.pdf

[109] **AutoinsuranceEZ**: Gas vs. Electric Car Fires in 2024 (Shocking Stats). Accessed on: December 13, 2024. Available [online]: https://www.autoinsuranceez.com/gas-vs-electric-car-fires/

[110] **Department of Energy and Climate**: Electric vehicles fact check. Accessed on: December 13, 2024. Available [online]: https://www.energyandclimate.qld.gov.au/energy/vehicles-and-energy/electric-vehicles/fact-check

[111] **Now GmbH**: Neue Broschüre zu Brandsicherheit von E-Pkw: Aktuelle Forschung und Wissen für den Alltag. Accessed: December 13, 2024. Available [online]: https://www.now-gmbh.de/aktuelles/pressemitteilungen/neue-broschuere-zu-brandsicherheit-von-e-pkw-aktuelle-forschung-und-wissen-fuer-den-alltag/

[112] **LionCare GmbH**: Brände bei Elektroautos löschen. Accessed: December 13, 2024. Available [online]: https://www.lion-care.com/braende-bei-elektroautos-loeschen

[113] **VDIK**: Unfallhilfe & Bergen bei Fahrzeugen mit Hochvolt- und 48V-Systemen: Antworten auf häufig gestellte Fragen. Accessed on: December 13, 2024. Available [online]: https://www.vdik.de/wp-content/uploads/2020/07/Unfallhilfe_Bergen_FAQ_dt_072020_VDIK-1.pdf

[114] **AGBF – Arbeitsgemeinschaft der Leiter der Berufsfeuerwehren und des Deutschen Feuerwehrverbandes**: Keine erhöhte Brandgefahr durch in Tiefgaragen-abgestellte Elektrofahrzeuge. Accessed on: December 13, 2024. Available [online]: https://www.feuerwehrverband.de/keine-erhoehte-brandgefahr-durch-in-tiefgaragen-abgestellte-elektrofahrzeuge/

[115] **A. Scherrer**: How media coverage of technologies affects public opinion: Evidence from alternative fuel vehicles in Germany, Environmental Innovation and Societal Transitions, Volume 47, p. 100727, 2023, doi: 10.1016/j.eist.2023.100727.

[116] J. Tröger and S. Preuß: Charging at the workplace: boosting acceptance for electric mobility on the go? Empirical evidence from a pre-post-design study in Germany, 2024, doi: 10.24406- Publica -3338

[117] J. Tröger, M. Helferich and E. Dütschke: Ergebnisse des Projekts MobilKULT. Accessed on: December 13, 2024. Available [online]: https://www.isi.fraunhofer.de/de/competence-center/energietechnologien-energiesysteme/projekte/mobilkult/ergebnisse.html

[118] R. Kunze, S. Preuß, J. Zwirnmann, P. Plötz and M. Wietschel: Determining the share of renewable electricity in electric vehicle charging in Europe, Energy-Reports, vol. 12, p. 5834–5845, 2024, doi: 10.1016/j.egyr.2024.11.044.

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