Scenarios of Development for Non-Ferrous Metal Markets amid the Spread of Alternative Fuel Vehicles

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Abstract

Advances in technology, growing concern about climate change, and the setting of greenhouse gas emission reduction targets in many countries have contributed to a significant increase in the demand for alternative fuel vehicles globally over the last decade. Electric vehicles, which include all-electric vehicles (BEVs) and plug-in hybrids (PHEVs), are the most promising alternative to conventional hydrocarbon vehicles. It is very likely that in some regions of the world electric vehicles will dominate the market as early as the 2030s. However, compared to internal combustion engine vehicles, the production of electric vehicles requires a wider range of non-ferrous metals, which may become one of the bottlenecks for further electrification of transportation. This paper presents a scenario analysis of the development of the electric vehicle market, and then calculates the key metal requirements for each of the scenarios considered. The results of this analysis reveal that, between now and 2050, the accelerating spread of electric vehicles will have a significant impact on the cobalt market, a moderate impact on the lithium, nickel, and copper markets, and a minor impact on the manganese and aluminum markets. The results of the analysis demonstrate that the increasing use of electric vehicles in the coming decades opens up significant opportunities for countries specializing in the production of non-ferrous metals, including Russia, to increase their supply to global markets.

Keywords: alternative fuels; electric vehicles; all-electric vehicles; plug-in hybrid vehicles; non-ferrous metal market.

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Introduction

Transport is the second largest contributor, after the energy industry, to greenhouse gas emissions, especially carbon dioxide. According to the International Energy Agency (IEA), in 2023 the transport sector accounted for 21.8% of global CO2 emissions, with road transport's share being about 75% of that (IEA, 2024).

Electric vehicles with zero direct greenhouse gas emissions are seen as a key way to reduce the transport sector's carbon footprint (IPCC, 2022). However, compared to internal combustion engine (ICE) vehicles, electric ones have certain design, technological, and operational features limiting their mass adoption. One of the key constraints is the need for parts and components which require materials the automotive industry either did not previously use at all or used in much smaller quantities. This primarily concerns certain non-ferrous metals.

As the world markets' carbon regulation becomes more ubiquitous and stringent, demand for low-carbon vehicles will increase, especially electric vehicles as the segment with the greatest potential. These vehicles' increased adoption, supported by government subsidies, will result in lower production and operating costs due to economies of scale. Such changes will inevitably have a significant impact on metal markets. However, the opposite effect is also possible: the changes in metal prices might affect electric vehicles' global prospects.

The impact of electric vehicles on related industries, including the non-ferrous metals sector, has been widely covered in academic research and industry analytics. The value of such studies largely depends on the relevance of the underlying data (the electric vehicle market only started to emerge in the second half of the 2010s), and on the models applied. Xu et al. (2020) present three most likely scenarios for the development of electric vehicle battery technologies, assess the likelihood of their implementation and future demand for certain non-ferrous metals. To map battery-powered electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) adoption trajectories, the authors relied on the IEA vehicle fleet figures and scenario estimates (IEA, 2020), taking into account various long-term factors (Xu et al., 2020).

The BloombergNEF 2023 report presents two scenarios for the electric vehicle market growth: the Economic Transition Scenario (ETS), dominated by market incentives with no significant regulatory changes, and Net Zero 2050 scenario aimed at making the global vehicle fleet carbon-neutral by 2050. In the less ambitious ETS, the share of electric vehicles in global passenger vehicle sales by 2040 is estimated at 73%. To achieve carbon neutrality by 2050, fossil-fuel vehicle sales must be completely phased out by 2038. Significant growth in demand for lithium, copper, aluminium, and nickel is projected, to ensure sufficient battery production levels. To qualitatively assess demand for non-ferrous metals, the report compares cumulative demand with the available reserves and envisaged production capacity (BloombergNEF, 2023; 2024).

This study examines potential changes in global non-ferrous metals markets based on three scenarios for the electric vehicle segment growth. The scenarios are presented for both the electric vehicle market as such, and the derived demand for metals required to produce vehicle components. To estimate the long-term global electric vehicle market growth (until 2050), the development of disruptive technologies was modeled through scenario analysis based on the most recent available data (for 2024). The cumulative demand for non-ferrous metals was estimated individually by battery types in which these metals are used. Electric vehicles' impact on non-ferrous metal markets was assessed using criteria suggested in various sources.

The objective of this paper is to identify, through scenario analysis, non-ferrous metal markets to be particularly affected by the increased adoption of electric vehicles, and consequently determine the metals, the insufficient supply of which may hinder the development of electric transport. The second section compares the main alternative vehicle fuel types and assesses the prospects for replacing traditional hydrocarbon-powered vehicles with electric ones. The third section models automobile market growth and presents a scenario analysis of the growth of the electric vehicle segment based on the S-curve concept and retrospective data, taking into account a number of long-term factors. The fourth section assesses the cumulative demand for non-ferrous metals needed to produce key electric vehicle components and the effect of consumer reorientation to electric transport for various industry markets. The conclusion summarizes the scenario analysis results and describes compensatory mechanisms on the markets under consideration.

The Potential of Alternative-Fuel Vehicles

The structure of motor vehicles' greenhouse gas emissions is dominated by direct emissions of the products of hydrocarbon fuel combustion. Reducing automobiles' carbon footprint is primarily envisaged by abandoning traditional fuel types such as petrol, diesel, and other oil products. It would hardly be possible to achieve global and national climate goals without decarbonizing the transport industry. Countries with active climate agendas (in particular the European Union (EU) nations, the United Kingdom, and Canada) are already announcing plans to ban non-zero emission cars, while some companies intend to cut the production of ICE vehicles (IEA, 2023; IEA, 2024). This will significantly increase the use of alternative fuels and demand for them.

An analysis of existing alternative fuel types' life cycles reveals a number of major environmental limitations in their use.

Firstly, petrol and diesel can be replaced by natural gas, propane, alcohol and its derivatives, synthetic fuel components and their mixtures with traditional fuels, and so on. However, the combustion of these fuels also produces greenhouse gases such as CO2, CH4 (methane), and N2O (nitrogen oxide), which contradicts the global emission reduction goals, including achieving carbon neutrality and keeping the increase in global average temperature within 1.5-2°C above pre-industrial levels (as stated in the 2015 Paris Agreement).

Secondly, though biofuel cars do exist, many biofuel production technologies are based on processing plant materials (sugar cane, corn, soybeans, etc.) suitable for human and animal nutrition (first-generation biofuels).[1] The use of biofuels in the transport sector reduces the carbon footprint, but in some cases may contradict the social responsibility principle and the objective of eradicating hunger - one of the UN Sustainable Development Goals.[2] The production and broad use of such fuel types as the mainline replacement for traditional fuel potentially may be limited or prohibited.

As to advanced biofuels made of non-food materials (waste fats and oils, wood biomass, organic waste, algae) and carbon-neutral synthetic fuels, high capital intensity and insufficient production capacity reduce their medium-term prospects to facilitate a major reduction in motor vehicles' carbon intensity (IEA, 2024). Until 2050, cars running on such fuels will remain inferior to electric and hydrogen vehicles regarding their potential to reduce the total cost of ownership (TCO) (Khomutov et al., 2021). There are practically no carbon-neutral synthetic fuels on the market and the envisaged capacities for their production remain orders of magnitude below the current needs of the economy (Krajinska, 2021).

Thirdly, despite its potential, the hydrogen electric vehicle segment is developing slowly due to limited hydrogen production and its specific nature as an energy carrier. The production of fuel cell systems is technologically complex and involves the use of expensive platinum group metals, so the costs are comparable to the price of a small ICE car. Also, unlike standard fuel types, hydrogen's chemical and physical properties require the transformation of the entire logistics chain including transportation, storage, and refueling. With low sales, fuel stations' and other infrastructure projects' profit margins will remain insufficient (Khomutov et al., 2021). Hydrogen production also remains inefficient: low demand hinders investment in new capacities and process optimization, leading to higher prices for hydrogen fuel and cars running on it, which undermines their competitiveness. In turn, high TCO and insufficiently developed infrastructure hinder the emergence of mass demand for hydrogen electric vehicles. A vicious circle arises, overcoming which requires the introduction of comprehensive non-market support mechanisms.

Today, BEV and PHEV electric vehicles have the greatest potential among alternative-fuel vehicles. In the former, the electric motor converts stored energy into mechanical energy, while in the latter an electric motor supplements the internal combustion engine, which engages when the battery is exhausted.

Electric vehicles' potential is determined by two key factors. The first is the annual reduction in costs due to the availability of cheaper components, primarily batteries (see Figure 1) and the economy of scale (fixed capital costs are distributed over a larger number of vehicles). When electric vehicles are introduced on national markets, government subsidies to purchase low carbon footprint cars play an important role (as shown in the experience of EU, US, and China). The prices also drop due to vehicle manufacturers' competition as the market grows (IEA, 2023).

The second factor is the fact that the direct carbon footprint of an electric vehicle is minimal, since the conversion of electrical energy into mechanical energy does not involve chemical combustion and CO2 emissions. The indirect carbon footprint of burning fossil fuels to generate electricity still remains significant, but will decrease with the development of low-carbon renewable energy.

In addition to the electric vehicle types mentioned above, various intermediate options are available on the market, such as hybrids (hybrid electric vehicles, HEV), powered primarily by an internal combustion engine, which charges the battery when the car is used thus eliminating the need to connect it to an external power source. Such designs are structurally close to conventional cars and, due to high direct emissions, will not be classified as electric vehicles or taken into account in the further analysis. Long-term IEA and BloombergNEF forecasts predict that the share of BEVs in sales will grow, while that of PHEVs will gradually decline (IEA, 2024; BloombergNEF, 2024).

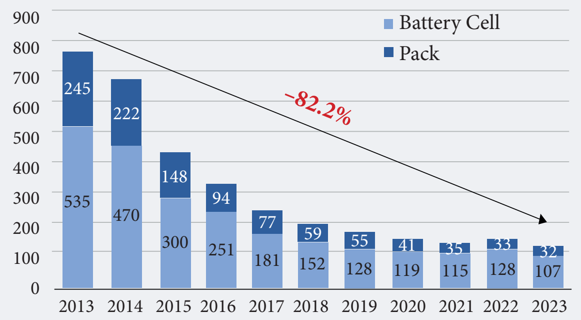
The Current State and Specific Features of the Electric Vehicle Market

The BEV market began to emerge in the 2010s following the development of electricity storage technologies, first of all, rechargeable lithium-ion batteries for home appliances and electronics. Compared to other common types (such as lead and nickel batteries), lithium ones have a higher specific energy capacity by weight and volume, and a longer service life, i.e., it maintains performance characteristics over a greater number of charge-discharge cycles (Liang et al., 2019). Their light weight and small size allowed for using them more widely in the automotive industry, without the need to make significant design changes.

To date, electric vehicles have become the fastest-growing passenger car segment. In 2020 their sales grew by 43% y/y, against a 16% decline in global demand for passenger cars. In 2021 this figure exceeded 120% y/y amid a shortage of components due to the pandemic. In 2022, amid geopolitical instability and the disruption of global supply chains, it decreased to 55% y/y. In 2023, growth slowed to 35% due to a reduction in subsidy programs for the purchase of electric vehicles on a number of major markets and limited penetration into developing markets (IEA, 2024). As a result, this segment's share in global passenger car sales increased from 2.8% in 2019 to over 18% in 2023 (Figure 2).

Direct subsidies and tax deductions for the purchase of electric vehicles remain the key demand drivers on the largest European, North American, and Asian markets, along with economies of scale and high fossil fuel prices (IEA, 2023). There is also a long-term investment flow from the conventional cars segment to the production of new electric vehicles due to the adopted course for decarbonization. The rapid penetration of BEVs is accompanied by the development of relevant infrastructure, such as charging stations (CS) and specialized service centers. By the beginning of 2024, the number of public CS in the world has reached 3.9 million (IEA, 2024).

Figure 1. **Weighted Average Battery Component Cost (Electrochemical Cell and Case/Container)** (*USD per kWh*)



Source: authors, based on (BloombergNEF, 2023).

The share of BEVs is also growing in the commercial segment, having reached 3.4% of total sales in 2023. However, the requirements for increased range and priority of load capacity limit the use of batteries as an energy source (Figure 3). Increased battery capacity and the greater density of the ultra-high-power charging station network would facilitate the electrification of these segments.

Despite the significant growth of electric vehicles' share in global sales, their geographical distribution remains uneven. China, Europe, and North America account for about 95% of all passenger electric vehicle sales and for more than 85% in the commercial segment (Figure 4). China is the absolute world leader in electric vehicle sales in both segments. In 2023, its share in sales of passenger electric vehicles has reached 60%, and in the commercial segment, about 55%.

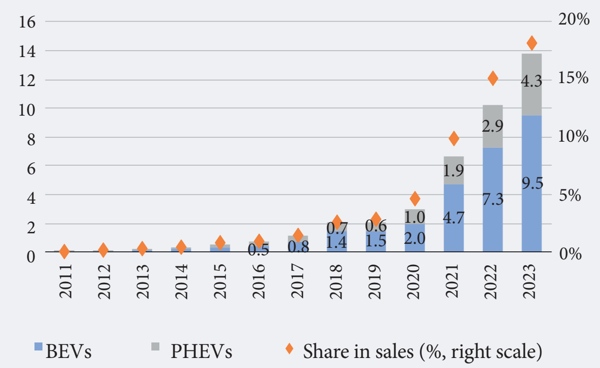
China's leadership remains sustainable due to a combination of several factors including government support programs for buyers and producers offered during the market's early development stage, sufficient control over global supply chains for metals and minerals critical to battery production, and the large-scale domestic production of various classes of electric vehicles.

[1] https://bigenc.ru/technology_and_technique/text/3878201, accessed on 15.03.2025.

[2] https://www.undp.org/sustainable-development-goals, accessed on 15.03.2025.

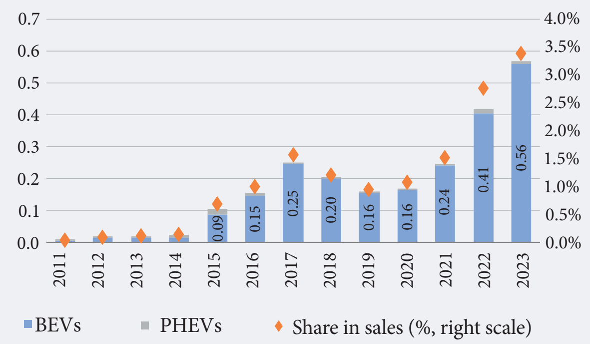
[3] We analysed the passenger car market using OICA data adjusted for North America due to the peculiarities of statistical accounting of large SUVs and pickup trucks. These vehicles are widely used in the region as personal transport, but are not included in the passenger car segment.

Figure 2. **Growth of Global Passenger Electric Vehicle Sales in 2011-2023 (million)**



Source: authors, based on (IEA, 2024; OICA, 2024).

Figure 3. **Growth of Global Commercial Electric Vehicle Sales in 2011–2023 (*million*)**



Note: The commercial segment includes light commercial vehicles, trucks, and buses.
Source: authors, based on (IEA, 2024; OICA, 2024) data.

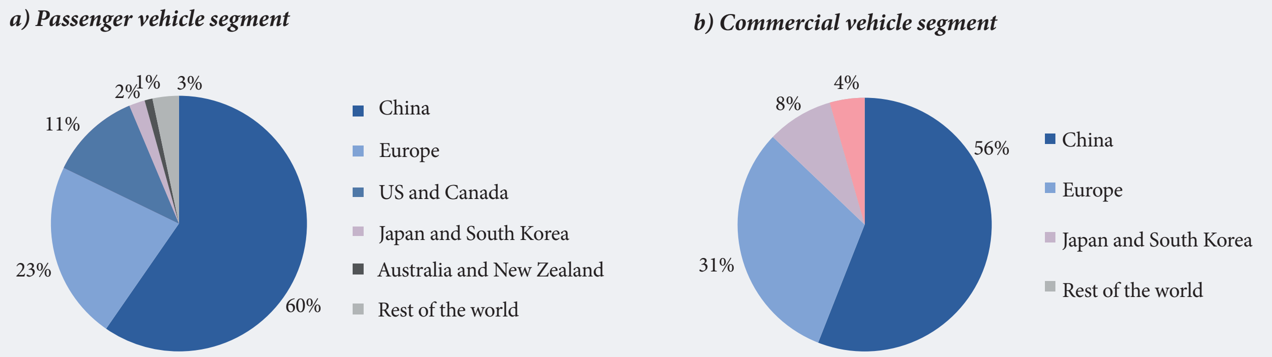
The shares of Europe and the United States and Canada in passenger electric vehicle sales in 2023 amounted to 23% and 11%, respectively. In the commercial segment, in addition to China and Europe, South Korea's share is also worthy of note: the sales of electric light commercial vehicles (LCV) and electric buses made by the national manufacturers Kia and Hyundai are rapidly growing.

Electric Vehicle Market Growth Scenarios

The following key parameters were used to build scenarios for the analysis of non-ferrous metal markets:

1. The target modeling parameter was global new electric vehicle sales (BEV and PHEV).
2. The model was based on the S-curve concept mathematically expressed by the sigmoid function. This approach has demonstrated high accuracy in studies of disruptive technologies, in particular electric vehicles (Foster, 1986; Geroski, 2000; Mahajan, Muller, 1979).
3. The analysis time horizon was the period until 2050. This milestone serves as a benchmark for most long-term greenhouse gas emission reduction targets set by international climate agreements and national decarbonization programs.
4. We have built three scenarios describing the electric vehicle market growth trajectories. Each scenario was determined by factors af-

Figure 4. **Geographical Structure of Passenger and Commercial Electric Vehicle Sales in 2023**



Source: authors, based on (IEA, 2024).

fecting only the rate of electric vehicle adoption; the growth of electric vehicles' share was considered a stable long-term trend. A detailed description of the differences in the scenarios is presented in Table 1.

5. Given the heterogeneity of the electric vehicle market and the differences in transportation models and government policies across countries, global demand was estimated by aggregating the results of regional markets' modeling. The characteristics of the latter are presented in Tables 2 and 3.
6. The distribution of BEV and PHEV market shares is based on historical data and the relevant IEA estimates for 2025, 2030, and 2035 (IEA, 2024)
7. Sales were modeled separately for the passenger and commercial vehicles segments.

The scenario analysis was based on historical data on new electric vehicles sales in 2012-2023 published by the IEA (IEA, 2024), and by the European Automobile Manufacturers' Association (ACEA)[4]; on sales data for all vehicle types in 2005-2023 published by the International Organisation of Motor Vehicle Manufacturers (OICA) (OICA, 2024), and by analytical agencies (S&P Global, 2024). This data was aggregated in line with the methodology described above.

Let us take a step-by-step look at the modeling of new electric vehicle global sales.

At the first stage, the sales of all vehicle types were estimated. Passenger car sales for the period until 2031 were estimated on the basis of S&P Global world light vehicle (up to 6 tons) market forecasts for the regions under consideration (S&P Global, 2024). In 2031-2050, the growth of sales in the passenger car segment was assumed to be equal to the forecasted per capita GDP growth rate. The choice of per capita GDP as a proxy measure was due to the fact that demand for electric vehicles mainly comes from households. Sales in the commercial segment for the entire 2024-2050 period were modeled on the basis of real GDP growth in each region, by equating the

Table 1. **Electric Vehicle Market Growth Scenarios**

Model configuration	Model and scenario characteristics	Examples of application
	Scenario 1. Generalised logistic function	
$s(t) = \frac{1}{(1+e^{-bt})^{1/\vartheta}}$ Where t is the sequence number of the year (the first year in the time series is set at 1); is the share of electric vehicles in sales at time ; is the parameter that determines the growth rate; is the parameter that affects the change in the curvature of the function (function value at the inflection point), and thus the function's growth rate at the asymptotes.	- A generalised sigmoid function with flexibly adjusting S-curve. The S-curve flexibly adjusts to match the historical data; the function's inflection point has a floating ordinate value. - Low probability of complying with the declared deadlines for banning sales of internal combustion cars. - Gradual increase in the share of BEVs and decrease in the share of PHEVs.	Assessing the level of motorisation in China (Huo, Wang, 2012)
	Scenario 2. The Gompertz function	
$s(t) = e^{-be^{-ct}}$ Where t is the sequence number of the year (the first year in the time series is set at 1); is the share of electric vehicles in sales at time ; is the parameter that determines the growth rate; is the parameter which determines the function's shift along the abscissa axis.	- A type of asymmetric (relative to the inflection point) sigmoid function which reflects rapid growth at the initial stage of technology adoption, followed by a smooth slowdown after reaching the inflection point. - A slower adoption of electric vehicles when government support initiatives are curtailed. - Low probability of complying with the declared deadlines for banning sales of internal combustion cars. - Gradual increase in the share of BEVs and decrease in the share of PHEVs.	- Modeling the size of the automobile market in China (Qian, Soopramanien, 2014) - Modeling electric vehicle sales in 20 large countries (Kumar et al., 2022) - Modeling the level of motorisation in 59 countries (Rota et al., 2016)
	Scenario 3. Standard logistic function	
$s(t) = \frac{1}{1+ae^{-bt}}$ Where t is the sequence number of the year (the first year in the time series is set at 1); is the share of electric vehicles in sales at time ; is the parameter that determines the function's intersection point with the ordinate axis (the shift along the abscissa axis); and is the parameter that determines the growth rate.	- Standard logistic function with a symmetrical S-curve relative to the inflection point, with a constant ordinate value of 50% and a steeper slope on the modeled time horizon. - Faster growth rates of the share of electric vehicles, and of abandoning ICE vehicles, in some cases matching the declared deadlines for the complete decarbonisation of transport. - Faster growth in the share of BEVs, and decrease in the share of PHEVs.	- Modeling the size of the automobile market in China (Qian, Soopramanien, 2014) - Modeling electric vehicle sales in 20 major countries (Kumar et al., 2022) - Modeling the electric vehicle fleet in 26 countries in various regions of the world (Rietmann et al., 2020)
Source: authors.		

[4] https://www.acea.auto/nav/?content=publications, accessed on 15.03.2025.

Table 2. **Regional Electric Vehicle Markets and Their Specific Features: The Passenger Car Segment**

Regional market	Specific features
China	The world's largest electric vehicle market in absolute terms, the global component production hub
Scandinavia	Leading countries in electric vehicle penetration. Includes Denmark, Iceland, Norway, Finland, and Sweden
Europe with a mature electric vehicle market	A mature electric vehicle market comprising major Western and Central European economies
Rest of Europe	An emerging electric vehicle market, primarily comprising Eastern European and smaller Western and Central European nations
Japan and South Korea	Highly developed Asian countries with established electric vehicle markets
US and Canada	North American nations actively adopting electric vehicles. Regional features include long routes, and a car-centric culture/
Australia and New Zealand	These countries promote electric vehicles adoption, and experience energy limitations due to their isolated geographic location
Rest of the world	Other countries with low EV penetration
Source: authors.	

growth rate of sales to that of GDP. The current estimates of the long-term real GDP growth until 2060 were published by the Organisation for Economic Cooperation and Development (OECD) in 2023.[5] This indicator was chosen because the commercial segment is more dependent on the overall economic situation and foreign trade flows. The modeling was carried out separately for each region and vehicle type; details are presented in Tables 2 and 3, the complete results are in Appendix 1.[6]

At the second stage, the share of electric vehicles in total vehicle sales was modeled, using the S-curve concept. The choice of modeling a relative value was due to the need to adjust for the limiting factor - sales of all vehicle types. This allowed the authors to avoid unrealistic predictions exceeding market demand and the automobile industry's production capacity.

Various modifications of the sigmoid functions with a distinctive S-shaped form were applied to map three growth trajectories for the electric vehicle market (Table 1).At the second stage, the share of electric vehicles in total vehicle sales was modeled, using the S-curve concept. The choice of modeling a relative value was due to the need to adjust for the limiting factor - sales of all vehicle types. This allowed to avoid unrealistic predictions exceeding market demand and the automobile industry's production capacity.

Various modifications of sigmoid functions with a distinctive S-shaped form were applied to map three growth trajectories for the electric vehicle market (Table 1).

The flexibility of the function applied in Scenario 1 allowed for adjusting the S-curve to historical data, setting the baseline electric vehicle market growth trajectory while maintaining current trends. The Gompertz function applied in Scenario 2 reflects a rapid growth at the lower asymptote, followed by a gradual slowdown after the inflection point (fixed 1/e value). This allowed for modeling a market slowdown after the curtailing of government demand support programs.

Scenario 3 represents an optimistic market growth option. Electric vehicle penetration can be promoted and accelerated by several factors:

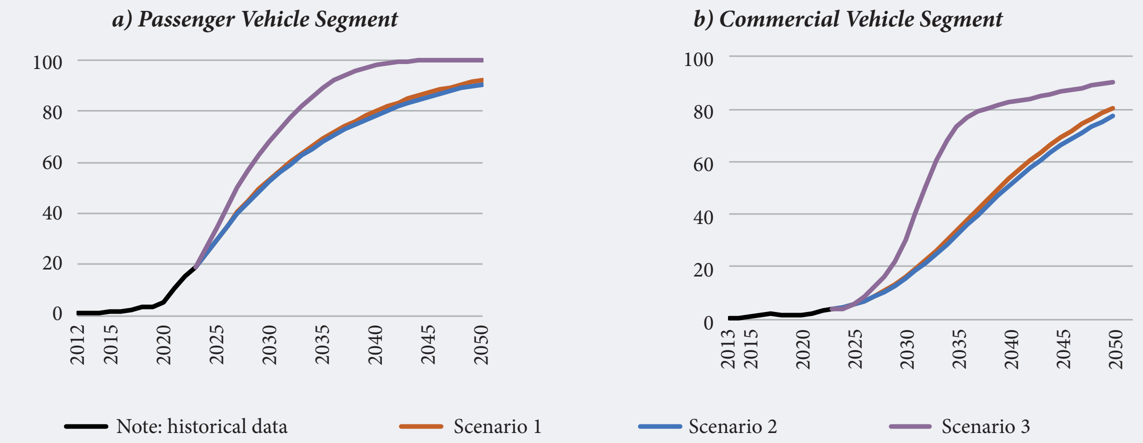
Table 3. **Regional Electric Vehicle Markets and Their Specific Features: Commercial Segment**

Regional market	Specific features
China	World leader in commercial electric transport, a high rate of public transport electrification
Europe (EU + EFTA)	Large EU and EFTA economies are the second commercial electric transport development hub. Active market scaling is taking place in Western and Central Europe
Japan and South Korea	Asian nations with growing commercial electric transport segments; their leading automakers have sufficient competences in the production of electric trucks
Rest of the world	Countries with rudimentary or non-existent commercial electric vehicle market
Source: authors.	

[5] https://www.oecd.org/en/data/indicators/real-gdp-long-term-forecast.html?oecdcontrol-ed8cfcbb26-var3=2005&oecdcontrol-ed8cfcbb26-var4=2060, accessed on 15.03.2025.

[6] Appendices are available at the separate file (see the link on the article webpage https://foresight-journal.hse.ru/article/view/24480

Figure 5. **Electric Vehicles' Shares in Global Passenger and Commercial Vehicle Sales (%)**



Note: actual (historical) data until 2023, followed by modeling results until 2050.
Source: authors, based on (IEA, 2024; OICA, 2024) data.

1) fluctuations in hydrocarbon fuel prices and progress in renewable energy generation, which can facilitate relevant changes in consumer preferences;

2) increased investments in research and development (R&D) to reduce the key battery component costs and the per kWh cost of energy produced by the batteries;

3) the implementation of ambitious plans to ban fossil fuel vehicles due to the priority of the climate agenda;

4) increased attention to energy security, along with a wider range of energy sources.

At the modeling stage, the functions' lower asymptote is assumed to be 0 (the smallest possible share in sales) and the upper one - 1 (the largest possible share). The analysis of the passenger car segment was based on historical data for 2012-2023 and of the commercial segment - on historical data for 2013-2023. Models for the three scenarios were trained using the nonlinear least square method applied to fit nonlinear curves.

At the final stage of the calculations, the target variable was computed using the results of modeling total vehicle sales and the share of electric vehicles: new electric vehicle sales in absolute terms. The results of modeling the electric vehicles' share in sales by world region are presented in Appendix 2. The growth of electric vehicles' shares in global passenger and commercial vehicle sales is shown in Figure 5.

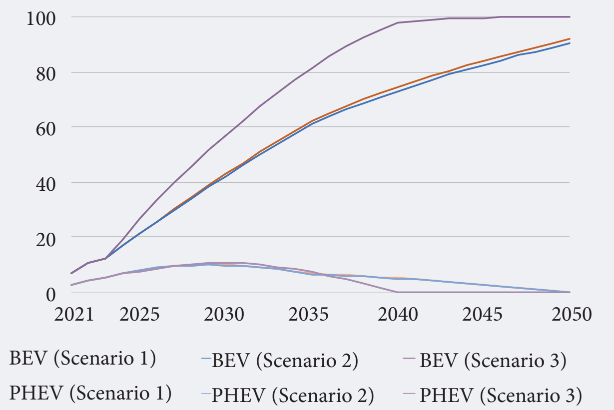
At the third stage total global sales of electric vehicles were examined. The ratio of BEV to BEV+PHEV was calculated using historical data for 2012-2023. To forecast this ratio for the period until 2050, IEA estimates for 2025, 2030, and 2035 (IEA, 2023) and regression analysis were used. On the basis of the obtained proportions, global sales of new electric vehicles were broken down into BEVs and PHEVs.

Thus, in Scenario 1 in the passenger car segment, the share of BEVs in global vehicle sales will increase to 42.8% by 2030, to 74.5% by 2040, and to 91.7% by 2050. Meanwhile the share of PHEVs will peak at 10.1% in 2029 and then gradually decline until 2050. In the commercial segment, the share of BEVs in total sales will reach 76.1% by 2050; while PHEVs will only amount to 3.8% (Figures 5 and 6).

The growth of the EV market under Scenario 2 has turned out to be very close to the trajectory obtained in Scenario 1. In the passenger car segment, the share of BEVs in global sales could reach 42.2% in 2030, 73.1% in 2040, and 90.3% in 2050. The share of PHEVs will reach its top value of 10% in 2029, and then gradually decline. In the commercial segment, the share of BEVs in total vehicle sales will increase to 73.1% by 2050; and that of PHEVs decrease to 3.7% (Figures 5 and 6). This similarity of the scenario results suggests that the historical sales data largely reflects the pattern of initial rapid growth of electrical vehicles' share in sales, followed by a slowdown after reaching 37%, which corresponds to the ordinate value of the Gompertz function's inflection point.

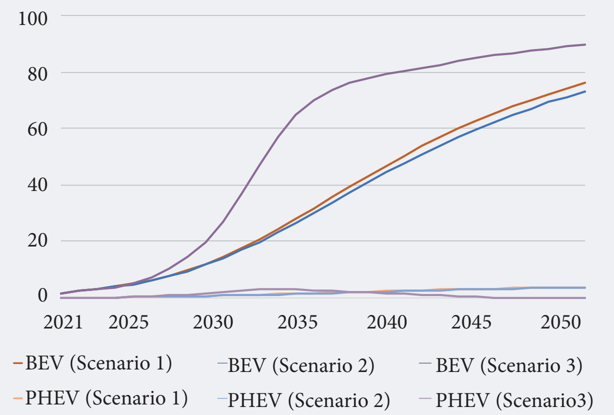
Under Scenario 3, the penetration of both electric vehicle types is expected to accelerate: the share of BEVs in global car sales could reach 56.8% by 2030, 97.7% by 2040, and 100% by 2050. The share of PHEVs will increase from 6.9% in 2024 to 10.9% in

Figure 6. **Shares of Passenger BEVs and PHEVs in Global Vehicle Sales until 2050, All Scenarios (%)**



Source: authors.

Figure 7. **Shares of Commercial BEVs and PHEVs in Global Vehicle Sales until 2050, All Scenarios (%)**



Source: authors.

2030, and then gradually decline in favor of BEVs. In the commercial segment, the share of BEVs could reach 90% of all vehicle sales by 2050, with PHEV sales ceasing completely from 2045 onwards (Figures 6 and 7).

Long-Term Demand for Non-Ferrous Metals for Electric Vehicle Components

Non-ferrous metals are used to make various electric vehicle components. The ones which could significantly affect raw material markets as the adoption of electric vehicles accelerates include batteries and related electrical conductors[7].

Electric vehicle batteries vary in the chemical composition of their components, but lithium-ion ones are the most popular. The most common batteries are lithium-nickel-cobalt-manganese-oxide (NCM), lithium-nickel-cobalt-aluminium-oxide (NCA) or their mixtures (more than 90% of the market in 2020), and lithium-ferrum-phosphate (LFP) batteries used in early electric vehicle models, which are gaining popularity again given the rising prices of nickel and cobalt (IEA, 2022). Battery type is determined by the composition of the cathode, while the anode is usually made of graphite.

In addition to lithium-ion batteries, lithium-sulphur and sodium-ion ones have good prospects since they offer a number of advantages (Kumar, 2024). Lithium-sulphur batteries have a relatively high energy density, while sodium-ion ones boast a long service life. Plus, they are potentially more economical and environmentally friendly than their lithium-ion analogues. Currently, these battery types are just beginning to enter the electric vehicle market (mass production of sodium-ion battery electric vehicles was launched for the first time only in 2023)[8], which makes it difficult to forecast demand in the medium and long term.

The development of electric vehicles can change the market situation not only for metals used in battery cathodes, but also for copper and other non-ferrous metals. Electrification of the automotive industry will require a significant increase in the share of materials with high electrical conductivity. The list of key non-ferrous metals markets for which are affected by the proliferation of electric vehicles, is presented in Table 4.

Now we will estimate electric vehicles' impact on the non-ferrous metal markets described above until 2050, using a scenario approach. The relevant effects were in several stages:

1. The market for lithium electric vehicle batteries quickly changes due to active R&D, which lead to replacing some of the chemical components with others. Two battery types with the largest potential were identified: NCX (NCM and NCA), and LFP (Xu et al., 2020; Maisel et al., 2023).

[7] https://about.bnef.com/blog/lithium-ion-battery-pack-prices-hit-record-low-of-139-kwh/, accessed on 15.03.2025.

[8] https://carnewschina.com/2023/12/27/volkswagen-backed-jac-yiwei-ev-powered-by-sodium-ion-battery-starts-mass-production-in-china/, accessed on 15.03.2025.

Table 4. **List of Non-Ferrous Metals under Consideration, Their Specific Characteristics, and Application in Electric Vehicles**

Non-ferrous metal	Application in electric vehicles	Specific characteristics
Lithium	A key cathode component in all types of lithium-ion batteries (positively charged ions carry electric charge)	About 95% of the production and 80% of the reserves are concentrated in four countries: Australia (4 enterprises), China (3), Argentina (2), and Chile (2). More than 90% of battery and component production capacities are located in Asian countries, first of all China (over 70%).
Nickel	Cathode component in NCM- and NCA-type batteries	The main application is the production of steel and alloys. The largest producers are Indonesia and the Philippines (about 60% of global output). Russia, Australia, and Brazil also have significant reserves. Russia is a leading supplier of high-quality nickel for electric vehicle batteries (20% of global supply).
Cobalt	Cathode component in NCM- and NCA-type batteries	More than 70% of global production is concentrated in the Congo, which has almost half of the world's reserves. Global supply chains are controlled by China, which is the world leader in the production of industry-ready cobalt.
Manganese	Cathode component in NCM-type batteries	The main consumer is metallurgy (steel production). Global reserves are estimated as significant; about 85% of profitable reserves are located in South Africa, Australia, Brazil, China, and Ukraine. Can be replaced by aluminium in the widely used NCA technology.
Aluminium	Cathode component in NCM-type batteries; also applied to make elements and packaging (electrode foil, case material) for all battery types	Applied in areas where the weight of the product is critical. About 90% of bauxite (raw material) mining is concentrated in Australia, Guinea, China, Brazil, Indonesia, and India. More than 50% of the enrichment and primary metal production are carried out in China; other countries' shares do not exceed 6%-7%. Can be easily recycled many times over.
Copper	The main cable and wire material in all electric vehicle types	The largest global players are Chile and Peru. Reserves have been discovered and explored on all inhabited continents and are estimated to be sufficient.

Source: authors, based on (US Geological Survey, 2024; Xu et al., 2020; Yao, Luman, 2021).

The shares of each battery type were determined on the basis of estimates available in (Maisel et al., 2023). The scenarios presented in this study, initially built for the period until 2040, were extrapolated to 2050 maintaining the original logic. The authors built two battery market growth scenarios depending on the prevailing electric vehicle technology. The NCM scenario assumes the dominance of NCM-type batteries, with a gradually increasing share of nickel. The key metals here are lithium, nickel, cobalt, manganese, and aluminium. The LFP scenario is based on the predominance of LFP-type batteries, with key metals being lithium and aluminium.

Each scenario assumes similar battery designs for both the passenger and commercial segments; the only difference being in capacity.

Data on different battery types' metal content in relation to their power, used to calculate battery composition and build the scenarios, is presented in (Maisel et al., 2023). Data on battery power required for passenger and commercial BEVs is available in the IEA reports for 2023 and 2024 (IEA, 2023; IEA, 2024). Considering that the commercial segment includes three vehicle types (light commercial vehicles, trucks, and buses), the market structure data for 2023 was used to calculate the average battery power (IEA, 2023). In the end, the required power for passenger BEVs was set at 60 kW, for passenger PHEVs at 15 kW, for commercial BEVs 211 kW, and for commercial PHEVs at 50 kW. The composition of various battery types is described in Appendix 3.

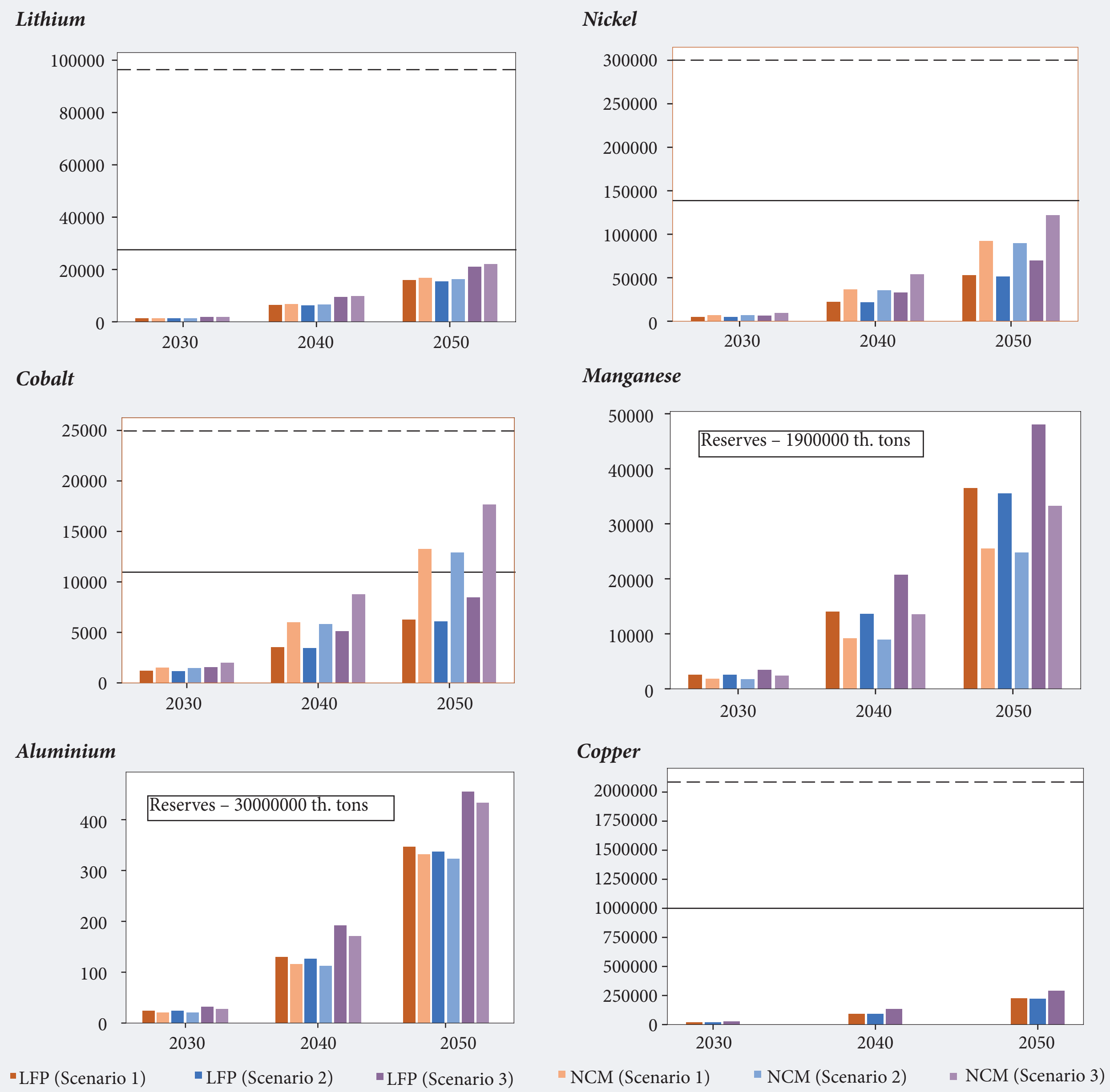
Composition was considered at the battery level, so materials needed to make wiring and casing, including copper and aluminium, have not been directly taken into account when building the scenarios.

2. Empirical data was used to calculate the amount of copper in an electric vehicle. A passenger BEV contains 89 kg, a commercial one 200 kg, a passenger PHEV 40 kg, and a commercial PHEV 89 kg (ICA, 2017). Unlike other metals, which have been taken into account only regarding their application in batteries, copper content values were calculated at the level of the entire battery pack ready for installation in the vehicle.

3. At the final modeling stage, scenarios for cumulative demand for each non-ferrous metal for 2024-2050 were built, on the basis of the following estimates::

1) chemical composition of electric vehicle batteries;
2) non-ferrous metals' content in batteries, fuel cells, and conductors;
3) new electric vehicle sales.

Figure 8. **Cumulative Demand for Non-ferrous MetalsApplied in Electric Vehicle Batteries, Under Different Scenarios (thousand tons)**



Note: solid line denotes reserves, dotted one resources.

Source: authors.

For metals applied in batteries, an additional breakdown into NCM and LFP was made.

4. The obtained estimates of demand for non-ferrous metals were then compared with the data on their explored reserves and available resources. The latter was understood as the availability of the chemical elements in the earth's crust in a form and quantity, which would economically justify mining, now or in the future. Reserves were understood as the part of available resources mining which would be feasible in the current economic situation, given the present-day requirements for raw materials' physical and chemical characteristics and the technology level.

Graphs for comparative analysis are presented in Figure 8, numerical values in Appendix 4.

The electric vehicles' impact on non-ferrous metal markets can be minimal, moderate, significant, or substantial. The following criteria were used to classify the metals into these categories:

1) how much metal is needed to meet the demand for electric vehicles;
2) country structure of metal production, reserves, and available resources;
3) possibility of metal recycling and secondary use.

Substantial Market Impact: Cobalt

Under the NCM scenario, demand for cobalt may exceed the available reserves. Even under the LFP scenario, demand would reach 55%-77% of the reserves. Given that 74% of the current production and 55% of proven reserves are in the Democratic Republic of the Congo, significant price discrimination is possible if the shortage increases.

Currently, recycling lithium-ion batteries is often less profitable and riskier than mining and purchasing the metal. The main reasons include commodity markets' volatility, the remote location of recycling plants, problems with transporting batteries, and their diverse designs. Shipping batteries to a recycling site accounts for about 40% of the overall process costs (Slattery et al., 2021). This is due to their large weight and the high technical requirements for transportation. Sometimes it is easier for car dealers to ship the entire electric vehicle to the recycling site than extract and transport the battery.[9]

Given that battery production is expected to keep growing, not only for electric vehicles but also for energy storage systems, its impact on the cobalt market could be significant).

Significant Market Impact: Lithium and Nickel

Total demand for lithium to manufacture electric vehicles could reach 55%-78% of the current reserves, which is significant given the high demand for lithium-ion batteries in other industries. Lithium-free alternatives do exist, but their technological readiness remains low. An additional factor is the fact that 79% of reserves are concentrated in four countries, while more than 90% of production capacities are located in the Asia-Pacific region and South America. This strengthens their negotiating positions in the dialogue with North American and European manufacturers.

The demand for nickel may amount to 40%-94% of the reserves, while batteries currently account for about 7% of this metal consumption (IEA, 2022). The share of nickel in NCM-type batteries will grow, replacing more expensive elements, first of all cobalt (Barber, Marshall, 2021). The future of the nickel market will be affected by multidirectional factors: about 20% of the world's battery-grade nickel is produced in the Russian Federation, which in the current geopolitical situation creates market pressure (IEA, 2022). On the other hand, recycling and reuse capacities are being developed in nickel's main application area, alloy production.

Recycling used batteries to recover lithium and nickel has the same limitations as in the case of cobalt, but lithium and nickel recovery is even less cost-effective (Barber, Marshall, 2021).

Moderate Market Impact: Copper

By 2050, cumulative demand for copper for use in electric vehicles may amount to 23%-30% of its reserves. Despite the availability of sufficient processing capacities, this value is significant, since the main consumers of copper are the energy and construction sectors where the development of renewable energy sources and distributed generation support high demand.[10] Growing demand for copper in the automotive industry may lead to a structural change in the market, and the emergence of competition for available supply with the traditional consumers of the metal.

Minimal Market Impact: Manganese and Aluminium

Aluminium and manganese markets were estimated to be minimally affected by the increased adoption of electric vehicles because of the small aggregate demand for these metals relative to their reserves in 2050: less than 0.1% for aluminium, and 1.3%-2% for manganese. Though only aluminium directly used in batteries was considered in this paper, this metal's reserves significantly exceed the demand for it. Also, aluminium is relatively easy to recycle and is already among the most recycled and reused materials. About 75% of mined aluminium still remain in circulation. [11] Aluminium and manganese

[9] https://www.wired.com/story/cars-going-electric-what-happens-used-batteries/, accessed on 15.03.2025.
[10] https://ar2020.nornickel.com/commodity-market-overview/copper, accessed on 15.03.2025.
[11] https://www.aluminum.org/Recycling, accessed on 15.03.2025.

reserves are sufficient to meet the demand for electric vehicle batteries.

Conclusion

The study analyzed how increased the adoption of alternative-fuel vehicles will affect global non-ferrous metal markets until 2050.

Electric vehicles (BEVs and PHEVs) have the greatest potential to dominate the alternative-fuel vehicle segment. They are characterized by a near-zero direct carbon footprint, growing penetration of global markets, and steadily declining prices and TCO supported by incentives offered by national governments and created by economies of scale.

According to our scenario analysis, by 2050 the share of passenger BEVs in sales may reach 90%-100%, while the share of PHEVs will reach a peak of 10%-11% around 2030 and then begin to decline. In the commercial segment, the share of BEVs by 2050 may reach 73%-90%, while that of PHEVs will not exceed 4% throughout the entire period under consideration. The demand for non-ferrous metals to manufacture electric vehicles was compared with the main characteristics of these metals' markets: the amount of reserves and resources, the country structure of production, and major industry consumers. It was established that in the long term, wide adoption of electric vehicles can significantly impact the cobalt market, moderately impact the lithium, nickel, and copper ones, and only minimally affect the manganese and aluminium markets.

Setting up a network of enterprises recycling electric vehicle components, which would cover major electric vehicle development hubs; increasing the density of electric charging station networks to allow the use of smaller-capacity batteries; and reusing spent electric vehicle batteries for stationary energy storage could facilitate balancing non-ferrous metal markets. The risk of significant shortages of nickel and cobalt can be overcome by redistributing the market in favor of LFP-type batteries that do not use these metals. Today, NMC batteries are being actively replaced by LFP ones. In particular, according to some estimates, the share of cobalt-containing batteries in China in 2024 will be 31%, compared to 44% in 2022.12 The sustainability of the copper market can be improved by increasing investments in secondary processing, and in exploring ore deposits currently classified as available resources.

The results of electric vehicle sales modeling are consistent with emerging market trends and the specifics of regional automotive markets, but the presented scenarios have a number of limitations and uncertainties, in particular:

1) highly uncertain prospects for the hydrogen segment, due to hydrogen-powered vehicles' being significantly inferior to PHEVs in terms of TCO and infrastructure availability parameters, which are key for consumers;

2) the rate of electric vehicle penetration into developing countries' markets with weak CO2 emission regulations and low economic and technological development;

3) potential disruptions in related industries, such as electricity generation and distribution;

4) potential disruptions in global component and material supply chains due to growing geopolitical tensions.

For energy storage and transmission technologies, key uncertainties are related to the possibility of radical changes in their components (e.g., the introduction of new lithium-sulphur and lithium-air batteries to the market) and the improvement in their recycling.

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